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Demand Controlled Ventilation (DCV) Systems in Commercial Buildings

Functional Requirements on Systems and Components

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Building Services Engineering
Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Demand controlled ventilation (DCV) is considered as an energy efficient solution for air-based cooling and indoor air quality control. Considerable energy savings can be achieved when the airflow rate is continuously adapted to the actual load condition. However, in order to assure the desired performance of the system, it is essential to know the requirements that the DCV system and its components should fulfil. The objective of this work has been to clarify the requirements for a well functioning DCV system. This includes cooling performance as well as sensor based air quality control. The work is based on theoretical analysis, field measurements of occupancy and system performance as well as laboratory investigations of DCV supply air diffusers and sensors for air quality control.

This thesis shows that it is possible to implement in existing as well as in new buildings an uncomplicated DCV solution that requires no active control dampers in the duct system. This, however, requires variable supply air diffusers with good airflow control properties and with a low noise generation even at a high pressure drop over the device. Also, in cooling applications the devices must provide a comfortable airflow pattern in the room within the entire airflow range and with low supply air temperature. In addition, the duct system must manage the wide airflow range, including the design minimum supply air temperature for cooling, with negligible heat gains. Tests carried out with such a DCV configuration show that high requirements set on the system components can be fulfilled.

An additional focus in this thesis is the application of DCV systems for air quality control. This requires sensors that can monitor the air quality and/or pollution to control the hygienic ventilation rate. Quantitative requirements for such sensors have been developed based on ventilation guidelines and standards. A detailed sensor study was carried out with a number of CO_2-sensors and mixed-gas sensors. Results show that, depending on the requirement, several tested CO_2-sensors could fulfil the established requirements set on sensors. However, the application of the tested mixed-gas sensors for ventilation control is undecided. It is not clear how the output of mixed-gas sensors should be interpreted. Another limitation comes from the lack of available standards describing acceptable concentrations for many common air contaminants for non-industrial buildings.

Finally, this thesis also provides some information on the actual occupancy patterns in a commercial building in operation. One year monitoring in an office building indicates that during 90 % of the time the aggregated occupancy in the building is equal to or less than about 53 %.

Keywords: CAV, CO_2-sensors, DCV, energy efficiency, indoor climate control, mixed-gas sensors, occupancy patterns, VAV, VAV diffuser

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Foreword

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Gothenburg, March 2009

Mari-Liis Maripuu

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0 Symbols, abbreviations and definitions

0.1 Symbols

0.1.1 Latin Letters

dA	surface area of a duct element, [m^2]
A_1	inner area of a duct layer per meter of length, [m]
A_2	outer area of a duct layer per meter of length, [m]
A_i	inner area of a duct per meter of length, [m]
A_o	outer area of a duct per meter of length, [m]
A_m	logarithmic middle area of a duct layer per meter of length, [m]
b	the ventilation rate for a unoccupied office divided by the ventilation rate for an occupied office
c_{pa}	specific heat capacity of air at constant pressure, [J/(kg·K)]
C_{gas}	gas concentration
C_S	corrected sensor reading of volume concentration, [ppm]
C_{iS}	gas concentration indicated by the test sensor, [ppm]
C_r	the pollutant concentration indoors, [ppm]
C_{sp}	the pollutant concentration in the supply air, [ppm]
C_{ref}	concentration of reference gas in the test chamber, ppm]
C_{CO2}	concentration of carbon dioxide in the gas bottle, [ppm]
C_{SA}	concentration of reference gas in the synthetic air gas bottle, [ppm]
C_{VOC}	concentration of the reference VOC gas in the gas bottle, [ppm]
C	VOC concentration measured with the Tenax sampling, [$\mu g/m^3$]
c_i	sensitivity coefficient
$\dot{C}$	heat capacity flow rate of air, [W/K]
DR	Draught Rating, [%]
D_h	hydraulic diameter of a duct, [m]
D	diameter of a duct, [m]
f_{mixing}	coefficient of mixing
f_{rec}	recovery factor due to possible breakthrough of acetone from the Tenax tubes sampled in a series
F	F-ratio in F-test in statistical analysis
K	factor which depends on the airflow rate and on the device setting
k	coverage factor
k_{VOC1}	coefficient for calculating from mass concentration of toluene to volume concentration of toluene
k_{VOC2}	coefficient for calculating from mass concentration of acetone to volume concentration of acetone
l	thickness of a duct layer, [m]
l_i	thickness of the insulation on a duct layer, [m]
L	duct length, [m]
l_c	characteristic length, [m]
L_0	perimeter area of a duct, [m]
$\dot{M}_a$	mass flow rate of air, [kg/s]
M_{VOC1}	estimated mass of toluene present in the sampling tube that was used in the test, [ng]

M_{VOC2}	estimated mass of acetone present in the sampling tube that was used in the test, [ng]
$\tilde{M}$	molar mass, [g/mol]
n	number of observations in a sample
N	number of input estimates x_i on which the measurement output depends
Nu	Nusselt number
P	probability value in a statistical analysis
PD	Percentage of dissatisfied due to indoor air quality, [%]
p_a	ambient pressure, [hPa]
p_0	pressure at standard test conditions, [hPa]
Pr	Prandtl number
Re	Reynolds number
r_i	inner radius of a duct, [m]
r_o	outer radius of a duct, [m]
y_j	j^{th} repeated observation of randomly varying quantity y
$\dot{q}_{tr}$	transmission heat loss, [W/m^2]
$d\dot{Q}_c$	change in the heat capacity of the air flowing along the duct, [W]
R_S	electrical resistance of the sensing element, [Ω]
R_L	load resistance, [Ω]
R_0	baseline resistance, [Ω]
$\tilde{R}$	gas constant, [J/(kmol·K)]
S_{rel}	relative sensitivity of mixed-gas sensors to different pollutant emission sources
S	output of the tested mixed-gas sensor at a given test condition with specified pollutant source
S_0	output of the tested mixed-gas sensor at an empty test room condition before the test with specified pollutant source
$s(\overline{X}_i)$	standard deviation of a sample mean of n independent repeated values for an input quantity X_i
s	simultaneity factor;
SFP	Specific Fan Power for design conditions, [kW/(m^3/s)]
SFP_A	Specific Fan Power for average airflow rates, [kW/(m^3/s)]
t_x	steady state air temperature along a duct, [°C]
t_a	air temperature, [ºC]
t_{in}	inlet air temperature of a duct, [°C]
t_{op}	operative temperature, [°C]
t_o	outside temperature of a duct, [°C]
t_{pr}	plane radiant temperature, [°C]
t_{room}	room air temperature, [°C]
$\bar{t}_r$	mean radiant temperature, [°C]
t_{supply}	supply air temperature, [°C]
T_a	ambient temperature, [K]
T_0	temperature at standard test conditions, [K]
u_l	linear thermal transmittance of a duct, [W/(m·K)]
U	expanded uncertainty of output estimate y that provides a confidence interval $Y = y \pm U$
U	thermal transmittance of a duct, [W/(m^2·K)]
U_n	supply voltage for the sensors, [V]

$u(x_i)$	standard uncertainty associated with the estimated value of each input quantity x_i
$u_c(y)$	combined standard uncertainty of output estimate y
u_e	expanded uncertainty of output estimate y
$u_c(c_S)$	combined standard uncertainty of the CO_2-sensor reading in the test chamber, [ppm]
$u_c(c_{ref})$	combined standard uncertainty of the estimated reference concentration in the test chamber, [ppm]
$u(t_{cal})$	uncertainty assigned to the calibration of a temperature sensor, [°C]
$u(t_{dif})$	uncertainty associated with comparison of a temperature sensor with a reference instrument, [°C]
$u(t_{log})$	uncertainty assigned to the measurement with the logging system to which the temperature sensor is connected, [°C]
$u(t_{read})$	uncertainty assigned to the reading from the reference temperature instrument, [°C]
$u(t_{inst})$	uncertainty assigned to the positioning of the temperature sensors, [°C]
$u(t_{res})$	uncertainty assigned to truncation due to the resolution of the logger to which the temperature sensor was connected, [°C]
$u(\dot{V}_{cal})$	uncertainty assigned to the calibration of the airflow measuring devices, [%]
$u(\dot{V}_{inst})$	uncertainty associated with the installation of the airflow measurement devices into the supply air duct, [%]
$u(\Delta p_m)$	uncertainty associated with measuring differential pressures with the electronic pressure transmitter connected to the logging system, [%]
$u(\varphi_{cal})$	uncertainty assigned to the calibration of a humidity sensor, [%]
$u(\varphi_{log})$	uncertainty assigned to the measurement with the logging system to which the humidity sensor is connected, [%]
$u(\varphi_{res})$	uncertainty assigned to truncation due to the resolution of the logger to which the humidity sensor was connected, [%]
$u(C_{CO2})$	uncertainty due to variable composition of the carbon dioxide in the gas bottle, [ppm]
$u(C_{SA})$	uncertainty due to variable composition of the synthetic air in the gas bottle, [ppm]
$u(V_{CO2})$	uncertainty of measurement of high concentration CO_2-gas with the gas flow measuring and control equipment, [l/min]
$u(V_{SA})$	uncertainty of measurement of synthetic air with the gas flow measuring and control equipment, [l/min]
$u(f)$	uncertainty associated with mixing the reference gas with synthetic air and possible concentration gradients inside the test chamber
$u(C_{log})$	uncertainty assigned to the measurement with the logging system to which the test sensors were connected, [ppm]
$u(C_{res})$	uncertainty assigned to the truncation due to the resolution of the logger, [ppm]
$u(C_{iS})$	uncertainty associated with the CO_2-sensor readings, [ppm]
$u(T_a)$	uncertainty associated with estimating the temperature value in the test chamber, [K]
$u(p_a)$	uncertainty associated with estimating the ambient pressure, [hPa]
$u(M_{VOC1})$	uncertainty associated with determining the mass of toluene present in the Tenax sampling tube, [ng]

$u(\tau_{tenax})$	expanded uncertainty associated with estimating the sampling time, [min]
$u(\dot{V}_{tenax})$	uncertainty associated with measuring the airflow rate through the Tenax adsorption tube, [l/min]
$u(M_{VOC2})$	uncertainty associated with determining the mass of acetone present in the Tenax sampling tube, [ng]
$u(f_{rec})$	uncertainty associated with the recovery factor.
$u(C_{VOC1})$	uncertainty associated with the variable composition of VOC gas (toluene) in the gas bottle, [ppm]
$u(C_{SA})$	uncertainty associated with the variable composition of the synthetic air in the gas bottle, [ppm]
$u(V_{VOC1})$	uncertainty associated with the measurement of reference VOC-gas with the gas flow measuring and control equipment, [l/min]
v	air velocity in the duct, [m/s]
v_a	local mean air velocity, [m/s]
v_{ar}	relative air velocity, [m/s]
v_d	supply air velocity from the diffuser, [m/s]
V_C	circuit supply voltage in a sensor transducer, [V]
V_{out}	output signal from the sensor transducer, [V]
$\dot{V}$	air volume flow rate, [l/s]
$\dot{v}_{olf}$	specific airflow rate, l/s per olf;
$\dot{V}_{CO_2}$	flow rate of high concentration carbon dioxide from the gas bottle, [l/min]
$\dot{V}_{SA}$	flow rate of synthetic air from the gas bottle, [l/min]
$\dot{V}_{tenax}$	airflow rate through the Tenax adsorption tube by active pumping, [l/min]
$\dot{V}_{VOC1}$	flow rate of the high concentration VOC gas (toluene) from the gas bottle, [l/min]
$\dot{V}_p$	pollutant generation rate, [l/s]
$\dot{V}_{\min}$	minimum air volume flow rate, [l/s]
$\dot{V}_{\max}$	maximum air volume flow rate, [l/s]
$\dot{V}^{Design}$	design airflow rate, [m^3/s]
$\widetilde{V}$	molar volume, [dm^3/mol]
$\dot{W}_t^{Design}$	design fan power, [m^3/s]
W	absolute humidity, [g/kg]
X_j	j^{th} repeated observation of randomly varying input quantity X_i
$\overline{X}_i$	arithmetic mean of n repeated observations of randomly varying input quantity X_i

0.1.2 Greek letters

α_i	convective heat transfer coefficient between the air and inner duct surface, [$W/(m^2 \cdot K)$]
α_o	heat transfer coefficient between the outside air and outside duct surface, [$W/(m^2 \cdot K)$]
λ_d	thermal conductivity of a duct layer, [$W/(m \cdot K)$]

λ_i	thermal conductivity of a duct insulation layer, [W/(m·K)]
λ_m	thermal conductivity of metal, [W/(m·K)]
λ_{air}	thermal conductivity of air, [W/(m·K)]
Δt_{rel}	relative temperature change along the duct
$\Delta\dot{V}$	deviation in airflow rate, [l/s]
Δc_r	uncertainty of measurement of the pollutant concentration indoors, [ppm]
Δc_S	uncertainty of measurement of the pollutant concentration in the supply air, [ppm]
$\Delta(c_r\text{-}c_S)$	uncertainty of measurement of the concentration deviation, [ppm]
ΔPD	deviation in percentage of dissatisfied, [%]
Δp_m	measured pressure difference in the measuring device, [Pa]
Δp_{dif}	pressure difference in the test room measured with a manometer.
φ	relative humidity, [%]
τ_{63}	time constant , [min]
τ_{90}	rise time 90%, [min]
τ_{80}	rise time 80%, [min]
τ_{tenax}	sampling time for the Tenax test, [min]
υ	kinematic viscosity of air, [m^2/s]
ρ	density of air, [kg/m^3]

0.2 Abbreviation

ANOVA	ANnalysis Of VAriance
ABC	Automatic Baseline Correction
ACR	Air Change Rate
AQ	Air Quality Class
BTA	gross thermally controlled area of a building
CAV	Constant Air Volume flow
CC1	frequency inverter with PID control
CC2	Control Centre
CD	Connection Duct
CLIMPAQ	Chamber for Laboratory Investigations of Materials, Pollution and Air Quality
COD	Control-On-Demand
D	Duct diameter
DCV	Demand Controlled Ventilation
ED	Exhaust air device
EF	Exhaust air fan
F	Duct Filter
FID	Flame Ionization Detector
FM	Flow Measurement
HC	Heating Coil
HVAC	Heating, Ventilation, Air-Conditioning
IAQ	Indoor air quality
LOA	non-residential building floor area
MEMS	Micro Electronic Mechanical Systems
MOS	Metal Oxide Semiconductor
NDIR	Non-Dispersive InfraRed
OF	Occupancy Factor
P	Proportional Control
PC	Personal Computer
PD	Percentage of Dissatisfied due to indoor air quality

PI	Proportional-Integral control
PID	Proportional-Integral-Derivative control
PPD	Predicted Percentage of Dissatisfied
PS	Pressure sensor
SC	Suspended Ceiling
SD	Standard Deviation
SA	Sound Attenuator
SF	Supply-air Fan
T	Thermometer
TS	Temperature Sensor
VAV	Variable Air Volume flow
VOC	Volatile organic compound
$TVOC_{GC}$	Total volatile organic compound measured with gas chromatography
$TVOC_{PAS}$	Total volatile organic compound measured with photoacoustic spectroscopy

0.3 Definitions

Accuracy: defined in chapter 3.2.2.1.
Active control damper: an actuator controlled damper
Baseline offset: defined in chapter 3.2.2.1.
Coanda effect: A negative pressure or suction that pulls each layer of the air in a surface-close jet towards the surface
Constant air volume flow system: defined in chapter 1.1.2.
Cross-sensitivity: defined in chapter 3.2.2.1.
DCV diffuser: A VAV diffuser, which changes its outlet configuration automatically to suit a controlled supply-air flow rate. A DCV diffuser includes all the control and regulating equipment for automatic control of the airflow rate.
Demand controlled ventilation: defined in chapter 1.1.3.
Diversity factor: defined in chapter 4.3.3.
Draught: an unwanted local cooling of the human body caused by air movement in the room.
Draught rating (DR): Percentage of people predicted to be bothered by draught and is based on studies on people at light sedentary activity, with an overall thermal sensation for the whole body close to neutral.
Drift: defined in chapter 3.2.2.1.
Electrochemical sensor: defined in chapter 3.3.1.2.
Fall time: defined in chapter 3.2.2.1.
Hygienic ventilation rate: The ventilation airflow rate determined by requirements on air-composition or air-quality.
Hysteresis: defined in chapter 3.2.2.1.
Indoor air quality: Condition of air perceived by humans, which depends both on the substances in the air and the individual persons exposed to the substances.
Indoor air quality sensors: defined in chapter 3.1.
Input range: defined in chapter 3.2.2.1.
Linearity: defined in chapter 3.2.2.1.
Metal oxide semiconductor sensor: defined in chapter 3.3.1.1.
Minimum detectability: defined in chapter 3.2.2.1.
Mixed-gas sensor: defined in chapter 3.3.1.1.
Non-dispersive infrared sensor: defined in chapter 3.3.1.3.
Occupancy factor: defined in chapter 4.3.1.3

PPD index: Predicted percentage of dissatisfied index establishes a quantitative prediction of the number of thermally dissatisfied people.
Relative sensitivity: defined in chapter 3.2.2.1.
Reliability: defined in chapter 3.2.2.1.
Repeatability: defined in chapter 3.2.2.1.
Reproducibility: defined in chapter 3.2.2.1.
Resistance to environmental conditions: defined in chapter 3.2.2.1.
Resolution: defined in chapter 3.2.2.1.
Response time: defined in chapter 3.2.2.1.
Rise time: defined in chapter 3.2.2.1.
Selectivity: defined in chapter 3.2.2.1.
Sensing element: defined in chapter 3.2.1.
Sensitivity: defined in chapter 3.2.2.1.
Sensor: defined in chapter 3.2.1.
Sensor baseline: defined in chapter 3.2.2.1.
Sensor uncertainty: defined in chapter 3.2.2.1.
Signal conditioning: defined in chapter 3.2.1.
Simultaneous factor: defined in chapter 4.3.3.
Solid-state electrolyte sensor: defined in chapter 3.3.1.2.
Span offset: defined in chapter 3.2.2.1.
Stability: defined in chapter 3.2.2.1.
Thermal comfort: Condition of mind which expresses satisfaction with the thermal environment [101].
Time constant: defined in chapter 3.2.2.1.
Transducer: defined in chapter 3.2.1.
Transmitter: defined in chapter 3.2.1.
Variable air volume flow system: defined in chapter 1.1.2.
VAV box: An airflow control device in the duct, which consists of control section including a damper for airflow measurement and a sound attenuator for decreasing the noise generated by the damper.
VAV diffuser: A supply air diffuser with the outlet configuration of which may be changed to suit a variable air flow rate.
Warming-up time: defined in chapter 3.2.2.

1 INTRODUCTION

Demand Controlled Ventilation (DCV) is a method to continuously match the ventilation airflow rate with the actual demand. This is a natural answer to the frequently asked question on how to maintain or improve the indoor climate and simultaneously reduce the use of energy.

In order to understand this concept and the functional properties of such systems it is essential to first provide some background. This chapter presents the concept of controlling ventilation based on the demand. In addition, the objectives and scope of this thesis will be presented, as well as the structure of the thesis and a summary of the state-of-the-art review on DCV systems.

1.1 Background

This chapter introduces the basic requirements set for indoor climate control and the possible technical solutions to fulfil them. Additionally the concept and definition of demand controlled ventilation that is applied in the current thesis is presented.

1.1.1 General

In commercial buildings the need of energy for operation of the building services systems often accounts for a substantial part of the total energy use. For example, in Swedish office buildings the electrical energy needed for building services systems may account for about 40 % of the total electricity use[69]. In schools and hospitals the need for electrical energy for building services is audited to be just above 50 %[68, 70]. This includes electrical energy needed for fans, pumps, water chillers, heat pumps, etc. The energy needed for the fans in these types of premises may account up to 35 % of the total electrical energy use, e.g. for hospitals. Additionally, the need of heat for supply air heating can constitute to a considerable part of the total need of heat, depending on the air-to-air heat recovery systems.

For the real estate owners it is of interest to keep the running cost of the building at a low level and provide good terms and conditions for the tenants. Therefore, finding more energy efficient heating, ventilating and air conditioning system solutions has become of great interest. Energy conservation measures are looked for both when retrofitting existing buildings and building new ones.

1.1.2 Ventilation systems for comfort and indoor air quality

The main goal of heating, ventilating and air-conditioning systems is to create a good indoor climate for building occupants, with reference to indoor air quality, thermal comfort and acoustic environment. These parameters may have a significant influence on health and productivity[77, 216].

The requirements on indoor air quality from the occupants side are firstly that there should not be a health risk and secondly that the air should be perceived as fresh and pleasant[39]. It must be noted that indoor air quality refers to the condition of air as perceived by humans. It depends both on the substances in the air and the individual persons exposed to the substances. With ventilation and air conditioning systems it is possible to influence only the composition of air in the rooms.

The requirements for thermal comfort define the thermal conditions that the building occupants would perceive to as acceptable. Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment[101]. The human response to the thermal environment depends on parameters such as air temperature, mean radiant temperature, air velocity and air humidity. It also depends on personal factors such as the occupants' physical activity and the thermal resistance of the clothing.

The requirements for the acoustic environment define the maximum acceptable noise levels generated by the different installations, including heating, ventilating and air-conditioning systems. These noise levels should be kept in a level that will not cause a significant nuisance or health effects for building occupants and will not disturb work.

Figure 1.1 illustrates the principle possibilities of a technical system to influence the thermal climate and air composition in a room[73]. This may be accomplished by terminal units connected to a space such as heating units, cooling units, dehumidifiers, humidifiers, filters, addition or removal of gases, etc. Each terminal unit may be controlled in relation to a defined demand. This is referred to as Control-On-Demand (COD). If, for instance, the room temperature is controlled by means of heating units and cooling units in a constant air volume air-handling unit, this is air-conditioning Control-On-Demand.

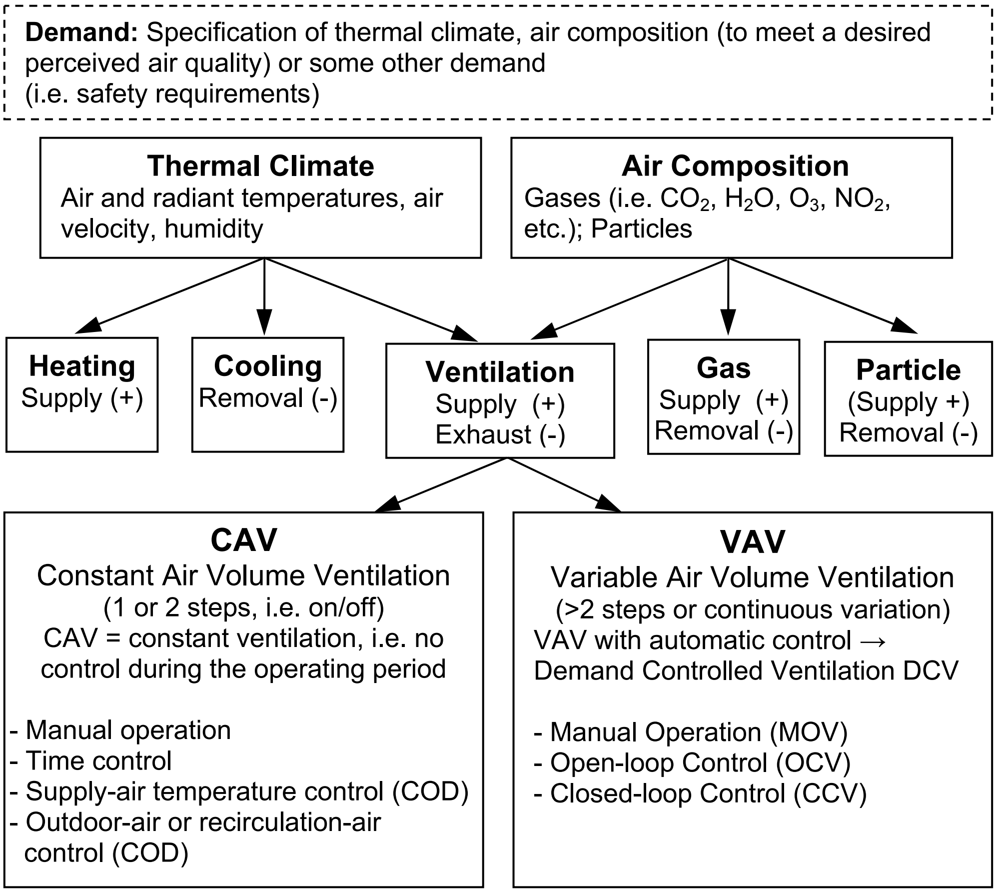

Figure 1.1 HVAC possibilities to influence the thermal climate and air composition of a room[73]. DCV is one of many Control-On-Demand solutions.

The demand at room level may also be met by adjusting the removal rate of pollutants and/or excess heat by means of ventilation airflow rate. There are two principally different ways to control the indoor climate with mechanical ventilation systems. The pre-conditioned air can be supplied to the room with Constant Air Volume (CAV) flow system, based on the peak load conditions or with Variable Air Volume (VAV) flow system, adapted to the specific conditions in the room.

A constant air volume flow system is here defined as a system where no continuous control of airflow rates to the room/ zone is applied. However, the ventilation airflow rates can be time controlled or manual controlled up to certain stages, e.g. on/off airflow control. Additionally, systems where the amount of fresh air and return air are varied so that the total supply airflow rate is constant are also considered as CAV systems. A VAV system in this thesis is defined as a ventilation system where the airflow rates are continuously varied. The flow of a VAV system may vary according to a predetermined pattern or it may be determined by actual demand, e.g. demand controlled ventilation, DCV[73]. In this study, a VAV system is taken to imply a system with continuous variation or variation in more than two steps.

The selection of the ventilation system approach is very much dependent on the variability of the loads in the rooms that the ventilation system is designed to meet, such as pollutant emissions, heat loads, etc. If the total loads are fairly constant a CAV system should be considered rather than a VAV system. However, when the loads are varying in time, which is common in commercial buildings, a VAV system would be advantageous in terms of energy use. If the airflow rate is continuously adapted to the actual load conditions, considerable energy savings can be achieved[96, 113, 208]. The average air volume flow rate will be lower and the energy needed for air distribution as well as for supply air heating and cooling is reduced[72, 99, 127].

1.1.3 Demand Controlled Ventilation (DCV) and VAV

In the literature there are different and often confusing concepts and definitions regarding demand controlled ventilation. Very often DCV is referred to indoor air quality control only. Furthermore, some reports state that DCV is based on variable air volume flow systems, while other reports describe that both CAV and VAV system solutions can be applied.

For example, in IEA Annex 18[153] report a DCV system is defined as follows: “Demand controlled ventilating system is a ventilation system in which the air flow rate is governed by measured or perceived level of airborne pollutants. Such a DCV system can utilize manual or automatic controls”. The technical system solutions for controlling the indoor air quality, referred to as DCV system strategies, can be time controlled CAV systems or VAV systems controlled by sensors, depending on the load profile and chosen ventilation profile over time.

The current European standard, EN13799:2007[64], defines the DCV system as “a ventilation system, where the ventilation rate is controlled by air quality, moisture, occupancy or some other indicator for the need of ventilation”. This definition implies that VAV systems are applied for demand controlled ventilation. Furthermore, there is no clear indication whether ventilation based on temperature control is also considered as part of DCV.

In other reports a wider concept is proposed for DCV [121, 205]. According to Sørensen[205], DCV should be considered as an overall ventilation strategy (“the software”) for governing the ventilation system (“the hardware”) in order to meet the predefined demands on indoor climate. The ventilation system solution itself can be based on constant or variable air volume flow rate.

This thesis adapts a concept of DCV as a ventilation system with automatic variation of airflow rate with demand. A following definition is applied, proposed by Fahlén[73]:

"Demand Controlled Ventilation system is a ventilation system with feed-back and/or feed-forward control of the air flow rate according to a measured demand indicator. Demand is decided by set values affecting thermal comfort and/or air-quality. The main factor for thermal comfort is the thermal state in terms of temperature and humidity (specific enthalpy). The main factor for air-quality is the composition of air in terms of gases, particles etc. The ventilation flow rate, as determined by requirements on air-composition or air quality, is known as the hygienic ventilation flow rate. Control may rely on the measured state of air (feed-back control), the measured load (feed-forward or predictive control) or a combination of these."

According to this concept a DCV system requires a VAV system and most VAV systems, but not all, operate as DCV systems[73]. Only the VAV systems where the airflow rate varies according to the actual demand and not based on the predetermined pattern or by manual operation are considered as DCV systems. This report concentrates on such VAV systems. Figure 1.2 indicates the principle control possibilities of a VAV system and the concept of DCV used in this report.

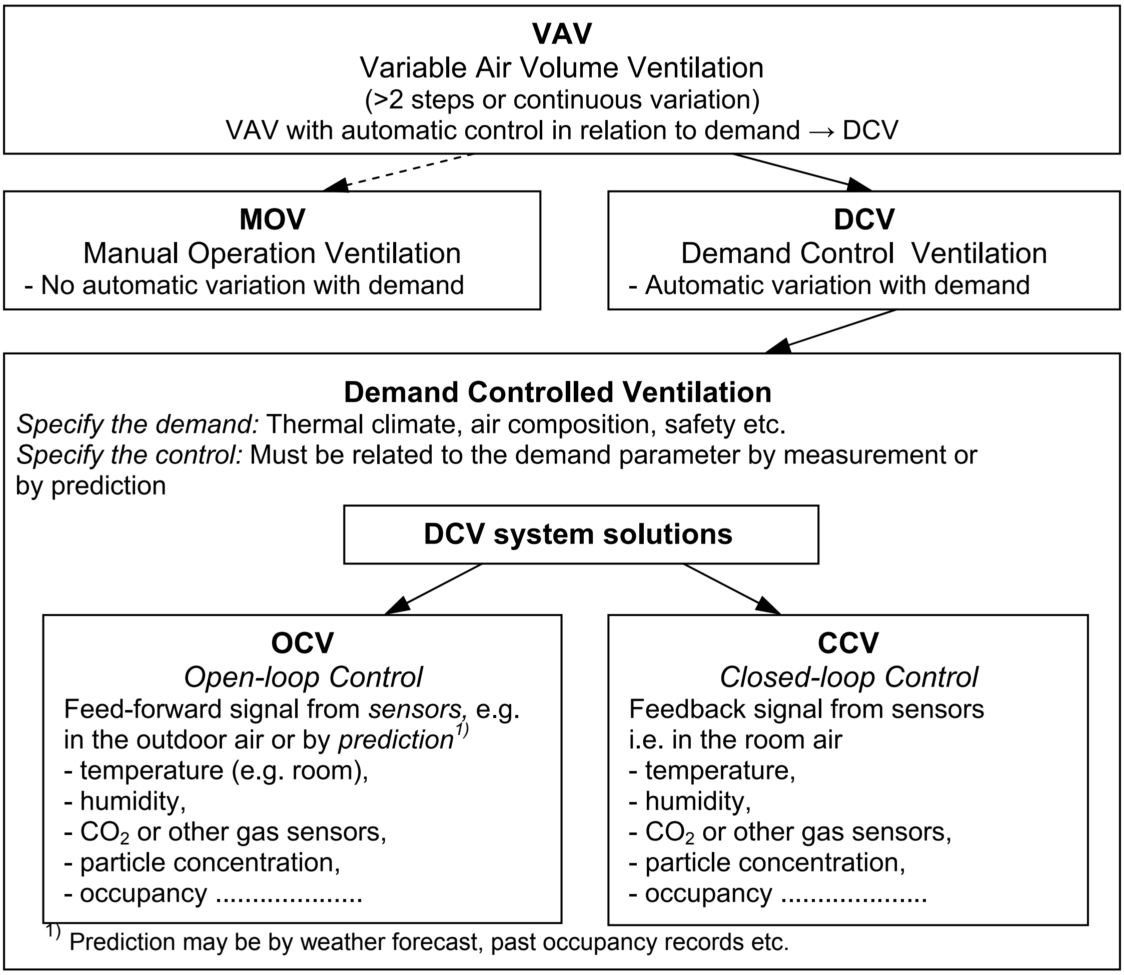

Figure 1.2 Classification of VAV and DCV systems.

It should be noted that the hygienic flow rate is decided by requirements on air composition and air quality. For convenience, we shall only use the term “air quality” in the discussion, even though in most DCV systems the demand indicators actually refer to the air-composition. Commonly used air quality indicators are carbon dioxide, volatile organic compounds (VOCs), air humidity in dwellings, the presence of people (occupancy) or operating equipment in a room. Emissions from building materials are considered as a constant background level, requiring a minimum basic ventilation rate, and not as a potential for demand control ventilation systems.

1.2 Objectives and scope

Adapting the ventilation to the actual requirement can very often substantially reduce the energy consumption of a ventilation system. However, when advanced system solutions are applied for indoor climate control, they should be as simple as possible to apply and operate, especially from a control point of view. Due to more complex design of a DCV system careful commissioning and maintenance is required in order to achieve the expected performance. The common problems associated with these systems concern indoor climate in rooms[177, 192, 207], but also operational and control problems have occurred[47, 49]. These faults have been reported to be due to improper design, installation or operation of the systems[100, 135, 138, 219]. In order to assure the desired performance of the system, it is essential to know the requirements that the DCV system and its components should fulfil.

The aim of this work is to:

- clarify the requirements for a well functioning DCV system and its components, in particular for airflow control devices and sensors applicable to indoor air quality control;
- evaluate, through experiments, to which extent these requirements are fulfilled by commercially available components;
- contribute to the knowledge of occupancy patterns in office buildings as a design guideline for application of DCV systems.

A special focus in this thesis is on uncomplicated DCV system solutions that are possible to implement in existing buildings as well as in new ones. Requirements on system components for such system solutions are analysed in detail from indoor climate, energy use, and technical points of view. Additional focus is placed on DCV systems for indoor air quality control. The prerequisites for sensors controlling the hygienic airflow rates are analysed and evaluated in detail.

1.3 Methodology and the key topics in this work

This thesis is divided into different sub-topics consisting of different studies as follows:

- *Comprehensive literature review*
  In order to analyse the requirements that must be set on a DCV system it is first essential to get an overview of the development and application of DCV. A thorough literature review has been carried out, with the special focus on DCV systems for indoor air quality control. Control of thermal comfort with a DCV system is not covered in the literature review of this study. This is partly because in the past DCV has been related to indoor air quality control, while DCV systems for thermal comfort control have been often referred to as VAV systems. An overview

of literature on various aspects of design, control and performance of temperature controlled DCV systems is listed by Shepherd [192]. However, some technical issues related to application of temperature controlled DCV are also discussed in the current literature review.

- *Clarifying the requirements on air distribution components in a simplified DCV system solution*
  When clarifying the prerequisites for a well functioning DCV system a special focus has been to study DCV system solutions that are not so complicated from a system control point of view. One criteria of an uncomplicated system is that the number of controlling components is minimized. Adapting DCV in a building without having to install active control dampers in the duct system is one way of building up a simple DCV system. The active control damper is defined as an actuator controlled damper. However, to build up a system without active dampers some special requirements must be set upon the air distribution components. These requirements have been analysed in this study. The function of one example of technical solution is tested both under laboratory conditions and in the field focusing on thermal comfort in the room and energy use of the system.

- *Clarifying the requirements for a duct system with variable airflow rate and low inlet temperature*
  Additional energy savings can be achieved if the supply air temperature to the room can be decreased. This will not only give energy savings in supply air heating during cold periods of the year, but it will also improve the cooling capacity of the air supplied to the room and lead to a better control of the room temperature. Thus, the average airflow rates needed for cooling are reduced even more. However, with the decreased airflow rates in ducts, the heat gains can have a significant effect on the supply air temperature. A mathematical calculation has been conducted to evaluate the temperature change in the air distribution system under varying airflow conditions. Additionally, measurements and simulations were carried out with a duct system with variable airflow rate in the field. Also the means of decreasing the heat gains in the cooled air system have been evaluated.

- *Formulation of requirements on DCV sensors*
  One of the key issues in the application of DCV systems is the choice of indicators that represent the demand. Here the available sensor technologies are the influencing factor. The requirements that must be set on the sensors for indoor air quality control have been analysed in this study. The performance characteristics of commercially available sensors have been evaluated in the laboratory and in the field. The analysis and evaluation is limited to sensors measuring the concentration of gases other than water vapour.

- *Study of occupancy patterns in an office building*
  The aim of applying DCV systems is to ventilate buildings more energy efficiently, by adapting the conditioned air to various time-dependent load conditions. Therefore, it is essential for DCV application to have an overview of the expected load conditions and their profiles. The last part of this work consists of a study on occupancy patterns in an office building. Field monitoring on occupancy conditions was carried out for a period of one year.

1.4 Outline of the thesis

The introductory part, chapter 1, gives the background and the objectives of the current work. The description of the chosen methodology and the key topics in this thesis is also included here. In addition, a summary of conducted state-of-the-art review of demand controlled ventilation is presented.

In chapter 2, the prerequisites for a DCV system without active control dampers in the ducts are discussed. Laboratory and field studies with possible technical solutions are described and results with discussion and conclusions are presented. The heat gains in a duct system with variable airflow rate are evaluated mathematically and verified in a duct system in the field.

Chapter 3 concentrates on evaluation of sensors applicable for indoor air quality control in a DCV system. First the requirements that must be set on DCV sensors are analysed and quantified. The performance of commercially available sensors has been evaluated through four separate studies. This chapter presents the methodology used in these studies and the results obtained with discussion and conclusions.

The evaluation of occupancy patterns in office buildings is described in chapter 4. The chapter concentrates on a conducted study in one office building.

The final discussion, conclusions and recommendations for future research are given in chapter 5.

Appendix A presents the state-of-the-art review of demand controlled ventilation systems.

Appendix B gives the detailed description of the experimental set-up and measurement techniques used in the different studies.

Appendix C describes the evaluated uncertainties of measurement for different experiments

Appendix D shows the indoor climate questionnaires that were used in two case studies.

1.4 Summary of the literature review

The state-of-the-art review of demand controlled ventilation systems is presented in APPENDIX A. The purpose of this review was to summarize the literature on the current technology and application of DCV systems for non-industrial buildings. The specific interest was the application of DCV systems for indoor air quality control, since control of thermal comfort with these systems have been studied already to a great extent. The literature review reveals that the technology of DCV systems has developed during the last decade, but further developments are expected. The information found in the literature review can be summarized as follows:

- Indicators, such as carbon dioxide, occupancy, VOCs and relative humidity, can been used as control parameters for ventilation control in DCV systems in order to assure the required indoor air quality. Carbon dioxide is commonly used as an indicator for occupancy generated pollutants. Additionally, when the number of people occupying the room is known the presence of people can be used as an indicator. For controlling the pollutants from other sources than people, the direct measurement of VOCs and particles can be of interest. However, it can be difficult to identify the reference VOC gases that need to be controlled based on the health and comfort effects on humans. In spaces with elevated humidity levels, relative humidity can be used as a control parameter for a DCV system. However, humidity is not recommended as a single decision variable in DCV systems for indoor air quality control.

- The following sensor types can be applied for indoor air quality control with DCV systems: humidity sensors, carbon dioxide sensors, mixed-gas sensors, occupancy sensors. Additionally, combined sensors, incorporating possibilities to measure more than one indoor climate parameter, have become available in the market, providing more flexibility to DCV systems. Development in sensor technology has made mass production of sensors possible, thus decreasing the price of sensors considerably. Moreover, the stability and accuracy of currently available sensors has improved, thus decreasing the costs for calibration and maintenance. Nevertheless, data on the performance of currently available sensor technologies of DCV systems is rather limited and more research is needed in this field.

- DCV systems have been used in a variety of applications including offices, schools, conference rooms/auditoria, dwellings, restaurants and entertainment clubs. DCV systems based on carbon dioxide or occupancy control are applied commonly to auditoria, schools and to office areas with variable and unpredictable occupancy patterns. The control based on measurement of mixed-gases has been applied to restaurant areas, entertainment clubs and other premises where non-occupancy related pollutants are dominating. In dwellings, the application of DCV systems has to a great extent concentrated on humidity control. However, different studies have shown that controlling the ventilation based on relative humidity as a single parameter may not be sufficient to maintain the required indoor climate and indoor air quality. Combined control based on occupancy, CO_2 and humidity levels is recommended in dwellings.

- The energy use of a DCV system depends on many parameters, such as variation of loads in time, hours of use, control strategy, system design, etc. Energy savings compared to the conventional CAV system are highest in rooms with fluctuating occupancy and high density occupancy. For estimating the energy use and potential energy savings of a DCV system it is essential to correctly evaluate the occupancy patterns in the building. The economic profitability of a DCV system is also affected by the initial investment costs, required maintenance of the system and the energy prices.

2 Requirements on a DCV system

This chapter describes the prerequisites for a well functioning DCV system and its components. A special focus has been on uncomplicated system solutions which are possible to implement in existing buildings, as well as in new ones. Requirements on components for such a system solution have been analysed regarding indoor climate, energy use and technical conditions. One example of a technical solution, which seemed to have properties that fulfil the requirements, has been tested in laboratory conditions, as well as tested and analysed in plants in use. A special focus in this study has been on indoor climate and the need of energy. In addition, different aspects of adapting the duct system for variable airflow conditions with low supply air temperature have been discussed. The heat gains in a duct system with variable airflow have been mathematically evaluated and verified in the field.

2.1 Introduction

Nowadays, the majority of new air based air conditioning systems in office buildings have variable air volume flow rate with automatic control in relation to the demand. By adopting the airflow rate to the actual load situation, the DCV system implies to an obvious advantage compared to conventional constant air volume flow systems. Due to the decrease of average airflow rate, less energy is needed for fan operation, heating and cooling the supply air. Moreover, the more the loads are varying in the building, the less energy is used by the DCV system.

In order to guarantee adequate performance of a DCV system, it must be designed, installed, commissioned and operated under a constant and complete commissioning process. It is essential to correctly understand the concept and functioning properties of the whole system and select the technical solutions in a way that the chances for possible failures are decreased. According to Cappellin[34], flawed conception and faulty design are common reasons to cause the system to under-perform, resulting in uncomfortable and/or undesirable conditions for the building occupants. Quite often, when reconstructing a ventilation system from CAV to DCV, the focus is mainly on how to adapt variable air volume flow to the fan system. It is a simple task to add flow control properties to a central fan system by installing frequency inverters and adding pressure control to the system. However, problems with indoor climate can occur if the rest of the system is poorly adapted to variable air volume flow. Improper selection of airflow control and supply air devices is a common cause of excessive noise and draught in occupied spaces[34, 135, 192]. Wrongly selected airflow control devices can lead to under- or over-cooling of the premises[131, 135].

In addition, one of the steps leading to DCV systems poor function is reported to be a too complex design. With additional complexity and elements, there is a greater chance of making a mistake in design, construction and operation[34]. More complicated control and design results in systems that are more sensitive to errors, due to the increased number of components that must work properly. Moreover, the more complex the system is, the more difficult its operation and maintenance will be. Improper and insufficient training of the operating personnel can result in additional problems with the system in function.

When technical solutions for DCV systems are selected, simplicity and tolerance against deviations in operating conditions should always be looked for. It is of great interest to build up the DCV system as simple as possible without jeopardizing the indoor climate.

2.2 Aim of the DCV system study

The purpose of this work is to clarify the requirements for a well functioning DCV system with the special focus on uncomplicated system solutions. One criteria of an uncomplicated system is that the number of controlling components is minimized. Reducing the number of active control dampers contributes to that. An active control damper is here defined as an actuator controlled damper. Nevertheless, to build up a system without these dampers some special requirements must be set upon the air distribution components in a DCV system. The aim of this study is to:

- clarify the requirements and prerequisites on air distribution components in a simplified DCV system solution
- study the possibilities to meet these prerequisites by laboratory tests
- examine the simplified DCV system function in buildings in full scale operation
- clarify the requirements for a duct system with variable airflow rate and low inlet temperature

2.3 Technical aspects of a DCV system

The complexity of the technical solutions of a DCV system is in a great extent dependent on how the pressure unbalance in the system is absorbed. As the variation in airflow rates at airflow control units leads to variation in static pressure in the system, pressure control methods should be applied to avoid an excessive increase in pressure at the airflow control devices. The requirement for duct pressure control is generally dictated by the amount of air volume flow rate reduction, overall acoustical requirements and properties of the airflow control devices[47, 149].

A common practice for static pressure control is to adjust the fan speed, while the static pressure in the system is kept on a level that can assure a proper work of the flow control devices at maximum airflow rates. Different recommendations exist regarding where the pressure sensor should be installed in the duct system[67]. The possible locations can be in the beginning, in the middle or in the end of the duct system. Depending on the location of the static pressure sensor and on the variation range of the airflow rates, the pressure rise that must be throttled off somewhere in the air distribution system can still be relatively high. It is essential that this pressure variation is managed in a way that good functioning properties of the airflow control devices are ensured.

In general there are two common solutions used for room airflow control in a DCV system:

- Controlling the airflow with a variable supply air diffuser, commonly called as VAV diffuser. This is a device, which changes its outlet configuration automatically when mastering the supplied airflow rate. The airflow can be controlled by the room temperature, CO_2 concentration, occupant presence or by some other indicator. In commonly installed devices the airflow rate is sensed based on the device's opening, which is between a few percent to 100 %, and the underlying constant static pressure. Therefore, in order to assure a proper work of this type of a supply air device, a stable pressure, approx. 20-50 Pa, should be maintained in the inlet side of the diffuser. This requirement is achieved by keeping constant pressure in the branch duct by active control dampers, as shown in scheme *A* in Figure 2.1.

- Controlling the airflow with a supply air terminal unit, commonly called as VAV box. It consists of control section including a damper for airflow measurement and control, and a sound attenuator for decreasing the noise generated by the damper. The airflow control properties of VAV box are not disturbed by the fluctuations of the static pressure at the inlet of the device. This means that the active control dampers on the ducts are not needed with this kind of a system solution. This kind of system is illustrated in scheme *B* in Figure 2.1.

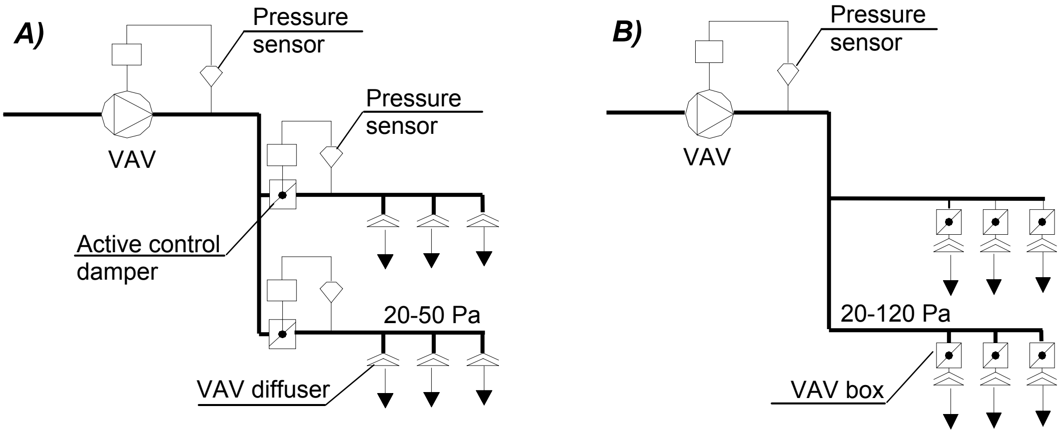

Figure 2.1 Commonly used DCV system solutions for room airflow control. *A)* A DCV system with active control dampers and VAV diffusers for airflow control. *B)* A DCV system with airflow control units (VAV boxes).

Even if controlling the airflow rate with VAV boxes is simpler from control point of view and fewer components are needed in the duct system, there are some drawbacks that limit the application of this solution. Despite the sound attenuator installed to the control box, noise problems may still occur at high pressure drops over the device. This is referred to be one of the most common problems associated with VAV boxes[135]. Moreover, due to the difficulties to control very low airflow rates, over-cooling the premises can happen with low internal heat loads.

Additionally, the selection of supply air outlets has a great impact on working properties of the system solution with VAV-boxes. It is essential that the selected supply air diffusers ensure good mixing of cold supply air into the room air at all airflow conditions in order to avoid problems with draught. The draught risk may especially occur when using VAV boxes together with supply air outlets with constant discharge area, such as CAV supply air devices. If the discharge area of the diffuser remains constant, the velocity of the supply air stream falls in direct proportion to the reduced airflow rate. Due to the naturally denser cold air a “dumping”, defined as dropping of a horizontal supply air jet into the occupied zone, can occur and result in a sensation of draught. Therefore, it is important that the air velocities of the supply air stream in different flow conditions are kept on the same level. This is usually considered in the design of a VAV diffuser, where the diffuser opening is controlled in a way that relatively constant air velocity range is maintained when controlling the airflow rate.

As mentioned before, the commonly used VAV diffusers are pressure dependent. In order to assure a proper work of this type of airflow control device, a pressure in a range of 20-50Pa should be maintained on the inlet side of the diffuser. This requirement is achieved by keeping constant pressure in the branch duct by active control dampers. In order to build up a DCV system without these active control dampers and to use variable supply air diffusers for airflow control in rooms, the VAV diffusers must be independent of the pressure changes in the system.

2.4 Design criteria for a simplified DCV system solution - requirements on a VAV diffuser

This study aims to look for uncomplicated DCV system configurations that can assure a good indoor climate, while at the same time minimize the energy use of the system. Reducing the number of active control dampers by building up a pressure independent system contributes to that. In addition, if the airflow control and room air distribution components can be added together into one unit, the number of required system components can be reduced even more. A possibility of building up a DCV system with pressure independent VAV diffusers has been considered. However, in order to apply this kind of system solution, following requirements must be set on the VAV diffuser:

- The supply airflow rate must be independent of the pressure variations in the duct and a high pressure difference over the device, at least 100 Pa, should be possible to manage without noise problems in an airflow range from minimum to maximum.

- The supply airflow pattern to the room must be stable and independent of the supply airflow rate in order to assure good air movement and to avoid the cold supply air dropping into the occupied zone.

- The diffuser has to control the airflow rate within a wide airflow rate range, from 5-100 % of the design airflow rate.

- It should be possible to supply air with a low temperature, +15°C or lower, without risk of disturbing draught. With lower supply air temperatures the cooling capacity of the supply air will be improved and better control of the room temperature can be achieved. Moreover, it would give a possibility to use free-cooling by outdoor air in temperate climates and decrease the energy use of the system even more.

2.5 Evaluation of the performance of the simplified DCV system solution – tests in the laboratory

This study evaluated the thermal environment and comfort in an office environment, where the VAV supply air diffuser has been chosen in accordance with the requirements discussed above. The tests were carried out in a full scale test room in the laboratory. The aim of this study was to evaluate how the requirements from the thermal comfort point of view are met under different supply airflow conditions and with low supply air temperature. Although the tests have been carried out with a specific diffuser, the results are general in the sense that they show that the high requirements on supply air diffusers can result in products which fulfil them.

This chapter describes shortly the methodology used and provides the results and discussion of the study. More detailed description of the test set-up and measurement techniques is presented in APPENDIX B. The evaluation of uncertainty of measurement is presented in APPENDIX C. More detailed information about the results at different test conditions can be found from Maripuu[141].

2.5.1 Experimental methodology

2.5.1.1 The test room

The function properties of the selected pressure independent DCV diffuser were tested in a full size cellular office room built inside a laboratory hall. The test room was constructed with plaster boards on a wooden framework. The internal dimensions of the test room were: length 3.9 m, width 2.8 m and height 2.7 m, which give a volume of 29.5 m^3 and 10.9 m^2 of floor area To imitate a common office environment the room was filled with usual office equipment: a table, a chair, a computer and lighting. The internal heat loads were simulated with a PC-model (150 W), a dummy (80 W) and lighting including desk lamp and ceiling lamps (total 220 W).

The test set-up included a supply air fan with a frequency inverter and with a pressure control, whereas the pressure level was set to approx. 50 Pa. Additionally, a sound attenuator, a supply air heater with an air temperature control and an airflow measurement device were installed on the supply air duct. The airflow rates in the room were controlled with the tested DCV diffuser. For the exhaust air a transfer air device was installed above the door, under the ceiling.

The technical properties of the tested DCV diffuser enable to measure the incoming supply airflow rate and adjust the discharge area respectively. Therefore strict pressure control at the inlet of the device was not needed. The discharge area of the diffuser varies according to the needed airflow rate and is internally controlled by a traversing motor, which gets impulses from the controlling sensor. The control and regulating equipment as well as the sensors are built into the supply air device and the simultaneous values can be read with the computer.

2.5.1.2 Conducted measurements in the laboratory

Thermal comfort measurements were carried out with different airflow rates under steady-state conditions and with constant supply air temperature about +15 °C. For all tests the operative temperature in the occupied zone and temperature outside the test room was kept +22.0 ± 1.0 °C. This corresponds to the winter conditions and *A* level comfort class according to the design criteria for office rooms[39]. Temperature conditions were continuously monitored inside and outside the test room as well as in the supply air duct.

Two different DCV diffuser mounting arrangements were tested: one with the diffuser free from the ceiling and one with the diffuser in the suspended ceiling. Without the suspended ceiling the height from the ceiling to the discharge area of the supply air diffuser was 0.3 m and from the diffuser to the floor 2.4 m. With the suspended ceiling the latter height was increased to 2.7 m. With the diffuser in the ceiling the *Coanda effect* would help the supply air stream to be close to the ceiling[192]. The *Coanda effect* is apparent as a negative pressure or suction that pulls each layer of the air in the jet towards the ceiling.

The heat loads in the test room were adapted to the airflow rate in order to obtain the correct room temperature. Table 2.1 presents the description of the conducted tests with different mounting conditions, cooling capacities and combined heat loads. There is a small difference between the heat load and cooling capacity values in the table. This is due to the heat transmission through the envelope of the test room.

Table 2.1 The test cases completed in the thermal comfort measurements in the full scale test room with the pressure independent DCV supply air diffuser

Test nr.	Mounting condition	Airflow rate, l/s	Supply air temperature, °C	Cooling capacity, W	Balancing heat load, W
1	no suspended ceiling	10	15	85	122
2	no suspended ceiling	25	15	210	250
3	no suspended ceiling	50	15	420	450
4	suspended ceiling	10	15	85	122
5	suspended ceiling	25	15	210	250
6	suspended ceiling	50	15	420	450

Air temperature and air velocities were measured in a number of room points, as shown in the Figure 2.2. At each position the measurements were taken at 3 heights: 0.1 m, 0.6 m, 1.1 m, which is based on the position of a sitting person. All together the results were obtained from 27 room points.

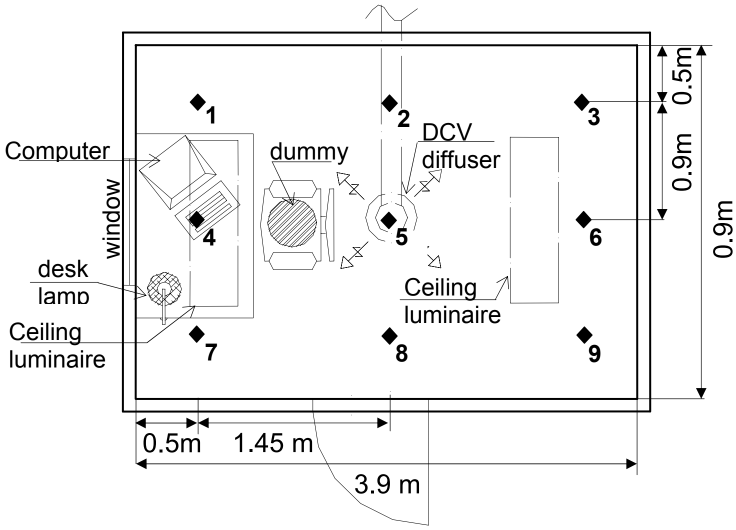

Figure 2.2 The layout of the test room and location of measurement points, marked with numbers. At each position the measurements were taken at 3 heights: 0.1 m, 0.6 m, 1.1 m

The sampling period for each measurement was 3 minutes. Every measurement case described in Table 2.1 was done in three replicates and the results are presented as an average over these three measurements. The risk of draught in the test room was evaluated by using the draught rating (*DR*) model and calculations for every measured point were done according to ISO 7730[101]. The draught rating expresses the percentage of people predicted to be dissatisfied due to draught and is based on studies on people at light sedentary activity, with an overall thermal sensation for the whole body close to neutral.

Additionally, the measurement results were statistically analyzed with an analysis of variance (ANOVA) test. The aim was to see if the measured values of air velocities in the occupied space depend on different parameters that were varied during the experiment. The statistical significance of an effect of different parameters such as the room point, the level of a measured point, the ceiling and the airflow rate was studied. The main and combined effects of the described variables were first found by analyzing all the airflow rates together and then by each airflow case separately. The chosen confidence level in the analysis accounted here is 95 % ($p = 0.05$).

2.5.2 Results and discussion

The mean air velocity and draught rating distributions at different supply airflow rates in the two mounting cases of the DCV diffuser are presented in Figures 2.3 and 2.4. The figures show the percentage of the measured points being in the specified range of air velocity and draught rating values. The values are given for three levels of airflow rates. For example, it can be seen from the figures that the average air velocity in the majority of measured points was less than 0.15 m/s at maximum airflow rate 50 l/s and less than 0.10 m/s at lower airflow rates.

According to thermal comfort guidelines, the air velocity in the occupied space should not exceed 0.15 m/s[24, 203] and the draught rating should be below 15 %[101]. These limits were exceeded only in few measured points in the room and that occurred mainly at maximum airflow rates, see fig. 2.3 and 2.4.

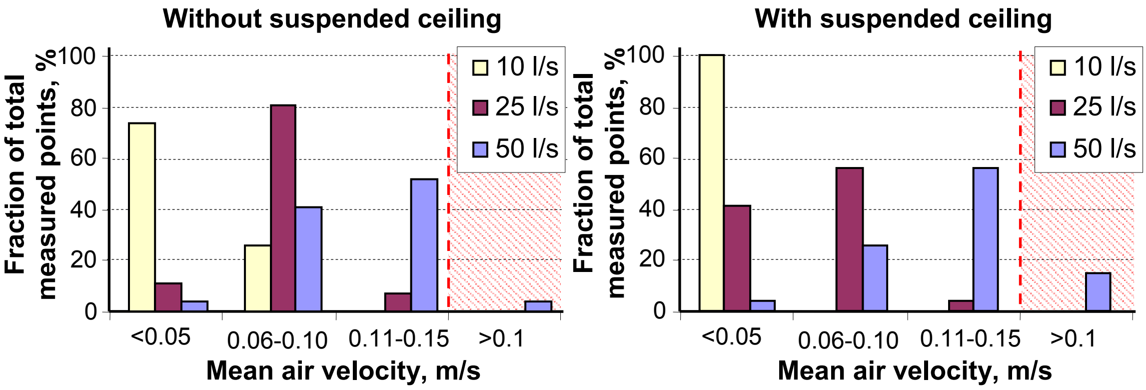

Figure 2.3 Air speed distributions in the test room with different supply airflow rates and with different mounting cases. The supply air temperature was about +15 °C. According to the thermal comfort guidelines, the air velocity in the occupied space should not exceed 0.15 m/s [24, 203].

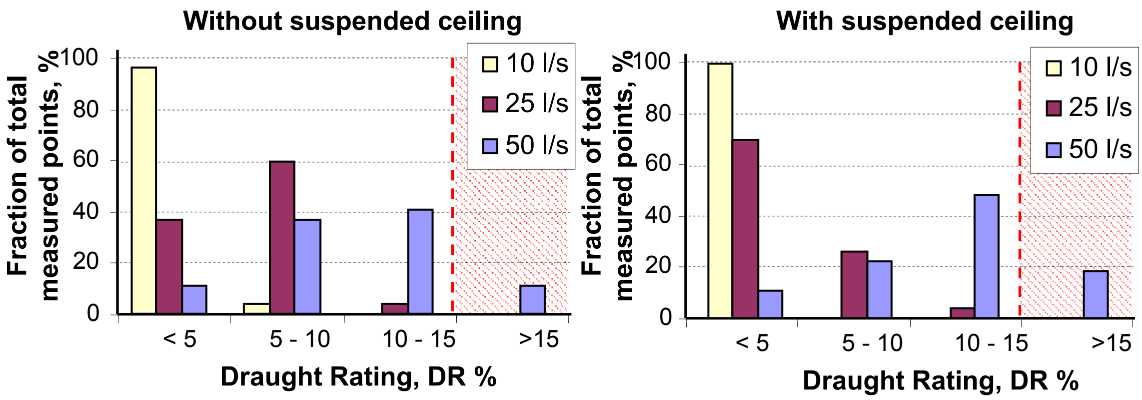

Figure 2.4 Draught rating distributions in the test room with different supply airflow rates and mounting cases. The supply air temperature was about +15 °C. According to the thermal comfort guideline ISO 7730, the draught rating is limited to 15 % [101].

In addition, there seem to be no substantial differences between the results with and without suspended ceiling mounting cases. However, some diversity can be seen at average airflow conditions (25 l/s), where the mean air velocities and draught ratings were somewhat lower with the suspended ceiling. The results from the statistical analysis of variance test, summarized in Table 2.2, also indicate that the ceiling has an effect at average and minimum airflow conditions. However, there is no effect at maximum airflow condition in the specified confidence level ($p = 0.05$). The Table 2.2 shows if an effect of each parameter that varied during the experiment is statistically significant or not. The probability values of calculated F value in *F-test* in statistical analysis compared to the value given for the *F-distribution* in the *F-table* are also presented for the variables which have an effect. The table accounts for the main effects only, meaning that the parameter alone and not in combination with other parameters influences the room air speed. The interaction effects of different parameters were also tested, but no higher order effects were revealed from the results.

Table 2.2 Statistically significant effects of different variables on the mean air velocity in the occupied space. The chosen confidence level is 95%

Main effect	Combined all airflows	10 l/s	25 l/s	50 l/s
Room point	NO	NO	YES $P(F>5,05) = 0,025$	YES $P(F>4,79) = 0,030$
Room level	YES $P(F>15,29)=0,0001$	YES $P(F>60,47)=9,005\cdot 10^{-13}$	NO	YES $Pr(F>6,45)=0,012$
Ceiling	YES $P(F>15,29)=0,0026$	YES $P(F>63,05)=3,52\cdot 10^{-13}$	YES $P(F>17,65)=4,42\cdot 10^{-5}$	NO $P(F>3,80)=0,053$
Airflow rate	YES $P(F>577,85) =2,2\cdot 10^{-16}$	-	-	-

Nevertheless, even though different parameters such as the room point, the room level and the ceiling revealed to affect mean air velocities in the occupied space, there seem to be no regularities between the main effects. With a maximum airflow rate 50 l/s the room point and the room level showed a significant effect, yet in the minimum airflow rate 10 l/s the effect revealed to be only from the room level and the ceiling. However, it was preliminary assumed that the airflow rate has an effect. As can be seen from the

Table 2.2, the probability that the variability of the mean air velocity values with different airflow rates can be attributed to experimental error is very low.

In general, it should be noted that the results of an ANOVA test do not show the size of a single effect, e.g. if the room level has a higher effect compared to the ceiling. Moreover, the direction of the variation is not known, e.g. in which case the highest results appear. The test shows statistically if different parameters affect the results or if the variation is mainly due to experimental error.

Figures 2.5 and 2.6 illustrate the velocity profiles evaluated from the results from the measurement with and without suspended ceiling and at maximum airflow condition 50 l/s (test conditions 3 and 6 described in Table 2.1). These were the test conditions where the required draught rating and air velocity values were exceeded in some room points. The critical points, where the air velocities were exceeding 0.15 m/s, are within the shaded areas shown in Figures 2.5 and 2.6. These are also the points where the draught rating was exceeding 15 %.

As can be seen in Figures 2.5 and 2.6, all of the critical room points were located on one side of the room, which were the measuring points 3, 6 and 9. This was the "empty side" of the test room. Moreover, the most critical point, room point nr 6, was located on the level of 0.1 m above the floor. The upper levels of the same measuring point did not have any high velocities. The processes in the room regarding the airflow dynamics are complex and influenced by many factors. Therefore, it can be difficult to explain why the risk of draught was occurring in the described points in the room.

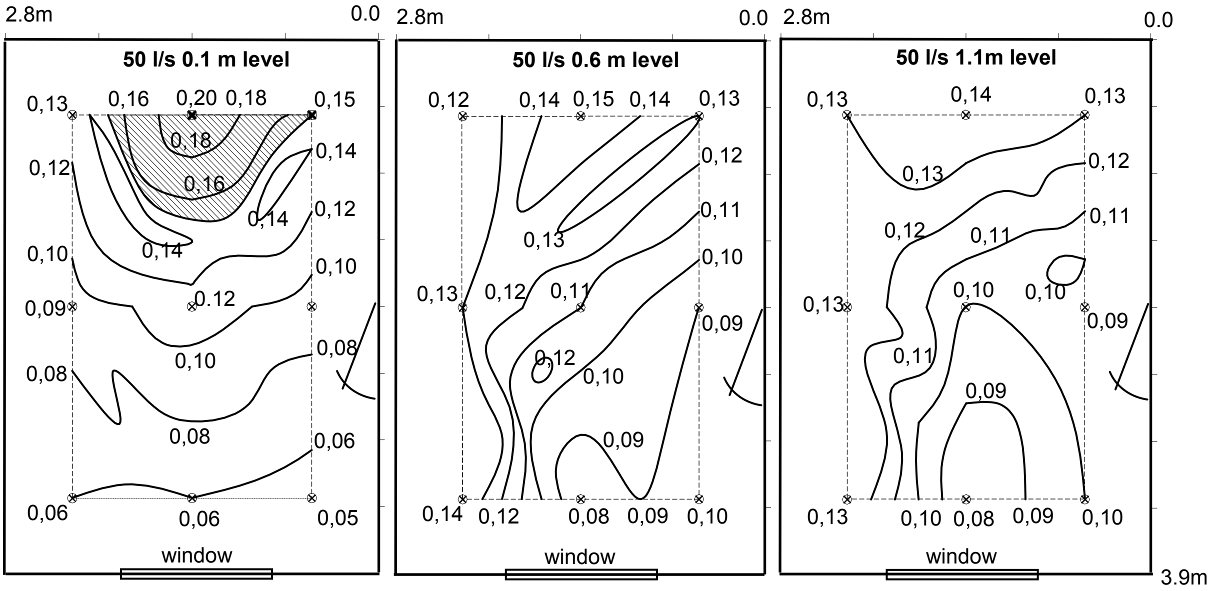

Figure 2.5 Iso-velocity profiles in the measurement case <u>without suspended ceiling</u> and at maximum supply airflow condition 50 l/s. Crossed dots mark the measured room points. The supply air temperature was about +15 °C.

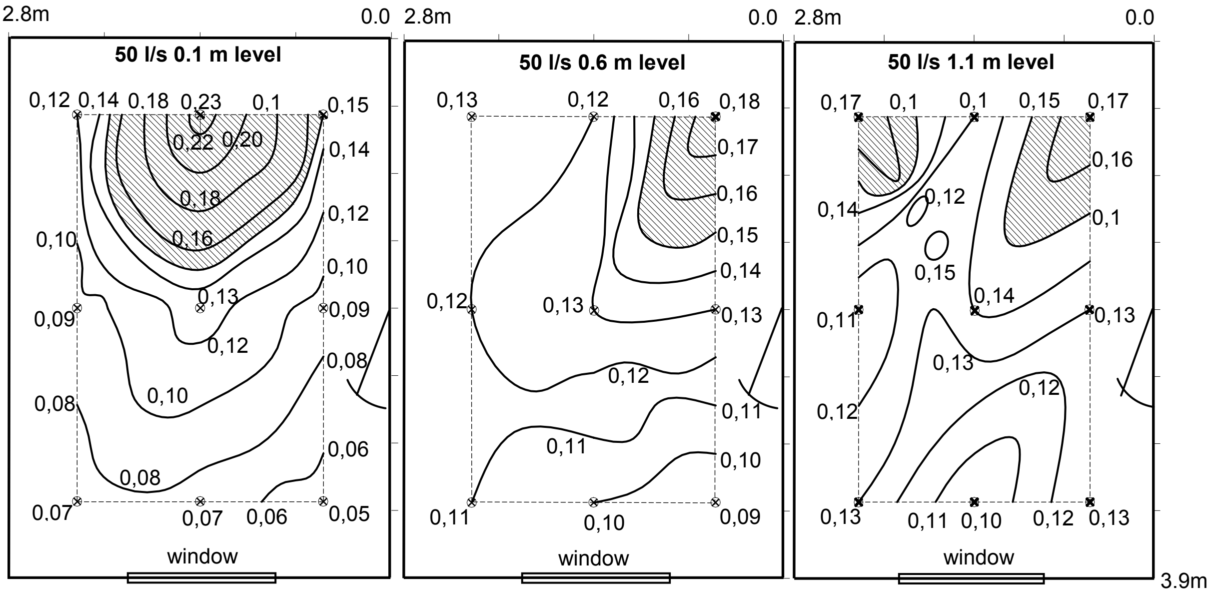

Figure 2.6 Iso-velocity profiles in the measurement case with suspended ceiling and at maximum supply airflow condition 50 l/s. Crossed dots mark the measured room points. The supply air temperature was about +15 °C.

Since the turbulence of airflow has an important influence on the perception of draught in the occupied space[101], the fluctuation of the air velocities in the test room has been further analysed. Figure 2.7 presents the standard deviation as a function of the mean air velocity with all different airflow conditions at three measurement levels for the without suspended ceiling mounting case. The results from the suspended ceiling mounting case were similar. It can be seen that the fluctuation of the air velocity was increasing when the average air velocity in the measured points increased. In addition, a small decrease in the gradient of the regression lines, as the measuring level decreased from 1.1 m to 0.1 m, shows that the velocity fluctuations were more significant at the ankle level. Similar data has also been found in previous studies about airflow characteristics[42]. However in the present case, this higher air turbulence on the ankle level may have partly been caused by a floor temperature, which was some degrees lower than the room temperature.

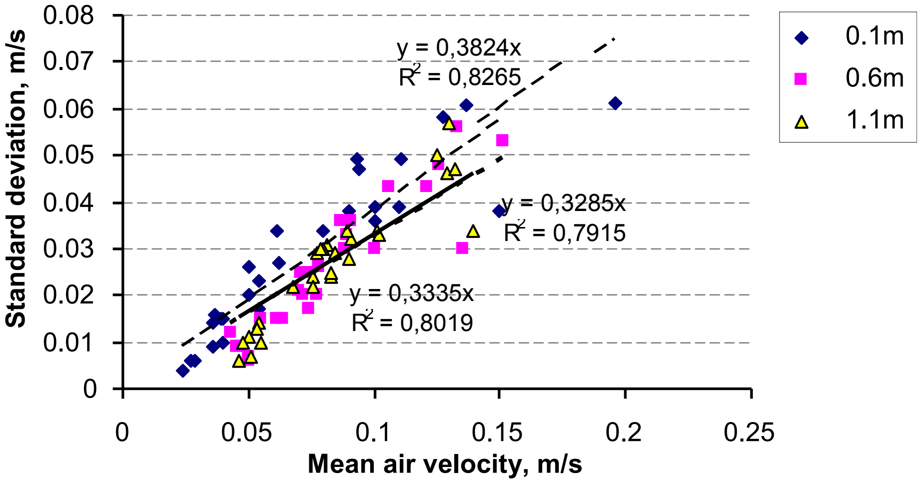

Figure 2.7 Evaluated standard deviation of air velocity in the measured room points at different levels and at the different airflow rate conditions in the test room. The diagram corresponds to the without suspended ceiling mounting case of the DCV diffuser. The supply air temperature was about +15 °C.

2.5.3 Discussion

The main requirement for a VAV diffuser is to have high induction properties with varying airflow rates. It is essential that the diffuser supplies cold air to the occupied space evenly under any airflow condition without causing uncomfortable drafts by air "dumping" or by excessive room air motion. This requirement means that the air should be introduced to the room at a sufficient but not too high velocity to ensure good mixing with the room air.

Thermal comfort guidelines address minimal draft levels by placing limits on the allowable mean air velocity in the room as a function of air temperature and turbulence of airflow[24, 101, 203]. The measurements in the test room with the tested pressure independent DCV diffuser showed that the air movements and the draught levels at medium airflow (25 l/s) and minimum airflow (10 l/s) conditions did not exceed the required levels stated by comfort standards and regulations [24, 101, 203]. Even at the lowest airflow rate, no risk of "air-dumping" was indicated. Marginal draught risk was registered in a few measuring points at maximum airflow conditions 50 l/s. In addition, the results showed no substantial differences between the two diffuser mounting cases depending on the ceiling. However, the ceiling had an effect at lower airflow conditions.

The statistical analysis test revealed that the measurement point and the measurement level have a statistically significant effect to the results at maximum airflow conditions. All of the critical points, where the required draught rating and air velocity values were exceeded, were situated on the empty side of the test room, opposite the workplace. No draught risk was observed in the simulated working zone. One possible explanation for this could be the specific distribution of heat sources in the room. In general, all heat sources in the room have an influence on the air motion in the room by giving rise to buoyancy induced velocities which can match the velocities generated by a jet in the occupied zone[71]. The only influencing heat source on the empty side of the test room was the ceiling luminaire, while the other heat sources where distributed to the other side of the room. Nevertheless, since the air motion in the room is complex, it is hard to make any definite conclusions for the causes of the draught risk in these specified room points. Further studies should be conducted in order to identify the reason.

2.5.4 Conclusions

This study evaluated the thermal environment and comfort in an office room where the VAV supply air diffuser has been chosen in accordance with the pre-defined requirements. In a full scale test room the thermal comfort parameters were studied under different flow conditions and different heat loads. All tests were carried through with the supply air temperature at about +15 ^{o}C. From the results of the laboratory study following observations and conclusions can be made:

- It is possible to fulfil the requirements that must set on the pressure independent VAV diffuser in order to apply it in the in a wide airflow range and at low supply air temperature conditions

- At medium airflow rate (25 l/s) and minimum airflow rate (10 l/s) the air movements and the draught levels in the room did not exceed the required levels stated by comfort standards and regulations. Even at the lowest airflow rate, no risk of “air-dumping” was indicated.

- At the high airflow rate (50 l/s) a marginal draught risk was registered in a few measured points (in 10% of the measured points). All these points with registered draught risk were situated on the empty side of the test room, opposite the workplace. No draught risk was observed in the working zone. Since the air motion in the room is complex, it is hard to make any definite conclusions for the causes of the draught risk in these specified room points and more research should be conducted in this area.

- There is a direct relation between air velocity and turbulence intensity. Moreover, the points with higher turbulence intensities were situated close to the floor, measured at ankle level. Similar findings are accounted for different air diffusers by other researches[42]. However in the present case, this higher air turbulence on the ankle level may have partly been caused by a floor temperature, which was some degrees lower than the room temperature.

Although the tests have been carried out with a specific diffuser, the results are general in the sense that they show that the high requirements on supply air diffusers can result in products which fulfil them.

2.6 Evaluation of the performance of the simplified DCV system solution – tests in the field

In order to study further if the requirements set on the uncomplicated DCV system solution are fulfilled, two case studies have been carried out. The aim was to evaluate the performance of the proposed DCV system solution without active control dampers in the field. The DCV supply air devices that seem to fulfil the pre-defined requirements have been installed in two office buildings. The same type of DCV diffuser was tested also in the full scale office room in the laboratory. The DCV system performance tests in the field were focusing on indoor climate conditions and the energy use of the system.

This chapter gives a summary of the methodology used and results obtained from the measurements and indoor climate evaluation. Additionally, discussion and conclusions from this study are presented. More detailed description of the case study buildings and experimental methodology is presented in APPENDIX B. The evaluation of uncertainty of measurement is presented in APPENDIX C.

2.6.1 Experimental methodology

2.6.1.1 The case study buildings

The first case study building, *Case study 1,* was a 1960s office building situated on a university campus, where the existing CAV ventilation system was replaced with a DCV system a few years ago. The ventilation system supports 107 cellular office rooms on five floors. During the renovation process the existing air handling unit with a regenerative air-to-air heat exchanger and the original duct system were preserved. The rest of the system was renewed in order to adapt it to variable air volume flow. Pressure control was added to the fan system by controlling the fan speed to maintain a specific static pressure at the fan outlet. In addition, a cooling coil was installed in the air-handling unit, which is supplied from the district cooling system of the campus.

The second case study building, *Case study 2,* was an office building, which has two parts, where one par, designated as *Case study 2A,* is newly built and taken into operation in 2004. It includes 14 cell office rooms, 7 meeting rooms, a lecture hall, the Faculty Club, a break room, a copy room, a storage room and a kitchen. The other part of the building, designated as *Case study 2B*, is fully renovated. The facility has 58 office rooms, 5 copy rooms, 5 meeting rooms, 5 break rooms, 3 rooms for archives and library and few storage and equipment rooms.

Both building parts have their own air-handling unit. The air-handling units include a regenerative air-to-air heat exchanger, which is designed to raise the outside air to the required supply air temperature, approx +15 °C, at the design outdoor conditions at -16 °C. The cooling and heating systems are connected to a borehole heat pump/water chiller system. The systems also have a heating coil installed on the exhaust side of the system for dumping the heat from the water chiller condensers in summertime. They also can be used for heating the supply air through the regenerative heat exchanger when needed in extreme cold outdoor conditions.

Both of the case study buildings have similar air distribution systems with the same type of DCV supply air diffusers for room airflow control. The airflow control properties of the DCV diffuser are not depending on the pressure variations at the inlet side. Therefore no additional active control dampers are installed in the supply air duct system. The supply and exhaust airflow rates are balanced on each floor by measuring the supply and exhaust airflow rates in the main ducts. The exhaust airflow rate at the floor is controlled with a damper installed in the main duct next to the exhaust air shaft. The supply air temperature is approx +15 °C all year around. The duct system in *Case study 1* is not insulated and therefore the supply air warms up to a certain extent in the ducts before reaching the outlets.

Every DCV diffuser, locating in the ceiling, is equipped with room temperature and presence sensors. Each supply air device is programmed for two low airflow rates and one maximum airflow rate. If the room is empty and the room temperature is under the required room temperature, the diffuser is working with the lowest set minimum airflow rate. When someone enters the room the airflow rate increases to the higher set minimum airflow rate. The supply airflow rate will increase up to the maximum when the room temperature increases over the required room temperature.

2.6.2.2 Measurements and techniques

Thermal comfort and noise measurements were carried out in a number of office rooms in both case study buildings. Local room air temperatures and air velocities were measured in five different rooms in both buildings. Also the supply air temperature from the DCV diffusers was measured, to indicate the supply air conditions. The aim of thermal comfort measurements was to evaluate a risk of draught in the occupied spaces. Draught problems can sometimes occur due to the properties of the supply air outlet and due to very low supply air temperatures. The laboratory studies carried out with the type of DCV diffuser installed in the case study buildings indicated no risk of "air-dumping" at low airflow rates (see chapter 2.5). Marginal draught risk was indicated at high airflow rates in the full scale test room in the laboratory. Therefore the thermal comfort measurements in the field were carried out at maximum airflow rate supplied to the room. The risk of draught in rooms was evaluated by using draught rating (*DR*) model according to ISO 7730[101].

The sound pressure levels and duct pressures were measured in two randomly selected rooms in *Case study 1* and in one room in *Case study 2.* All of the selected rooms were located far from the air-handling unit in order to avoid possible noise interference from the fans. Still, problems with background noise occurred during the measurement time. In order to evaluate the noise levels generated by the DCV diffuser itself, it was presumed that the noise from the diffuser not exceeds the minimum measured sound pressure level in the room. The noise measurements were carried out at maximum supply air conditions, since these conditions may increase the risk of extra noise[47].

The measuring sensors in both measurements were placed at the level of a sitting person's head, 1.1 m above the floor, near to the working station. The measurement time was approx 10 minutes in *Case study 1* and approx 3 minutes in *Case study 2.* The results are presented as an average over this time period. However, in *Case study 1* the local average air velocity and standard deviation of air velocity were calculated over the 3 minutes before the last measured minute. This was done in order to exclude the disturbing effect of air movement from people.

Besides the physical measurements, questionnaires of the users' perceptions and their preferences were carried out in both case study buildings twice during one year. The used questionnaire is based on the standard ISO 10551[102]. It consists of questions about indoor environmental parameters such as perceived room temperature, air movement, air humidity, noise, lighting and air quality. This kind of questionnaire has been commonly accepted and used also in many previous studies[194, 201]. The used questionnaire is presented in APPENDIX D.

In this questionnaire the building occupants were asked to evaluate their indoor climate conditions over two time periods: summer and winter. A seven point judgement scale was used for evaluating the perception of air temperature, air velocity, air humidity, noise, lighting and daylight. The values 1 and 7 corresponded to extreme situations and 4 was assigned to "neutral", which can be considered as an ideal case. The air quality and perception of overall indoor environment were judged on a scale 1 to 7, with the ideal point of 7. As a result, mean values of the occupants´ votes for different parameters were calculated for both case study buildings.

Additionally, the answers to the questionnaires were statistically analyzed in order to find possible significance for differences between the summer and the winter case. Significance tests were done by using *Student's T-test* (statistical hypothesis test), which compares the actual difference between two means in relation to the variation in the whole data. The chosen significance level in the analysis made here is 95 %.

The energy use of the air-handling system in both case studies was also monitored during a time period of one year. Electrical energy use for supply and exhaust air fans, thermal energy use for supply air heating and the cooling energy use for the supply air cooling was measured.

2.6.2 Results and discussion

2.6.2.1 Indoor climate in measured rooms

The results from the thermal comfort measurements and calculated draught ratings in both case studies are presented in Table 2.3.

In thermal comfort standard ISO 7730[101], the risk of draft is addressed by setting limits on the allowed mean air velocity as a function of air temperature and turbulence intensity. The standard recommends limiting the draught rating to 15 %, which would restrict the mean air velocity to 0.12 m/s at +20 °C and 0.2 m/s at +26 °C. This applies for a turbulence intensity of 40 %, which is typical for indoor office environments[101]. The measurement results in both case studies, given in Table 2.3, show that the mean air velocities and draught rating *DR* values did not exceed the recommended levels in the conditions when the supply airflow rate was at maximum and the supply temperature approx +15°C.

Table 2.3 Measured thermal comfort parameters and calculated draught ratings in selected rooms in the case study buildings at the maximum airflow rate from the diffuser (*Case study 1*: $\dot{V}_{max}$ =40 l/s, Air change rate 4.5 h^{-1}; *Case study 2*: $\dot{V}_{max}$ = 30 l/s, *ACR* ~3 h^{-1}). According to the thermal comfort guideline ISO 7730, the draught rating is limited to 15 % [101].

Room no.	**Supply air temp. t_{supply}, °C**	**Local room temp. t_{room}, °C**	**Local air velocity, v_a, m/s**	**Standard deviation of air velocity m/s, SD**	**Calculated draught rating DR, %**
Case study 1					
1	14.7	22.7	0.12	0.04	9.7
2	15.0	23.4	0.08	0.03	5.5
3	14.7	21.4	0.07	0.02	4.2
4	15.6	22.6	0.10	0.03	7.3
5	15.2	23.5	0.10	0.03	7.0
Case study 2					
1	15.4	21.3	0.08	0.02	5.5
2	15.1	21.3	0.12	0.03	10.4
3	15.1	20.3	0.10	0.03	8.2
4	14.5	20.7	0.07	0.02	4.5
5	14.5	21.0	0.11	0.04	11.0

The results from the noise measurements can be seen in Figure 2.8. The figure shows the noise levels at different airflow rates and pressure drops, measured in the laboratory by the manufacturer compared to values measured in the current study.

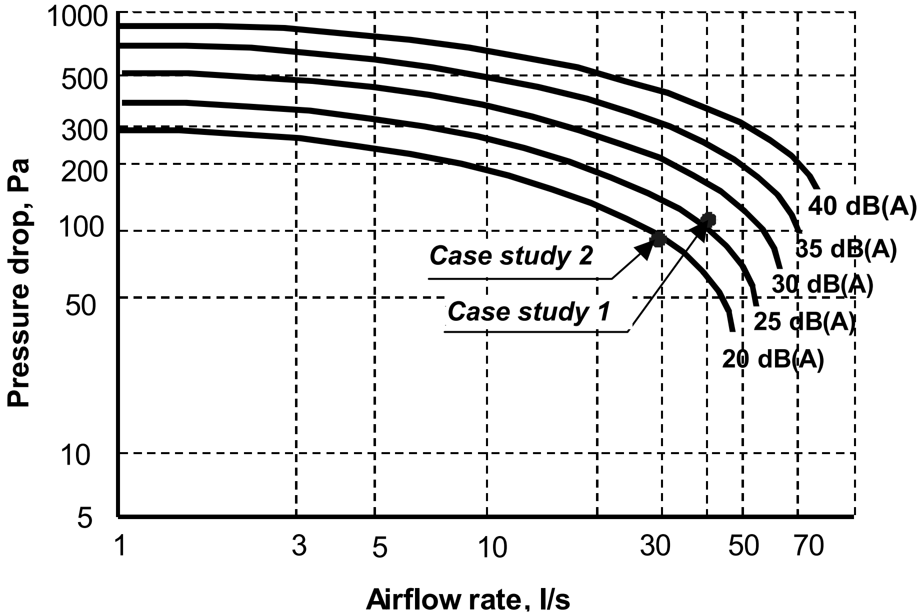

Figure 2.8 Results from the noise measurements at different airflow rates and pressure drops measured in the case study buildings, presented together with laboratory data from the device producing company.

As can be seen from the Figure 2.8, there is a good correlation between results measured in the field compared to data provided by the manufacturer. In *Case study 1* the minimum sound pressure level measured in both rooms was between 26 dB(A) and 27 dB(A) at the pressure drop of 107 Pa and at the maximum airflow rate 40 l/s. In

Case study 2 the results yielded the minimum sound pressure to be approx 19 dB(A) at the pressure drop 98 Pa and at the maximum airflow rate 30 l/s in the room.

The Swedish Standard for building acoustics[198] classifies the maximum acceptable noise levels generated by different installations into four different groups *A, B, C* and *D*. According to the highest noise requirements for the room (class *A/B*), the maximum acceptable sound pressure level from installations in an office room is 35 dB(A). The results from the case study show that the tested DCV system would fulfil the requirement.

2.6.2.2 Indoor climate evaluation – questionnaire

The results from the questionnaire from *Case study 1* show that the majority of the people evaluated their indoor climate to be close to neutral, see Figure 2.9. For evaluated temperature, air velocity and air humidity the values at ± 0.5 from the middle value "4" correspond to 10 % of predicted percentage of dissatisfied (PPD) based on the *PPD* index model proposed by Fanger[76]. The *PPD* index establishes a quantitative prediction of the number of thermally dissatisfied people.

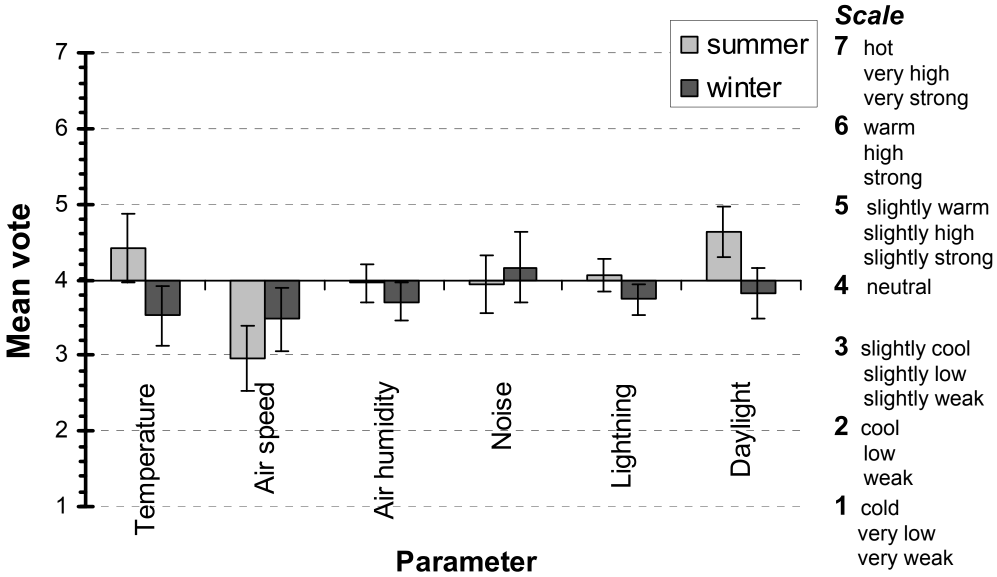

Figure 2.9 The results from the questionnaire in *Case study 1*. The diagram shows the difference of mean vote from the ideal value "4", which corresponds to neutral vote for the given parameter. The error bars represent 95% confidence limits of the mean value. For evaluated temperature, air velocity and air humidity the values at ± 0.5 from the middle value "4" correspond to 10 % of predicted percentage of dissatisfied based on the *PPD* index model[76].

As can be seen from the Figure 2.9, the perceived air temperature was evaluated to be between slightly cool and neutral during wintertime and between neutral and slightly warm during summer period. Colder sensation of room temperatures during the winter period was reported mainly from the room occupants on the first floor of the building, where the cold floor may have affected the results. The sensation of slightly low air movement during the summertime can be related to the sensation of higher room air temperature.

According to the statistical analysis a statistical significance was indicated for the difference between the mean values of summer and winter conditions for air temperature, air humidity, lighting and daylight.

Even if the respondents did not have strong complaints about noise levels, the questions about the preference revealed that the majority of the people would have favoured the noise level to be slightly lower. However, this may be related to the background noise that was indicated during the noise measurements. Noise from outside, people talking in the corridors, and noise from elevators and office equipment can be disturbing for the people working in the office rooms.

The perceived air quality and the average of the votes given for the indoor environment in *Case study 1* are presented in Figure 2.10. According to the results, both of the parameters have been evaluated to be close to acceptable.

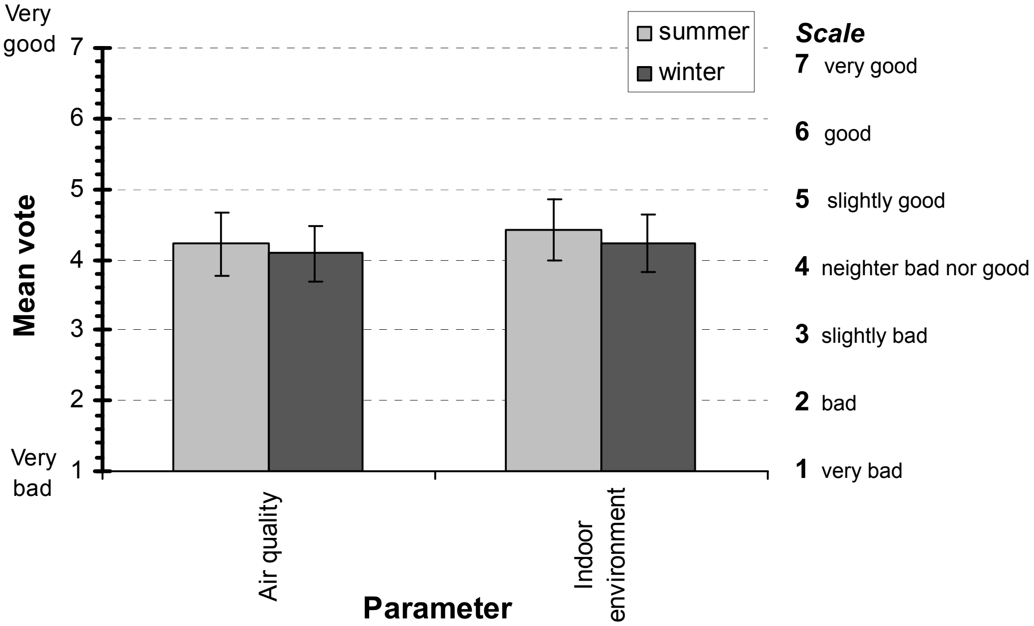

Figure 2.10 The results from the questionnaire in Case study 1. The figure shows the mean vote for perceived air quality and indoor environment. The “7” corresponds to the ideal case and the vote “4” is acceptable. The error bars represent 95 % confidence interval of the mean value.

Figure 2.11 presents the results from the questionnaire from *Case study 2*. The explanation of the figure is in accordance to Figure 2.9. Similarly to the results in *Case study 1,* the majority of the people in th*e Case study 2* building also evaluated their indoor climate to be close to neutral. The winter occasion was evaluated to be slightly cold regarding room temperature. However, the summer condition was evaluated to be slightly warm and the air movement to be slightly low. The statistical analysis revealed a statistically significant difference between the summer and winter conditions for air temperature, air velocity, air humidity, lighting and daylight.

The perceived air quality in *Case study 2* was evaluated as close to acceptable, as can be seen in Figure 2.12. Here the dust and stuffy air were reported to be affecting the air quality. The indoor environment was evaluated to be not good but also not bad

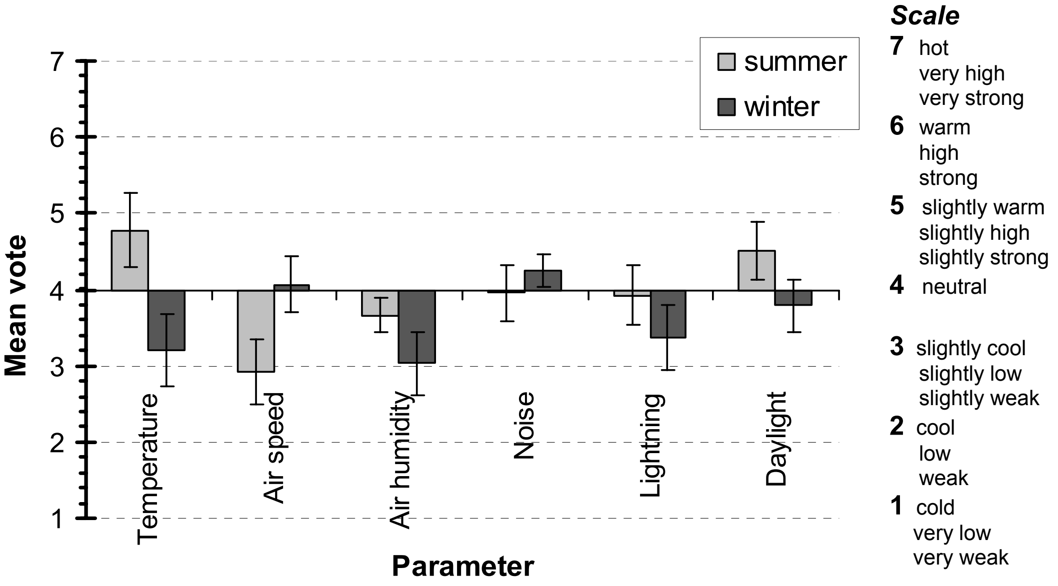

Figure 2.11 The results from the questionnaire in *Case study 2*. The diagram shows the difference of mean vote from the ideal value "4", which corresponds to neutral vote for the given parameter. The error bars represent 95 % confidence limits of the mean value. For evaluated temperature, air velocity and air humidity the values at ± 0.5 from the middle value "4" correspond to 10 % of predicted percentage of dissatisfied based on the *PPD* index model[76].

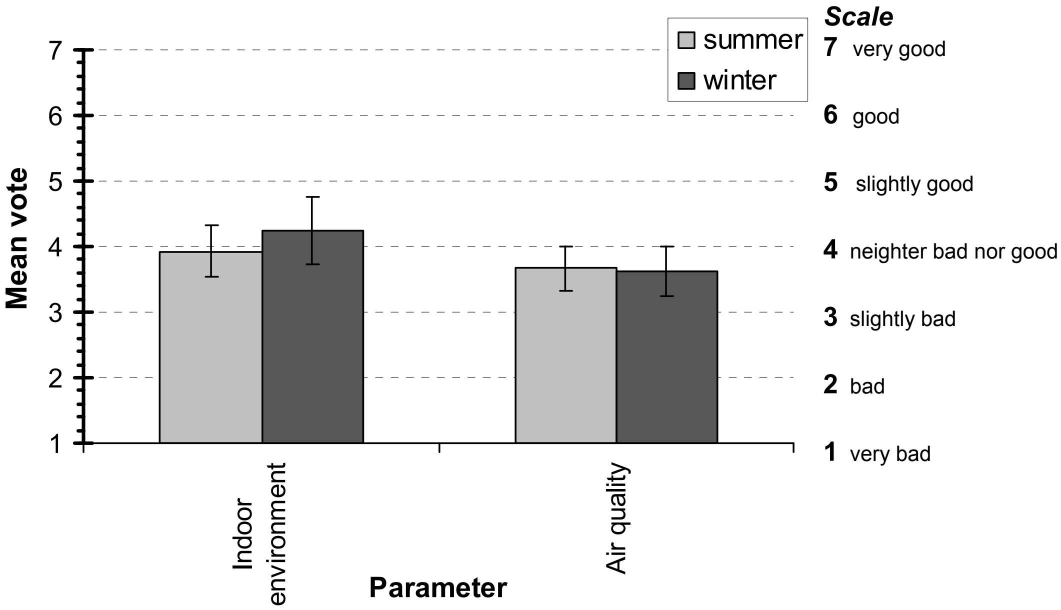

Figure 2.12 The results from the questionnaire in Case study 1. The figure shows the mean vote for perceived air quality and indoor environment. The "7" corresponds to the ideal case and the vote "4" is acceptable. The error bars represent 95 % confidence interval of the mean value.

In general, the questionnaires carried out in both case studies revealed no sensation of draught in rooms. Also the noise levels in the rooms were perceived to be acceptable. The most common complaint was slightly high room temperature during summer time, and slightly cold sensation during wintertime. Furthermore, the air movement was reported to be slightly low in both buildings. The sensation of slightly low air movement during the summertime can be related to the sensation of higher room air temperature. The cause for complaints about the room temperature can be affected by many things, such as heating system, high internal loads, solar shading, etc. Therefore, more detailed monitoring about the indoor climate conditions should be carried out in those rooms, where the complaints were reported.

2.6.2.3 Monitoring of energy use

Table 2.4 presents the results from the monitoring of energy use carried out in both case study buildings. According to the measurement results, there was no need for thermal energy for heating the supply air in any of the DCV systems. Also the need for electrical energy for the fan system was low. According to the previous study conducted in 123 office buildings in Sweden, the average electrical energy use for fans in an office building is 17.9 kWh/year per m^2 [69]. This study was done in office buildings with different types of ventilations systems.

Table 2.4 Measured total annual energy use in *Case study 1* and *Case study 2.* The values are given per gross floor area (*BTA*) of the buildings

System component	***Case study 1*** (3500 m^2 *BTA*) kWh/yr/m^2	***Case study 2A*** (2500 m^2 *BTA*) kWh/yr/m^2	***Case study 2B*** (2500 m^2 *BTA*) kWh/yr/m^2
Heating coil	0	0	0
Cooling coil	6.4	11.1	2.8
Return fan	3.4	4.5	2.0
Supply fan	3.4	2.6	1.1

Figure 2.13 gives a duration diagram of the total supply airflow rate presented together with corresponding energy use of the supply air fan measured in *Case study 1* during period of one year. According to the diagram, both of the durations seem to have a good correlation: with the decreased airflow rates the energy effect for the fans decreases respectively. Total operating hours of the system was approx 4400 hours/year.

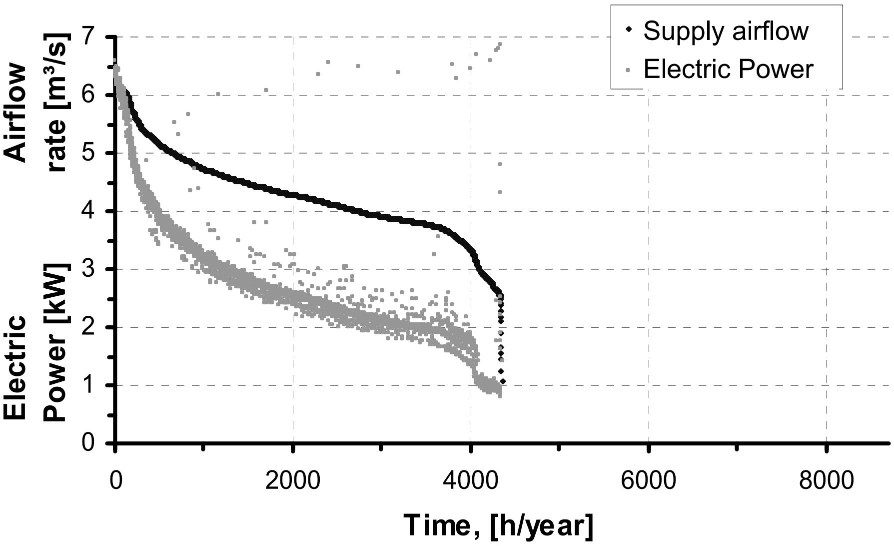

Figure 2.13 Duration diagram for the supply airflow rate with corresponding supply fan electric power in *Case study 1* during one year measurement period. The design airflow rate is 5.6 m^3/s.

The design airflow rate for the air-handling unit in *Case study 1* is 5.6 m^3/s. However, this value was exceeded during some hours during the measurement period and it occurred mainly during the warm period of the year. The maximum measured airflow rate was 6.3 m^3/s and maximum measured electricity use for the supply air fan was 7.1 kW. The maximum measured exhaust airflow rate was 5.6 m^3/s and the maximum measured electricity use for exhaust air fan was 5.1 kW.

The duration diagram for the supply airflow rates and corresponding electrical energy use for the supply air fan measured in *Case study 2A* is given in Figure 2.14. The total operating hours of the system was approx 7200 hours/year. The maximum measured supply airflow rate was 4.4 m^3/s and maximum measured electricity use for the supply air fan was 3.0 kW.

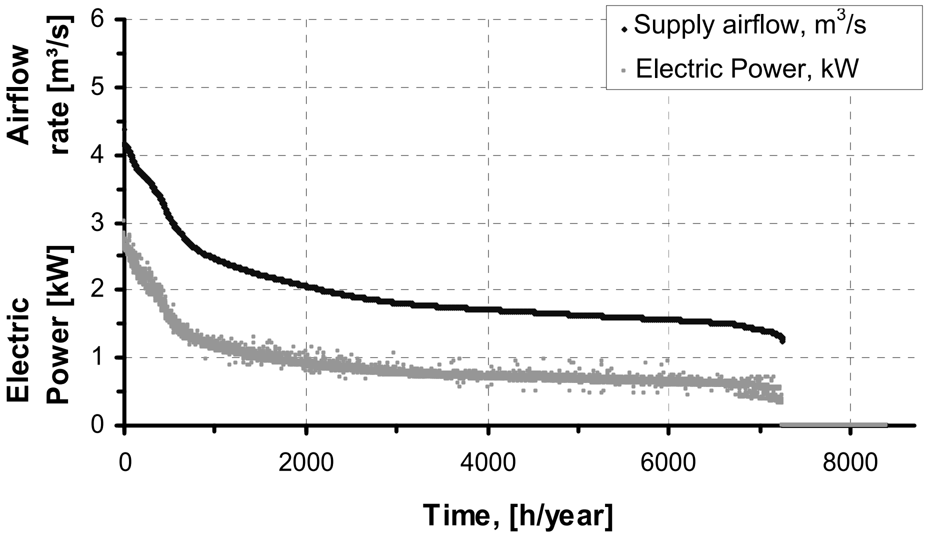

Figure 2.14. Duration diagram for the supply airflow rate with corresponding fan energy use in *Case study 2A* during one year measurement period. The design airflow rate is 5.0 m^3/s.

As can be seen from the Figure 2.14, the design airflow rate 5.0 m^3/s was never reached during the measurement period of one year. The maximum airflow rate of all supply air diffusers, which is 4.2 m^3/s, was exceeded only one hour during the whole monitoring period. During the majority of operating time, approx 5000 hours, the system operated below 45 % of the maximum airflow rate of all supply air diffusers. This could have been affected by the use of the lecture hall and conference rooms. These rooms give a quite big part to the total airflow rate in the system, approx. 90 % of the total airflow rate, and therefore determine the airflow need and energy use to a great extent. During the summer time when the heat gains in the rooms should be on the peak level, most of these rooms are sparsely used due to the vacation period.

The maximum measured exhaust airflow rate was 5.3 m^3/s and corresponding maximum electricity use 5.7 kW in *Case study 2A.* The higher values of return airflow rates correspond to the occasion where the extra heat from the condenser in the water chiller system is removed by exhaust air and therefore the return air fan is running on the maximum speed.

Figure 2.15 shows the duration diagram of the supply airflow rates and corresponding electricity use of the supply air fan measured in *Case study 2B.* The total operating hours of the system was approx 4900 hours/year. The design airflow rate is 3.6 m^3/s and the sum of all supply air diffusers is 3.0 m^3/s. As shown in the Figure 2.15, the system never reached the design airflow rate during the measurement period. Moreover, it operated with less than 45 % of the maximum airflow rate of all supply air diffusers during 80 % of the operating hours, about 3900 hours/year. The maximum measured supply airflow rate in *Case study 2B* was 2.3 m^3/s, which corresponds to approx 64 % of the design airflow rate. The maximum measured electricity use for the supply air fan was 1.4 kW. These low values compared to the design values can be contributed to a low use of the rooms. According to research carried out in office buildings, the actual use of office rooms has stated to be about 50% during working hours[111].

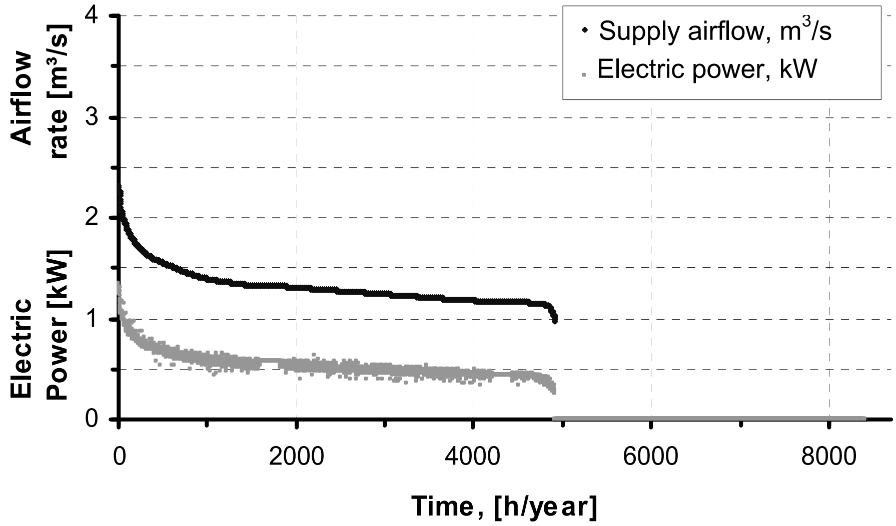

Figure 2.15. Duration diagram for the supply airflow rate with corresponding fan energy use in *Case study 2B* during the measurement period. The design airflow rate is 3.6 m^3/s.

The maximum measured exhaust airflow rate was 3.3 m^3/s and maximum energy use for exhaust air fan was 3.1 kW in *Case study 2B*. The somewhat higher maximum values compared to the supply airflow rates are due to the water chiller condenser heat, which is dumped to the exhaust air, as it is also the case in the air-handling system in *Case study 2A.*

Electrical efficiency of a ventilation system is commonly characterized by Specific Fan Power (*SFP*) value. It is calculated by dividing the electric power demand of all the fans in the air distribution system by the highest value of supply airflow rate or exhaust airflow rate through the building under design load conditions[158]. The equation can be written as follows:

$$SFP = \frac{\sum \dot{W}_t^{design}}{\dot{V}^{design}} \qquad [kW/(m^3/s)] \qquad \text{(eq.2.1)}$$

Where,

SFP	Specific Fan Power, $kW/(m^3/s)$;
$\dot{W}_t^{Design}$	Design fan power, m^3/s;
$\dot{V}^{Design}$	Design airflow rate, m^3/s

It is recommended that the *SPF* value for a new building project should not exceed 2.0 kW/(m^3/s). For rebuilding and conversion work the maximum *SFP* 2.5 kW/(m^3/s) should be aimed [28, 157].

Figure 2.16 gives the *SFP* values at average airflow rates (SFP_A) of DCV systems in different Swedish office buildings together with the data measured from *Case study 1* and *Case study 2.* The data is from the energy auditing funded by the Swedish Energy Agency in 2005[66]. All together the energy use of 123 office buildings was analysed. The Figure 2.16 presents the SFP_A values for 43 air-handling systems, which work with variable air volume flow. The figure also gives the data about the construction year of the building. However, the renovation year of the air handling systems is not known.

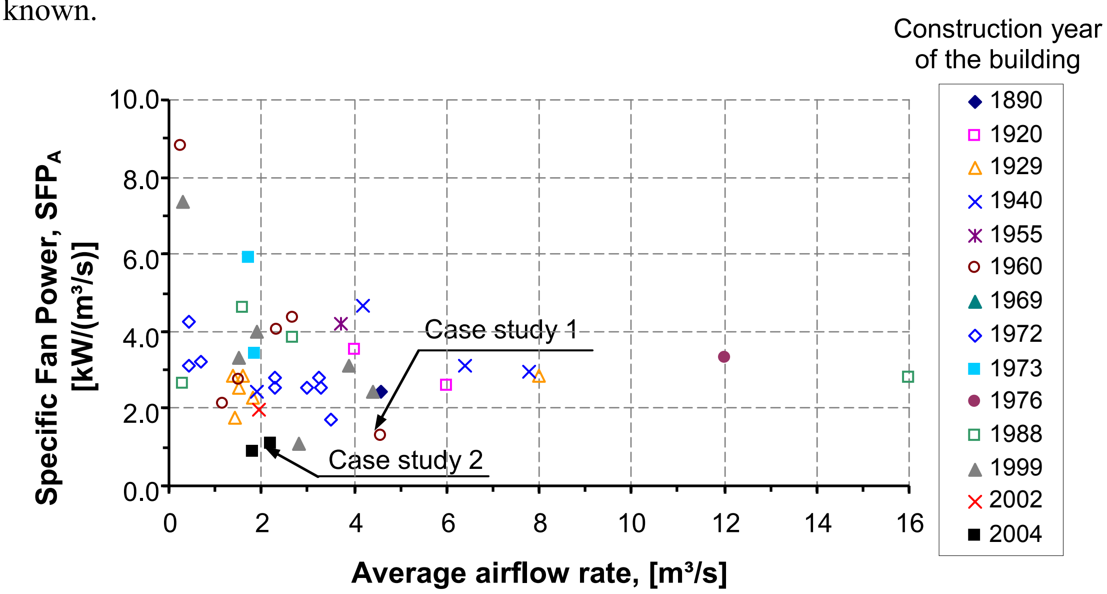

Figure 2.16. Specific Fan Power at average airflow rates of DCV systems in different Swedish office buildings. The data is from the energy auditing funded by the Swedish Energy Agency in 2005[66]. The figure shows also the construction year of the building itself. The renovation year of older buildings is not known. The SFP_A values for the average airflow rate of 4.6 m^3/s in *Case study 1* was 1.3 kW/(m^3/s), for *Case study 2A* these numbers are 2.2 m^3/s and 1.1 kW/(m^3/s); for *Case study 2B* 1.8 m^3/s and 0.9 kW/(m^3/s).

As can be seen from the figure, the SFP_A values for the average airflow rates in *Case study 1* and *Case study 2* are considerably lower than the SFP_A values for other office buildings with DCV systems. In *Case study 1* the average airflow rate per year was 4.6 m^3/s and the corresponding SFP_A value is 1.3 kW/(m^3/s). For the *Case study 2A* these numbers were 2.2 m^3/s and 1.1 kW/(m^3/s) and for the *Case study 2B* 1.8 m^3/s and 0.9 kW/(m^3/s).

2.6.3 Conclusions

The aim of this study was to evaluate the performance of the proposed uncomplicated DCV system solution without active control dampers in the field. The DCV supply air devices that seem to fulfil the pre-defined requirements have been installed in two office buildings, in one existing and one new. In the existing building the old CAV system was changed to DCV. In the new building it was a direct DCV design. The performance and function of both plants was monitored and tested. From the results of the case study following observations and conclusions can be made:

- The demands on indoor climate were fulfilled with the specific DCV system configuration with pressure independent DCV diffusers

- No risk of draught was indicated when the pressure independent DCV supply air diffusers were operating at the maximum flow conditions and at about +15°C supply air temperature

- The noise levels caused by the pressure independent DCV diffusers were acceptable. The sound pressure level in the measured rooms was lower than 30 dB(A) even when the pressure drop over the device was around 100 Pa.

- The tested DCV system solution worked energy efficiently. Due to the low supply air temperature, about +14 °C to +15 °C from the central air handling unit, the air-to-air heat recovery system accounts for almost all the air heating needed. There was no need for additional heating with the heating coil in both case study buildings. Due to the low supply air temperature, the airflow rate control versus the heat load in the rooms is effective. This contributes to a low average airflow rate, and therewith the energy need for air distribution becomes relatively low.

This verifies that the DCV system configuration, without active control dampers, works as expected from indoor climate and energy point of view, both when applied in an existing system and when installed in a new building.

2.7 Adapting the duct system to DCV with low inlet temperature

Energy use of a DCV system can be decreased during cold periods of year if the supply air temperature to the room can be decreased. Additionally, low inlet temperature would increase the cooling capacity of the supply air and lead to a better control of the room temperature all year around. However, with the decreased airflow rates in a DCV system, the heat gains in the duct system can have a significant effect to the supply air temperature.

A simple mathematical calculation has been conducted to evaluate the temperature change in the air distribution system at different airflow conditions. Additionally, measurements and simulations were carried out with a duct system with variable airflow rate in the field. The aim was evaluate the different scenarios of heat gains and possible means of decreasing the heat gains in a DCV system with low supply air temperatures.

2.7.1 Mathematical calculation of the temperature rise in a duct system

The cold air streams in ducts are influenced by heat gains due to the temperature difference between the supply air in the duct and the room air. The amount of heat transferred through the duct depends on the temperature difference, the properties of the insulation material and its thickness. It also depends on airflow rates in the duct and varies under different airflow conditions. In order to evaluate the supply air temperature and cooling capacity of supply air under different operating conditions, it is important to estimate the total heat gains to the system.

Figure 2.17 illustrates an air duct. The change of temperature of a ducted air stream under the influence of a heat gain can be evaluated from a heat balance equation as follows:

$$-d\dot{Q}_c + \dot{q}_{tr} \cdot dA = 0 \qquad \text{(eq.2.2)}$$

Where,

$d\dot{Q}_c$	change in the heat capacity of the air flowing along the duct, W;
$\dot{q}_{tr}$	transmission heat loss, W/m^2;
dA	surface area of a duct element, m^2.

The heat capacity flow of the air in the duct can be written:

$$d\dot{Q}_c = \dot{C} \cdot dt_x \quad \text{[W]} \qquad \text{(eq.2.3)}$$

Where,

$\dot{C}$	heat capacity flow rate of air, W/K;
dt_x	steady state change in air temperature along the duct, °C

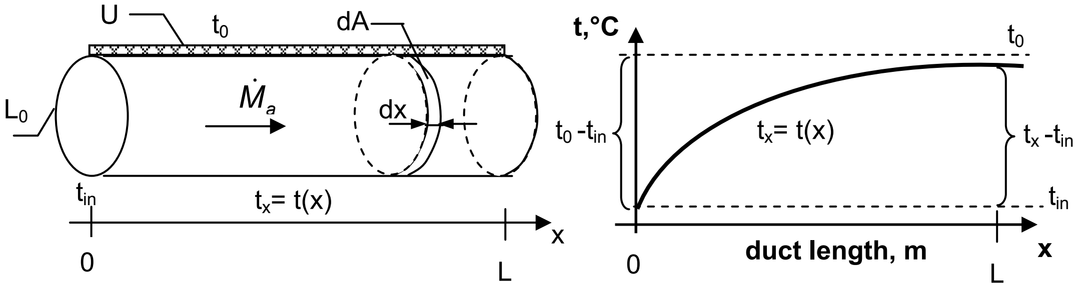

Figure 2.17 An example of an air duct and the temperature change inside the duct. From the figure: *L_0* –area of the duct per unit length, *U*- Thermal transmittance between the air in the duct and outside temperature, *$t_{in}(x)$* – inlet air temperature, *t_o* – Outside temperature, *t(x)* - steady state air temperature along the duct, $\dot{M}_a$ – air mass flow rate in the duct, *L*- duct length.

The transmission heat loss through the duct element *dx,* shown in Figure 2.17, can be written according to equation 2.4. It is assumed that the supply air temperature t_{in} is lower than outside temperature t_o: $t_{in} < t_o$

$$\dot{q}_{tr} \cdot dA = U \cdot (t_0 - t_x) \cdot L_0 \cdot dx \quad [\text{W}] \qquad \text{(eq.2.4)}$$

Where,

L_0 area of the duct per unit length, m;
U thermal transmittance between the air in the duct and outside temperature, W/(m^2·K);
t_o outside temperature, °C;
t_x steady state air temperature along the duct, °C

For determining the air temperature $t_x=t(x)$ along the duct following assumptions are made:

- the outside temperature is constant t_o = const
- internal temperature difference perpendicular to the airflow direction within the channel can be neglected.
- the surface temperature of the duct is assumed to be uniform

The steady-state air temperature $t_x=t(x)$ with constant outside temperature t_o, constant perimeter area of a duct L_0, constant thermal transmittance of a duct *U* and constant air mass flow rate $\dot{M}_a$ can be written as follows[86]:

$$t(x) = t_o + (t_{in} - t_o) \cdot e^{-\frac{x}{l_c}} \quad [°\text{C}] \qquad \text{(eq.2.5)}$$

Where,

t_{in} the inlet air temperature at x = 0, °C;
l_c characteristic length, m;

The length l_c in equation 2.5 is defined as a characteristic length for the interaction between convective heat flow along the duct and the transverse heat loss and can be expressed as follows:

$$l_c = \frac{\dot{M}_a \cdot c_{pa}}{U \cdot L_0} \quad [\mathrm{m}] \qquad \text{(eq.2.6)}$$

Where,

$\dot{M}_a$	air mass flow rate in the duct, kg/s;
c_{pa}	specific heat capacity of air at constant pressure, J/(kg·K);
u_l	linear thermal transmittance of a duct, W/(m·K)

The dominator UL_0 is linear thermal transmittance of a duct and can be written as follows[1]:

$$U \cdot L_0 = u_l = \frac{1}{\dfrac{1}{A_i \cdot \alpha_i} + \sum \dfrac{l}{\lambda_d \cdot A_m} + \dfrac{1}{A_o \cdot \alpha_o}} \quad [\mathrm{W/(m \cdot K)}] \qquad \text{(eq.2.7)}$$

Where,

U	total thermal transmittance of a duct, W/(m^2·K);
u_l	linear thermal transmittance of a duct, W/(m·K);
α_i	convective heat transfer coefficient between the air and inner duct surface, W/(m^2°C);
α_o	heat transfer coefficient between the outside air and outside duct surface, W/(m^2·K);
λ_d	thermal conductivity of the duct layer, W/(m·K);
l	thickness of a duct layer, m;
A_i	inner area of a duct per unit length, m;
A_o	outer area of a duct per unit length, m;
A_m	logarithmic middle area of a duct layer per unit length, m;

$$A_m = \frac{A_2 - A_1}{\ln \dfrac{A_2}{A_1}} \qquad \text{(eq.2.8)}$$

Where A_1 and A_2 are inner and outer areas of a duct layer per unit length, m. The equation 2.7 is based on the condition $A_i \neq A_o \neq A_m$.

For circular ducts, equation 2.7 can be written:

$$U \cdot L_0 = u_l = \frac{1}{\dfrac{1}{2\pi r_i \alpha_i} + \sum_{k=1}^{n-1} \dfrac{1}{2\pi \lambda_{dk}} \ln \dfrac{r_{k+1}}{r_k} + \dfrac{1}{2\pi r_o \alpha_o}} \quad [\mathrm{W/(m \cdot K)}] \qquad \text{(eq.2.9)}$$

Where,

r_i	inner radius of the duct, m;
r_o	outer radius of the duct, m

In practical calculations the thermal conductivity of a duct layer λ_d is considered only for the duct insulation, where the $\lambda_i \approx 0.04$ W/(m·K). The resistance of the metal is ignored, since the thermal conductivity is approx $\lambda_m \approx 200\text{-}500$ W/(m·K) and gives a very little impact to overall thermal transmittance.

The heat transfer coefficient α_o between the outside air and outside duct surface is dependent on the location of the duct and depending on both the convective heat transfer and heat transfer by radiation between surrounding surfaces. Most commonly the ducts are placed in the shafts and above false ceilings and in these cases the convective heat transfer between the outside air and outside duct surface is by natural convection. However, in practice the values for α_o are difficult to establish with any certainty. A value of $\alpha_o = 10$ W/(m$^2\cdot$K) is suggested[115] and this value considers both the convective and radiation part of heat transfer.

The linear thermal transmittance u_l is dependent on the flow conditions inside the duct and remains relatively constant with the air velocities and duct sizes in common range. However, a decrease of air velocity in the duct, which happens when airflow rates are decreased, can lead to a change in the flow conditions in the duct. There is a possibility that the flow conditions in the duct are changed from turbulent flow to laminar flow.

The airflow conditions in the duct are taken into account with the convective heat transfer coefficient between the air and inner duct surface. For determining the convective heat transfer coefficient between the air and inner duct surface α_i, equation 2.10 can be used:

$$\alpha_i = \frac{Nu \cdot \lambda_{air}}{D_h} \quad [\mathrm{W/(m^2 \cdot K)}] \qquad \text{(eq.2.10)}$$

Where,

α_i	convective heat transfer coefficient between the air and inner duct surface, W/(m$^2\cdot$K);
Nu	Nusselt number
D_h	hydraulic diameter of the duct, m. For circular ducts it is equal to the inside diameter of the duct;
λ_{air}	thermal conductivity of air, W/(m$\cdot$K). For the dry air with temperature +20°C the thermal conductivity of air is $\lambda_{air} = 26{,}03 \cdot 10^{-3}$ W/(m$\cdot$K).

The Nusselt number depends primarily on the flow condition, which is characterized by the Reynolds number Re and can be calculated according to equations 2.11, 2.12 and 2.13[1, 73].

For Re>2300 (from transitional region to fully turbulent flow region):

$$Nu = \frac{0.125 \cdot f(\mathrm{Re} - 1000)\,\mathrm{Pr}}{1 + 12.7(0.125 \cdot f)^{0.5} \cdot (\mathrm{Pr}^{2/3} - 1)} \qquad \text{(eq.2.11)}$$

Where,

$$f = (0.79 \ln \mathrm{Re} - 1.64)^{-2} \qquad \text{(eq.2.12)}$$

For $Re < 2300$ (laminar flow):

$$Nu = \left[3.65 + \frac{0.067 \cdot \left(\frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot D_h}{L} \right)}{1 + 0.045 \cdot \left(\frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot D_h}{L} \right)^{2/3}} \right] \qquad \text{(eq.2.13)}$$

Where,

Pr	Prandtl number. For the dry air with temperature +20 °C the Prandtl number is Pr = 0.7
L	length of the duct, m;
$n = 0.4$	if the duct surface temperature is higher than air temperature in the duct (heating the air)
$n = 0.3$	if the duct surface temperature is lower than the air temperature in the duct (cooling the air)
Re	Reynolds number.

The Reynolds number:

$$\mathrm{Re} = \frac{v \cdot D_h}{\upsilon} \qquad \text{(eq.2.14)}$$

Where,

v	air velocity of the airflow in the duct, m/s;
υ	kinematic viscosity of air, m^2/s. For the dry air with temperature +20 °C the kinematic viscosity is $\upsilon = 15.13 \cdot 10^{-6}$ m^2/s

It must be noted that it is difficult to determine the Nusselt number in the transitional region 2000 < *Re* > 4000 with a good precision. Therefore some uncertainties may be introduced to the results with equation 2.11 when the Reynold number values are close to 2300. The equation 2.11 does not take into account the entrance effect, which is important in short ducts and in laminar flow conditions, when Reynold number values are close to 2300.

As mentioned before, the u_l values remain relatively constant with the air velocities and duct sizes in common range. However, with air velocities lower than 1.5 m/s the u_l value decreases considerably as can be seen from the Figure 2.18. Here the change in flow conditions has an important influence. For example in a connection duct with the diameter of 250 mm and maximum airflow rate 50 l/s the air velocity in the duct is 1 m/s and the Reynolds number $Re \approx 16800$, which corresponds to fully turbulent airflow conditions. After decreasing the airflow in the same duct to a minimum airflow rate, for example to 7 l/s, the corresponding air velocity in the duct decreases to 0.14 m/s and the Reynolds number to $Re \approx 3300$. Here the flow conditions are in the transitional region.

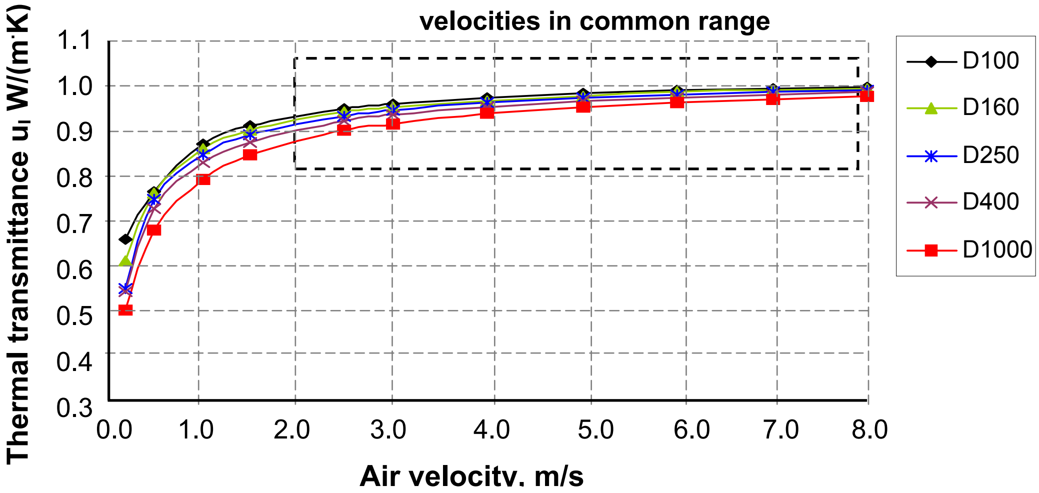

Figure 2.18 Linear thermal transmittance u_l with different air velocities and duct sizes in common use. The diagram is calculated for air ducts with constant insulation thickness $l_i = 30$ mm; $\lambda_i = 0.035$ W/(m$^{2\cdot}$K).

Additionally, as described before, there is possibility that the flow conditions in the duct are changed from turbulent flow to laminar flow when the airflow rates are decreased in the duct. Since at laminar flow conditions the linear thermal transmittance u_l can also depend on the length of the duct, as shown with equations 2.7, 2.10 and 2.13, the correct form of equation 2.5, for determining the air temperature $t_x = t(x)$ in the duct, would be:

$$t(x) = t_o + (t_{in} - t_o) \cdot e^{-\frac{1}{c \cdot \rho \cdot \dot{V}} \int_0^X u_l(x) dx} \qquad [°C] \qquad \text{(eq.2.15)}$$

Where,

$\dot{V}$	air volume flow rate in the duct, l/s;
ρ	air density, kg/m^3

Based on the equation 2.15, the relative temperature change can be evaluated as follows:

$$\Delta t_{rel} = \frac{t(x) - t_{in}}{t_o - t_{in}} = 1 - e^{-\frac{1}{c \cdot \rho \cdot \dot{V}} \int_0^X u_l(x) dx} \qquad \text{(eq.2.16)}$$

Where,

Δt_{rel}	relative temperature change along the duct length

Figure 2.19 gives an example of calculated relative temperature change along the duct length with different airflow rate conditions. The figure is calculated for a duct with diameter of D = 250 mm, insulation thickness of $l_i = 30$ mm and thermal conductivity $\lambda_i = 0.035$ W/(m$^{2\cdot}$K). As can be seen from this figure, with airflow rate of 100 l/s the relative temperature change would be about 10 % in a duct of 10 m. When the airflow rate is decreased to 10 l/s the respective change in temperature would be 45 %.

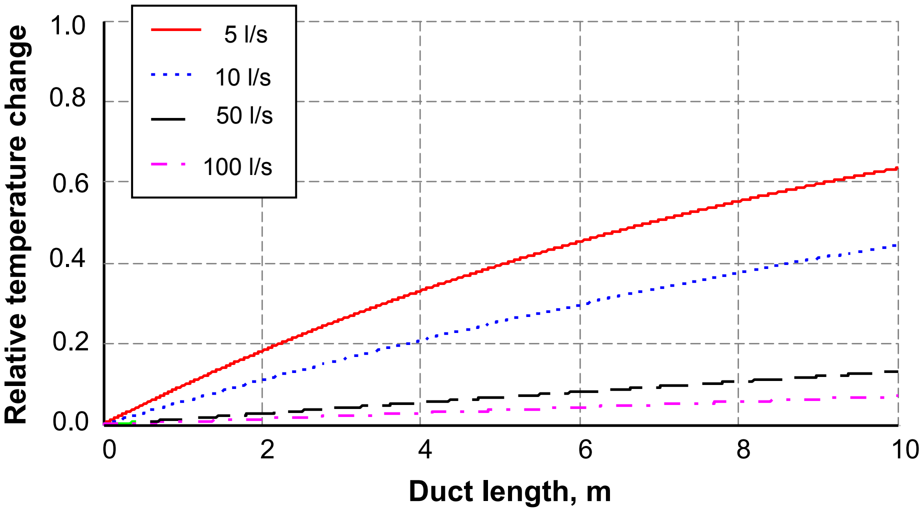

Figure 2.19 Relative temperature change along the duct length with different airflow rate conditions. The figure is calculated for a duct with diameter of D = 250 mm, insulation thickness of l_i = 30 mm and thermal conductivity λ_i= 0.035 W/(m^2·K).

The temperature change can be decreased with increased thickness of duct insulation. Figure 2.20 presents the effect of duct insulation for temperature change. As shown in the figure, increasing the insulation thickness from 30 mm to 50 mm would decrease the relative temperature change about 10 %. The insulation thickness 75 mm would result in relative temperature change of 26 % compared to 45 % with 30 mm of thickness.

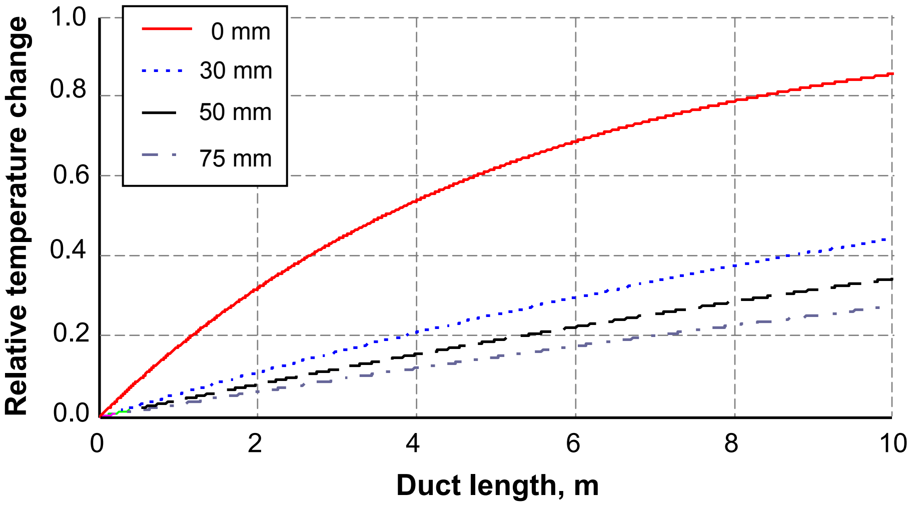

Figure 2.20 Duct heat gain: the effect of lagging in reducing temperature change. The figure is calculated for the airflow rate 10 l/s, duct with diameter of D = 250 mm, and insulation thermal conductivity λ_i = 0.035 W/(m·K).

2.7.2 Simulations and measurements with a duct system in the field

In order to study in more detail the effects of varying airflow rates to supply air temperature in the duct system, simulations and measurements were carried out with a small part of a duct system in the building of *Case study 2B*. The building was described in detail in chapter 2.6. The heat gain calculations are based on the equations presented in the previous chapter 2.7.1.

This chapter describes the methodology and provides the results and discussion of the simulations and measurements carried out. More detailed description of the measurement techniques is presented in APPENDIX B.

2.7.2.1 Experimental methodology

The scheme of the tested DCV air distribution system is shown in Figure 2.21. The duct system supplies air to 11 different office rooms (devices 1-11) and to one conference room (devices 12-13). The maximum designed airflow rate for offices is 30 l/s and for conference rooms 50 l/s per diffuser. The minimum airflow rate is 7 l/s for all devices. All the connection ducts from the main duct have the same length 2.5 m and in conference room 3.0 m. The distance between connection ducts is 2.8 m. All ducts are insulated with the insulation thickness of l_i = 30 mm and the thermal conductivity of the duct layer is λ_i = 0,035 W/(m·K). The designed supply air temperature from the diffusers is +15 °C.

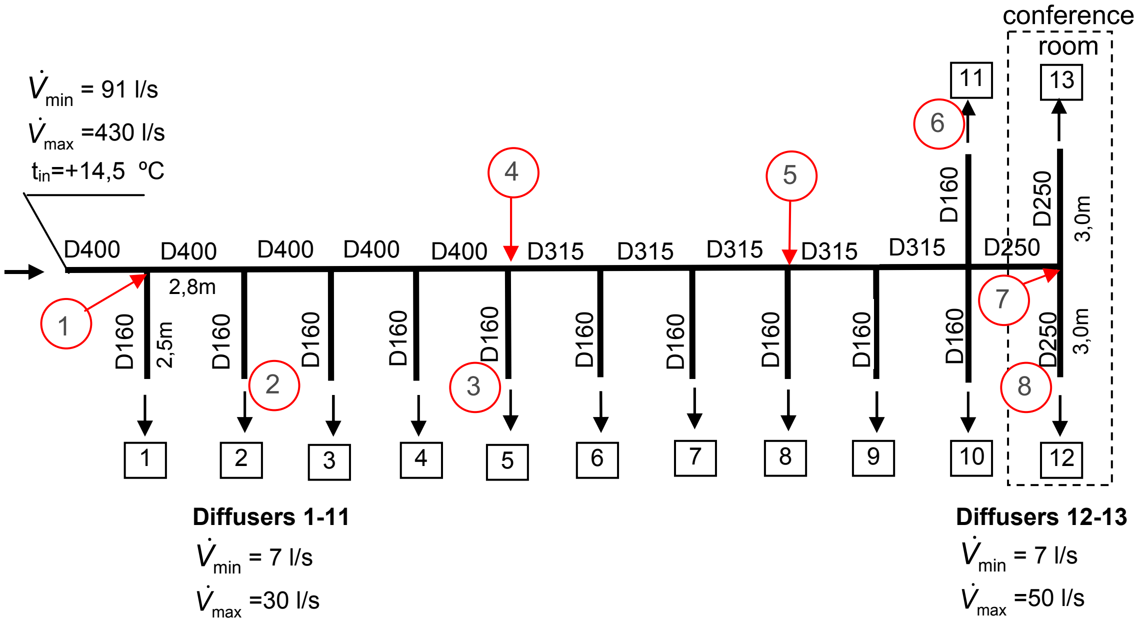

Figure 2.21. The scheme of the air distribution system used for evaluating the variable flow effects on temperature change in the duct system. The numbers in the circles mark the measurement points. The measured supply air temperature at the beginning of the main duct t_{in} = 16.3 °C, the temperature in the rooms about t_o = +22 °C. The duct diameters are marked as e.g. D400, which correspond to D = 400 mm.

The described DCV air distribution system was tested in the field with the aim to compare if the temperature change of the supply air in the duct system is similar to the theoretical calculations. The air temperatures in the duct were measured in 7 different points in the system and the results compared with the calculated temperatures for this system, shown in Figure 2.21. The measurement points 1, 4, 5 and 7 were inside the main duct. The points 2, 3, 6 and 8 correspond to the supply air temperatures from the DCV diffusers.

The measurements were carried out under different supply airflow conditions. The airflow rates from the diffusers were gradually changed from minimum to maximum. The different test conditions are shown in Table 2.5. The initial duct temperature was t_{in} = +16.3 ºC, the temperature in the corridor and in the rooms about t_o = +22 °C.

Table 2.5 The tested airflow conditions for the temperature change measurements in the duct system. The airflow rates from 13 diffusers in the test system were changed gradually from minimum to maximum.

	Airflow	**rates**											
Diffuser	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Case 1	5	8	7	9	7	8	6	8	9	6	6	10	10
Case 2	5	7	7	7	6	6	6	7	9	10	9	46	41
Case 3	5	7	7	5	6	5	5	6	7	26	27	41	50
Case 4	5	6	7	5	6	5	5	26	26	26	27	37	44
Case 5	5	6	7	5	6	26	28	29	26	29	28	35	43
Case 6	5	5	7	26	26	27	26	27	22	27	29	33	40
Case 7	26	26	7	27	29	28	27	27	26	28	27	29	38

The theoretical temperature change in the described duct system was calculated based on the equations presented in the previous chapter 2.7.1. Additionally, some simulations were carried out with the same air distribution system layout in order to evaluate the possible scenarios of heat gains and the impact of different insulation thickness. The simulations were done for the summer climate conditions with the room temperature t_o = +24 °C and with the supply air temperature at the beginning of the main duct t_{in} = +14.5 °C.

2.7.2.2 Results and discussion

Figure 2.22 gives the comparison between the results from the calculations and results measured in the field. The measured air temperatures in the duct shown in the figure represent the average values over the last minutes of each measurement condition. For the best correlation between the calculated and measured temperatures the points in the Figure 2.22 should be on the diagonal line.

It can be seen from the Figure 2.22 that with lower air temperatures there is a better fit between the measurements and calculation compared with higher supply air temperatures in the duct system. It should be also noted that in the calculations the duct insulation was considered to be l_i = 30 mm and the thermal conductivity of the insulation λ_i = 0.035 W/(m·K). One of the reasons for the deviation from the calculated temperatures can be that some parts of the ducts are not so well insulated. This is difficult to evaluate since all of the ducts are locating above the false ceiling.

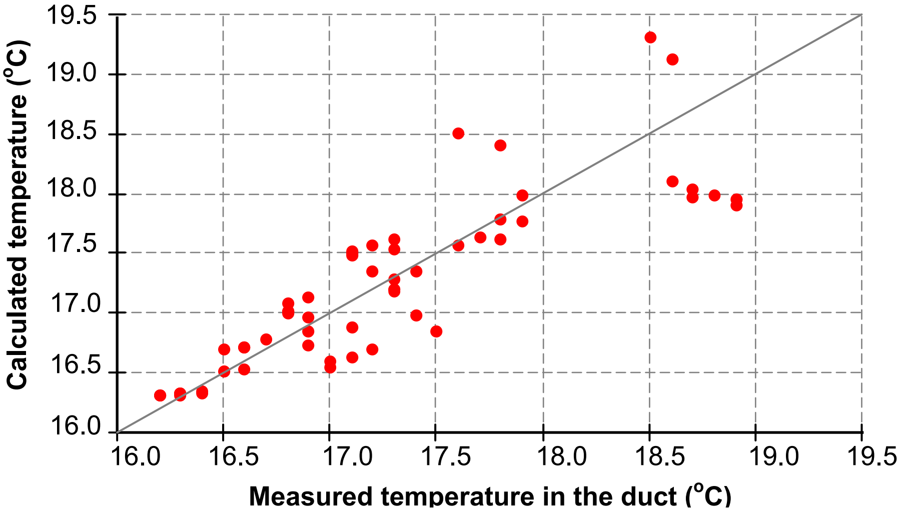

Figure 2.22 A comparison between the calculated and measured results from the temperature change evaluation in the duct system. In the ideal case, the points in the diagram should follow the diagonal line. The initial duct temperature was t_{in} = +16.3 ºC

Simulations were carried out with the described DCV air distribution, shown in Figure 2.21, to evaluate the relative temperature change of supply air at different operating conditions. The simulations were done for the summer climate conditions with the room temperature +24 °C and with supply air temperature at the beginning of the main duct +14.5 ºC.

The worst cases occur when the devices are running with the minimum airflow rates. In these conditions the air velocities in the ducts are lower and the supply air temperature along the duct increases considerably. As a result, a risk of not maintaining the required room temperature may occur due to decreased cooling capacity of supply air. This condition most probably occurs with the connection ducts at the very end of the main duct. The described situation may not only take place when all the devices are running with the minimum airflow rates, e.g. when the rooms are empty. It can also happen when the rooms at the end of the duct line are occupied, while the first rooms are empty.

Figure 2.23 presents the calculated relative temperature change in the described air distribution system with maximum and minimum load conditions and with different insulation thickness on the duct system. The diagrams in the figure show the relative temperature change in relation to the supply air temperature at the beginning of the main duct. It can be observed that while the relative temperature change with maximum airflow conditions at the end of the duct system is about 13 % then at with minimum airflow rates this change increases up to 54 %.

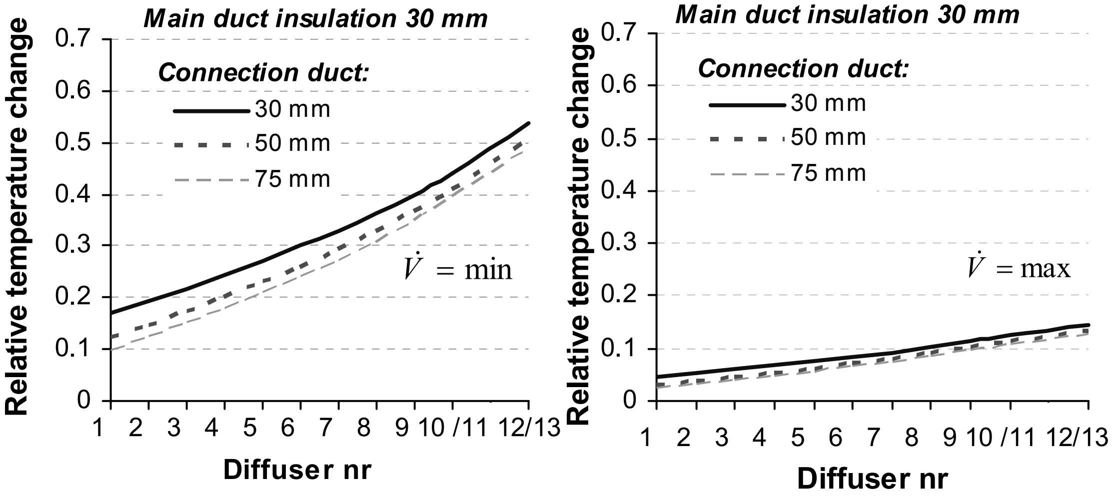

Figure 2.23 Evaluated relative temperature change in the DCV air distribution system with maximum and minimum load conditions and with different insulation thickness of the connection ducts. The figure shows the relative temperature change in the duct line till each diffuser. The initial temperature in the main duct is t_{in} = +14.5 ºC and the insulation thickness of the main duct is l_i = 30 mm.

In the situations when the rooms are all empty the supply air temperature will not have a great importance. Nevertheless, since the system is controlled by the room temperature, higher supply air temperatures and poor cooling capacity of the supply air can lead to the increase of supply airflow rates in order to maintain the required room temperature. This is however, a waste of energy and therefore methods for decreasing the heat gains to the duct system should really be considered already in the design process.

The supply air temperature conditions were additionally evaluated for the case when all of the rooms are empty and one room at the end of the duct line, corresponding to diffuser 11, is occupied. The results of this simulation are shown in Figure 2.24. In the described condition the relative temperature change in the system from the beginning of the main duct till the occupied room is up to 37 %, depending on the insulation thickness of the ducts. This means that it can be difficult to maintain the required thermal comfort conditions in the room due to the poor cooling capacity of the supply air. The design airflow rates are based on the supply air temperature from the diffusers +15 °C.

From the Figure 2.24 it can also be observed that increasing the duct insulation thickness from 30 mm to 75 mm would give relatively small effect to overall temperature change in these ducts. Moreover, since the supply air temperature from the diffusers is directly dependent on the air temperature at the beginning of the connection duct, controlling the temperature change in the in the main duct can give even bigger effect to overall temperature change. For example the supply air temperature from the diffusers will be lower when the insulation thickness on the main duct is 50 mm and connection ducts with 30 mm compared to respective 30 mm and 50 mm case, see Figure 2.24.

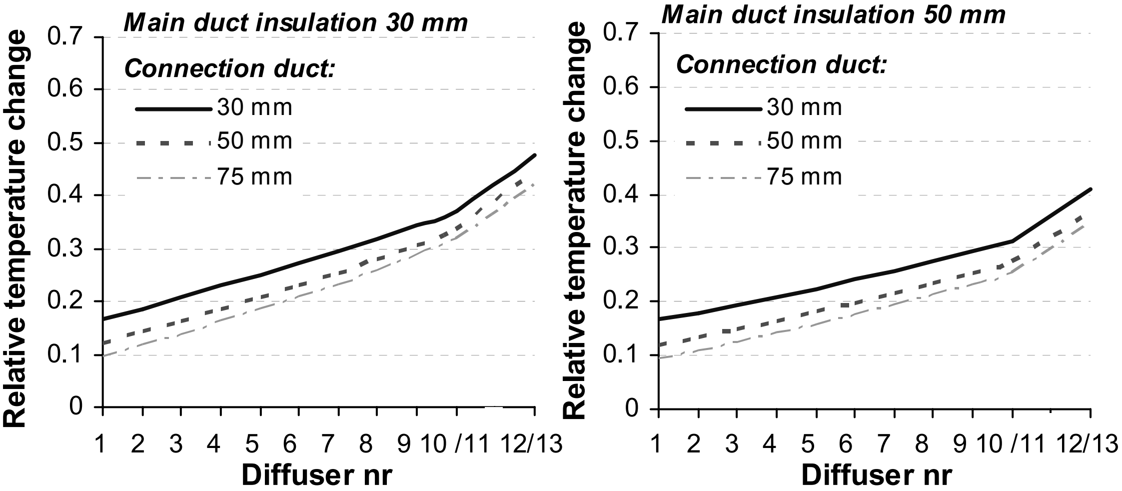

Figure 2.24 Evaluated relative temperature change in the DCV air distribution system with minimum load conditions from diffusers 1-10, 12 and 13 and with maximum airflow from diffuser 11. The figure shows the relative temperature change in the duct line till each diffuser with different insulation thickness of the duct system. The initial temperature in the main duct is t_{in} = +14.5 ºC and the insulation thickness of the main duct is 30 and 50 mm, respectively.

The somewhat higher supply air temperatures from the last connection ducts can be taken into account already in the design process. This would help to assure that the required room temperatures would be met also under extreme conditions, when only few rooms at the end of the duct line are occupied.

2.7.3 Conclusions

In a DCV system with low inlet temperature the heat gains of the air distribution system can have a significant effect on the cooling capacity of air. The heat gains are at maximum when the system operates under low supply airflow rate conditions.

In this study a simple mathematical calculation was conducted to evaluate the temperature change in the air distribution system under different airflow conditions. Additionally, measurements and simulations were carried out with a duct system with variable airflow rates in the field. The aim was evaluate the possible scenarios of heat gains and possible means of decreasing the heat gains in the duct system with cooled air. Based on the results following conclusions and recommendation can be made:

- The supply air temperature in the duct system is increasing considerably after the airflow rates are decreased in the DCV system. It can be difficult to maintain the required thermal comfort in rooms for example in situations when majority of the rooms are empty and one or few of the rooms at the end of the duct line are occupied. In this case the cooling capacity of the supply air may not be sufficient even with the maximum airflow rate supplied from the diffuser.

- In the situations when all rooms are empty the supply air temperature will not have a great importance. Nevertheless, since the system is controlled by the room temperature, poor cooling capacity of the supply air can lead to the increase of supply airflow rates in order to maintain the required room temperature. This, however, is a waste of energy and therefore methods for decreasing the heat gains to the duct system should really be considered already in the design process.

- Insulating all of the ducts in the system is a basic requirement to maintain the required cooling capacity of the supply air. Based on the calculations, bigger effect can be achieved with increasing the insulation thickness of the main ducts instead of increasing the insulation thickness on the connection ducts for decreasing the heat gains.

- The higher supply air temperatures from the last connection ducts can be considered already in the design process. The required airflow rates to these rooms can be determined according to the possible temperature increase in the system. This can assure that the required room temperatures are achieved also with the severe conditions that can occur with varying airflow rates in the system.

3 Requirements on DCV sensors

This chapter describes the prerequisites for sensor technologies applicable for demand controlled ventilation. The analysis and performance evaluation has been limited to indoor air quality control based on the composition of air only. In addition, only sensors measuring the concentration of gases other than water vapour have been included to the test program.

The available gas sensor technologies and the requirements that must be set on DCV sensors have been analysed in detail. Additionally, the performance of commercially available gas sensors has been evaluated in laboratory tests, full scale tests and field tests.

3.1 Introduction

A DCV system delivers conditioned air to the rooms to meet various demands. The demand is decided by a set of values affecting thermal comfort and/or air quality. The indicator chosen to control the ventilation airflow rates is in a great extent dependent on the possibilities to measure this parameter. Here first the available sensing technologies set the limits. Secondly, even if there are available technologies for measuring the required parameter, the sensors must fulfil certain requirements in order to be applicable for ventilation control. The performance of a DCV system is strongly influenced by the controlling sensors. Thirdly, it can be difficult to define the parameters that the sensor must measure, e.g. for indoor air quality control.

Measurement of temperature and humidity in thermal comfort management can be a relatively easy task to accomplish with available sensor technologies. These sensors are commonly applied in heating, ventilation and air-conditioning systems. On the other hand, measuring the parameters that influence indoor air quality can be rather complicated. The term “air quality” refers to the condition of air as perceived by humans and it depends both on the substances in the air and the individual persons exposed to the substances. There are no sensors that measure the “quality” of air. Instead, quantitative parameters, as the composition of air in terms of gases, particles etc, can be measured and linked to the perception of air quality. However, in many cases the link between the perception of air quality, the concentration levels of various substances and their influence on health is still not fully defined and known. Therefore, the meaning of “air quality” should be carefully considered and the parameters influencing indoor air quality should be identified and quantified for each application separately. For convenience the term “air quality” is used in the discussion in this study, even though the demand indicator actually refers to the air composition.

The demand controlled ventilation aims to control time varying pollutant emissions from activities and processes in the room. It is relatively simple to measure just one substance, as carbon dioxide. Carbon dioxide is considered as a quite good indicator of pollutants due to human occupancy. Bigger challenges are faced when a combination of substances, e.g. volatile organic compounds are to be considered. There is a large amount of different organic compounds at different concentrations in indoor air. The real health impact of many of these individual components and their combinations at the usually low concentration is still relatively unclear.

The purpose of this work has been to analyse the requirements that must be set on DCV sensors when applied for indoor air quality control. Additionally, it is aimed to evaluate the performance characteristics of commercially available sensors for indoor air quality control. This work is limited to sensor technologies for measurement of composition of air, excluding measurement of humidity. The sensors mentioned first are further referred to as “indoor air quality sensors”.

3.2 General specifications of a sensor

In order to evaluate the performance of indoor air quality sensors it is first essential to describe the functional properties of a sensor in general. This chapter gives the definition of a sensor used in the current thesis. Additionally, different sensor performance characteristics will be introduced. Several of these characteristics will be experimentally evaluated as part of the current sensor study.

3.2.1 Sensor definition

The word “sensor” is often used somewhat vaguely. It has been used to cover all the processes between the measured variable and the input to the control module system. Additionally, sensor, transducer, transmitter and detector are often erroneously used as synonyms. Here the following definition is applied throughout: “A sensor is a device which converts a physical, chemical, biological property or quantity into a conveniently measurable effect or signal”[209].

In this context the term “sensor” is used to designate a “sensor system”, which may consist of several components. Based on the functional properties, these components can be grouped in three different units:

- a sensing element
- a transducer
- a transmitter

The sensing element is a component that undergoes a measurable change in response to a change in the physical variable to be measured. The transducer is an active device that converts the raw, measured signal into a suitable signal, usually an electrical signal, which is a function of the change in the sensing element. The transmitter is a device that converts the measured value to a standardized electrical signal that can be used as an input to a control module[43]. The function of the transducer and the transmitter is often combined and referred to as signal conditioning. Signal conditioning may include signal filtering and averaging over time as well as linearization. A schematic structure of a sensor is shown in Figure 3.1.

The sensor may consist of a sensing element and a transducer only or it may have all components included, as shown in Figure 3.1. An intelligent sensor contains also a microprocessor which enables further data processing, such as calibration and compensation functions. With the microprocessor the measured values can also be converted into a digitally encoded signal for direct communication over a network for onward transmission to other intelligent devices for control and measurement purposes[43].

In HVAC systems sensors with analogue output are commonly used, where the output is an industry standard electrical signal, e.g. 0 - 10 V DC or 4 - 20 mA.

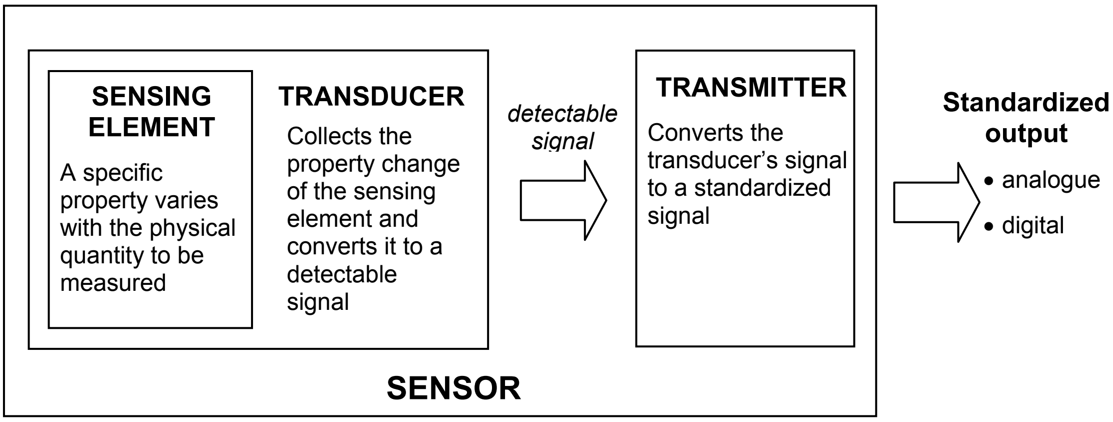

Figure 3.1 Schematic structure of sensor components

3.2.2 Sensor characteristics

Sensor characteristics may be grouped into [170]:

- static parameters
- dynamic parameters
- other parameters, e.g. environmental conditions and structural related parameters

3.2.2.1 Static parameters

Static parameters describe the properties of the system at steady state conditions, e.g. when the input does not vary with time. These parameters are associated with the static part of a transfer function of a sensor. Transfer function is the functional relationship between the physical input signal and electrical output signal of a sensor during static or dynamic conditions. It is normally a complex, a frequency dependent, function.

The static parameters include the following:

- *Input range*

An input range, often referred to as an operating range, describes the maximum and minimum value of the measured variable for which the sensor characteristics are maintained at stated values.

- *Minimum detectability*

Minimum detectability is the lowest reading/output that can be unambiguously discriminated from noise. On a digital unit the minimum detectability of a sensor is often given as the least significant digit. For example, on a 3½ digit meter, for a range of 0 - 199.9 ppm, this would be 0.1 ppm.

- *Resolution*

Resolution is defined as the least interval between two adjacent discrete details which can be distinguished one from the other[6]. For a sensor with an analogue output the resolution is the smallest division on the scale. In the digital display, the least significant digit will fluctuate, indicating that changes of that magnitude can only be determined.

- *Accuracy*

Accuracy is defined as closeness of agreement between a measured quantity value and a true quantity value of a measurand[162]. Accuracy should be used as a quantitative term to describe a measuring system. It is desired for the measuring system to have high accuracy. However, in order to estimate the accuracy of a sensor in a quantitative way a term "sensor uncertainty" is used. The sensor uncertainty is commonly specified in terms of either a fixed value; a percentage of reading; a fixed value plus a percent of reading; or a percent of the sensors full scale value. Sensor measurement uncertainty depends on several parameters, including uncertainty of the sensing element, resolution, linearity, hysteresis, repeatability, stability, cross-sensitivity, signal conditioning and calibration errors. Several of these influencing factors are included in the manufacturer-stated uncertainty data or are listed additionally in the specifications. Unfortunately, the available information on sensors is often rather limited, which makes comparisons between sensors complicated.

The sensor measurement uncertainty is obtained through calibration of a sensor. Testing the sensor at known reference conditions in a step change procedure is a common way to calibrate a sensor and make the adjustments if needed on sensor readings, e.g. removing bias. Instrumental bias is defined as the average of replicate indications minus a reference quantity value[162]. From a step change procedure a *sensor characteristic curve* can be determined.

- *Sensitivity*

Sensitivity can be defined as quotient of the change in the sensor output in response to a corresponding change of the sensor input over the sensor's entire range [73, 162]. When the output is a linear function of the input, sensitivity is a constant value and is equal to the slope of the transfer function line.

In the gas sensors field the *sensitivity* is also used to describe the ratio of the output response of the device in a given atmosphere to the output in a reference atmosphere and is a dimensionless value[170].

In the current study the term *sensitivity* is used to describe a sensor characteristic according to its common definition[73, 162]. However the term *sensitivity* is also used in a quantitative concept to describe the mixed-gas sensors behaviour in different environments. In this concept a parameter *relative sensitivity* is evaluated as the relative change of the sensor output signal against the initial output signal.

- *Repeatability*

Repeatability is a measure of the scatter of results from repeated measurements of the same property, using the same instrument and operator and with the same nominal ambient conditions. It expresses the sensors ability to reproduce consistently the same output from the same measured value. Repeatability is very often associated with *sensor precision*. Precision is defined as the degree of agreement of repeated measurements of the same property[15]. It is expressed in terms of dispersion of test results about the mean result obtained by repetitive testing of a homogeneous sample under specified conditions. Precision implies agreement between successive readings, not closeness to the true value.

Repeatability describes the precision of measurements taken over a short period of time interval. Another term used is *reproducibility*, which describes the precision of a set of measurements taken over long period of time, performed by different operators with different instruments.

- *Linearity*

It is often desirable for the sensors to have a linear transfer function between the measured variable and output signal. Nevertheless, deviations from the theoretical linear input and output relationship occur. The linearity, often also referred to as nonlinearity, is an expression of the extent to which the actual measured curve of a sensor departs from an ideal linear line between the output and the measured value across the range. There are several accepted methods for determining linearity. One method is based on the least-squares fit of the straight line to the measured data points. Another method is end point linearity, where the maximum linearity deviation is evaluated as the maximum deviation from the calibration curve and from the straight line between the end data points. With the two methods somewhat different results can be obtained.

- *Hysteresis*

The sensor readings may be affected by its past history, speed and direction of change of the measured variable. Hysteresis is a deviation in sensor output caused when the measured property reverses direction, creating an offset error between the two directions. It is a measure of the difference between the linearities with increasing and decreasing input respectively.

- *Stability*

Stability is a measure of the variation of sensor output signal with no intentional changes of the input signal. It is a property of a measuring instrument, whereby its metrological properties remain constant in time[162].

There are two parameters commonly evaluated when describing sensors' stability. The variations of a sensor signal over short period of time are associated with *noise*. Noise is a random fluctuation in the sensor output and is caused by the interferences in the conversion mechanisms in the sensor. Continuous or incremental change in output over longer periods of time, due to changes in metrological properties of a measuring instrument, is defined as *drift*[162]. Drift can be described as the degree to which the sensor fails to give consistent performance throughout its stated life. The drift is often referred to as *baseline offset.* Baseline corresponds to the sensor output at zero value of a quantity to be measured. For non-dispersive infrared CO_2-sensors the baseline should be zero. The commercial sensors commonly incorporate a self-adjustment system to compensate for the drift. However, it should be noted that *baseline offset* is not only caused by drift. It can also be caused by incorrect calibration in the factory and possible damage due to transportation/installation.

3.2.2.2 Dynamic parameters

Dynamic characteristics describe the sensor response to a variable input in time. These characteristics are more difficult to evaluate. The dynamic characteristics are determined by analysing the response of the sensor to different kind of input forms, e.g. impulse, step, ramp, sinusoidal, etc. However, in most cases these signals cannot be easily produced experimentally.

The most common dynamic characteristic tested is a response time of a sensor. The *response time* is a measure of how quickly a sensor output will change from an initial steady-state value to a new value as a result of a step change of the input. The speed of response is commonly characterized by the *time constant*. Time constant, τ_c is defined as a time interval, after which a variable that varies according to an exponential function would reach its final value if it were to retain its original rate of change[197]. It corresponds to the time required for the output signal to change from 0 to 63 % of the final value of a step response.

Another parameter used is *rise time*. Rise time, τ_r is defined as a time interval in connection with a step response, from the moment the output signal reaches a small specified percentage. e.g. 10 %, to the moment it first reaches a large percentage, e.g. 90 %, of the same steady-state value[197]. Very often also a *fall time* is specified, which can be determined similarly to rise time.

The speed of response of the sensor is influenced by its housing, the manner of mounting, the speed of the air flowing past the sensor, etc.[43]. The response time of the sensor should always be considered in relation to the rest of the controlled system. Too short response times at short term fluctuations in the measured variable may lead to unwanted control action. This must be compensated by the control software. Too long response times, on the other hand, may lead to too slow response of the control system to changes in the controlled variable. This can not be compensated by the controller.

3.2.2.3 Other parameters

There are a few additional sensor characteristics to consider, which can not be directly linked to static or dynamic sensor parameter categories. These include the following:

- *Cross-sensitivity*

Cross-sensitivity is a measure of the influence on a sensor output by other factors than the primary measurand. It is defined for each influence factor as the ratio between the change in output and the total change input. Common factors to influence the gas sensors are temperature, humidity, atmospheric pressure and interfering gases. Changes in the supply voltage and frequency conditions can also have a considerable influence on sensors output. In order to evaluate the impact of the different parameters, cross-sensitivity tests are carried out with a sensor.

- *Resistance to environmental conditions*

Resistance to environmental conditions describe the sensors resistance to possible extreme situations in the environment within the field of application of the sensor. The extreme environmental situations may include climatic parameters, e.g. dry heat, cold, damp heat and change of temperature; mechanical parameters, e.g. random vibration and electrical parameters, e.g. electrostatic discharge, electromagnetic radiation and surge voltage immunity[73].

- *Selectivity*

Selectivity is defined as a property of a measuring system, used with a specified measurement procedure, whereby it provides measured quantity values for one or more measurands such that the values of each measurand are independent of other measurands in the substance being investigated[162]. It is the ability of a sensor to measure only the specified parameter(s).

- *Warming-up time*

Warming-up time is the time needed by a sensor to operate within the specified uncertainty after applying the required operating power supply conditions.

- *Reliability*

Reliability is the sensor ability to operate under specified conditions with the specified characteristics for the specified period [170].

Structurally related characteristics are the parameters related to the specific design and components of the sensor, e.g. weight, power consumption, lifetime. These are also important parameters that must be borne in mind when selecting any type of sensor.

3.3 Principles of sensor technologies for indoor air quality control

Indoor air quality in the room is affected by different emission sources, which lead to changes in gaseous and particulate substances in indoor air. Therefore, the measurement of gaseous and particular substances is of interest for indoor air quality control. Unfortunately there are no commercial sensors currently available for detecting particles for continuous monitoring in terms of size and price[29]. Therefore, the measurement of gaseous compounds has been of interest.

This chapter describes the different sensing technologies available for measurement of gaseous pollutants. An overview of the gas sensing technologies is given that are used or have possibilities to be used for indoor air quality control.

3.3.1 Principles of sensing technologies for gaseous pollutants

3.3.1.1 Metal oxide semiconductor – Taguchi sensor

Measurement principle

The metal oxide semiconductor is a surface-active device. The gas adsorbs onto the sensing elements surface where it reacts and hence changing the resistance of the sensing layer. The sensing element consists of a tube coated with a thin/thick film semiconductor, such as polycrystalline tin oxide, aluminium oxide, etc, a pair of electrodes and a miniature heating element inside the tube. The sensor is heated up to a high temperature, which is kept constant. When in contact with the target gases a reaction with oxygen in the air will take place on the heated surface, which in turn alters the resistance across the two electrodes, producing a signal. The process is bi-directional, meaning that when the gas disappears, the sensor returns to its original condition. No sensor material is consumed in the process; hence the metal oxide sensors can have a long life time expectancy[41].

The change in resistance of the sensing element is usually converted, by a two- or four-point resistance measurement, to a voltage signal output from the sensor. Additionally, combining sensors with micro electronic mechanical systems technology, MEMS, integrated systems with control and measurement electronics on a single chip can be achieved[31].

The relationship between the resistance of the sensing element and the concentration of the target gas can be expressed by the following equation[7]:

$$R_S \approx A \cdot C_{gas}^{-\alpha} \quad [\Omega] \qquad \text{(eq.3.1)}$$

Where,
R_S electrical resistance of the sensing element, Ω;
C_{gas} gas concentration;
A and α are constants.

The constant α also describes the slope of the R_S curve on a logarithmic scale. A positive sign for the constant α is used for oxidizing gases, e.g. NO_2, O_3 and negative sign is used for de-oxidizing gases, e.g. CO, VOCs. In the presence of a deoxidizing gas the resistance of the sensing element is decreased and with an oxidizing gas the resistance is increased.

Sensor performance and application

The metal oxide semiconductor sensors measure non-selectively a wide range of gases. Traditionally the sensor signal gives no indication to the type of gases detected or in what concentration they are present. Different response characteristics can be achieved by the deposition of semiconductor materials, use of different operating temperatures and by operating the sensors in fast pulsed temperature mode[41, 84, 239, 241].

The metal oxide semiconductor sensors are commonly applied in electronic noses[10, 225, 241], detection of hazardous gases[41], automotive applications[4], indoor air quality monitoring[25, 82, 93, 147, 182], etc. The commonly available mixed-gas sensors for indoor air quality monitoring, often referred to as "VOC sensors" or "air quality sensors", are based on metal oxide semiconductor technology principle. In this study the term "mixed-gas sensors" is used and considered to be most correct, since with this technology principle it possible to measure also other gases than volatile organic compounds, VOCs. In the commercially available mixed-gas sensors the output signal is made proportional to "air quality ratings" of 0-100%.

The advantage of metal oxide semiconductor sensors is considered to be their sensitivity to a broad range of human-generated odours, cigarette smoke, long life expectancy, small size, low energy consumption and low price[41, 74].

Limitations for the application have reported to be lack of selectivity, low long-term stability, output dependency of environmental conditions and interfering gases, and difficulty in knowing what to calibrate these sensors against[84, 180]. In certain instances, the interferences from other gases can be minimized by using certain filters that absorb all other gases except the gas to be detected. For example, in order to monitor carbon monoxide and hydrogen, the sensor can be equipped with a charcoal filter, which eliminates the majority of interfering gases[41]. Water vapour also affects the sensor's conductivity. This effect has been analysed in many studies[18].A special algorithm can be implemented on a microchip in the control electronics of the sensor for compensation of humidity effects[85].

Even though the metal oxide sensor can detect a wide variety of gases at both low and high concentrations, their non-specific behaviour has been considered as an important drawback[74, 90]. According to other reports high selectivity is required, since some of the VOCs usually encountered at high concentrations in indoor environment are not harmful, while some other compounds can be toxic at very low concentration, e.g. benzene[242]. A development of a special device has been reported that would compensate these problems[242]. It includes micromachined gas chromatograph packed column used together with a metal oxide semiconductor sensor for achieving selectivity for certain toxic compounds. These devices are still under development for commercial use.

From the other point of view, indoor and outdoor air consists of thousands of different gases and it is extremely difficult and challenging to find the most important and representative gases for ventilation control. Therefore broad-band sensing of indoor air quality sensors can be an advantage[84]. An important requirement is that these sensors are able to detect the gases that are considered as pollutants, e.g. CO, several VOCs, and that they are not sensitive to traditional compounds in the atmosphere, e.g. water vapour.

3.3.1.2 Electrochemical sensors

Measurement principle

Electrochemical sensors are based on chemistry that produces an electrical signal when exposed to a target gas. A typical electrochemical sensing element consists of a sensing electrode and a counter electrode separated by a thin layer of electrolyte. The electrolyte can be a solid, a liquid or a gas. The sensing element can also include a third electrode, a reference electrode, for better performance of the sensor. The sensor operates by reacting with the target gas at the surface of the sensing electrode, involving either an oxidation or reduction mechanism. An electrical signal proportional to the gas concentration is produced. Depending on what kind of electrical signal is generated in the process these sensors can be characterized into three groups: potentiometric (measurement of voltage), amperometric (measurement of current) and conductometric (measurement of conductivity).

The typical electrochemical sensors available for detecting gases indoors are liquid-sate electrolyte sensors and solid-state electrolyte sensors.

Performance and application of a liquid-state electrolyte sensor

In a liquid-state electrolyte sensor a thin layer of liquid electrolyte is used together with a gas permeable membrane for preventing the electrolyte from leaking out. The selectivity of the sensor is influenced by the selection of electrode and electrolyte. The sensors are commonly applied for alarm detection of toxic gases for safety, e.g. CO, NH_3, H_2S [41] and explosive gases[193]. A development of a liquid-state electrolyte sensor for carbon dioxide measurement for indoor climate control applications has also been described in earlier reports[180].

The main advantages of a liquid-state electrolyte sensor are fast response, small power consumption, small size and it is not affected by the humidity in high gas concentration applications. Additionally, these sensors are only little affected by pressure changes[41]. The drawbacks of this type of sensing principle include cross-sensitivity to temperature and to other gases than the target gas, influence of humidity at low gas concentration, short lifetime[41, 180]. The specified life-expectancy is from one to three years. It is depending on the environmental contaminants, temperature and humidity conditions and baseline drift[41]. The lifetime of the sensor is also shortened when the detector is constantly exposed to the gas. The sensitivity to ambient temperature can be compensated in the microprocessor in the sensor by measuring the temperature and performing a temperature correction before linearization[180].

Performance and application of a solid-state electrolyte sensor

In this type of an electrochemical sensor a solid-state electrolyte is used. Since the solid-state electrolyte sensor has no gas permeable membrane the gas diffusion path is reduced resulting in improved sensor response times[204]. Solid-state electrolyte sensors are typically designed to operate at high temperature conditions and can operate either in a potentiometric or in an amperometric mode[200].

The solid-state electrolyte gas sensors have been traditionally used for detection of toxic gases[204], explosive gases[193] and for oxygen detection in automotive industry[200]. Additionally, carbon dioxide sensors based on solid electrolyte have been developed[120, 122].

The main advantages of this type of sensor is its reasonable selectivity, low power consumption, small size, rugged design and no risk for leakage of electrolyte and low cost[184, 204, 238]. Furthermore, detection methods have been developed for harsh conditions, where typical liquid electrochemical sensors are not suitable[200]. The main limitation is sensitivity to high humidity conditions[238].

3.3.1.3 Infrared spectroscopy

Measurement principle

The infrared spectroscopy measurement technology relies on the principles that every gas absorbs infrared light at specific wavelengths. The gas concentration is calculated by detecting the amount of absorbed light by specific gas molecules. There are two principally different ways of detection. The absorption of light increases the molecular vibration, which results in a raise in the temperature of the gas molecules. The temperature increases in proportion to the gas concentration and can be detected by the sensing element. Alternatively, the absorption of light will cause a decrease in the radiation energy, which can be detected as a signal too.

The key components of the infrared spectroscopy sensing element are an infrared light source, a gas cell/light path, an optical filter and a detector. There are different types of detectors, e.g. thermoelectric, pyroelectric, photon detector, photoacoustic detector, etc. Depending on how the specific wavelength is achieved the infrared sensor systems can be dispersive or non-dispersive. In non-dispersive infrared detection all the infrared light passes through the gas sample and is being filtered immediately before entering the detector. In the case of dispersive infrared detection the desired wavelength of infrared light is preselected with an optical device such as a grating or a prism. Commonly, non-dispersive infrared, NDIR, detection is applied in commercial infrared gas sensors[41].

Sensor performance and applications

The infrared sensors can be used to selectively measure a wide range of gases, e.g. carbon dioxide, carbon monoxide, VOCs, and it can be used in a wide range of applications, e.g. toxic and combustible gas monitoring[9, 124], atmosphere monitoring[164], indoor air quality monitoring[134, 163, 224], etc. The majority of carbon dioxide sensors in the market use non-dispersive infrared technology. Infrared spectroscopy measurement is also applied for leak detection of refrigerants in air conditioning and chiller systems in buildings[134] and in automotive systems[9].

The biggest advantage of the infrared technology is considered to be its accuracy. Once the zero point (baseline) corresponding to zero gas concentration is established and maintained, the accuracy of the detector should in theory remain intact. The other advantages of non-dispersive infrared technology include high selectivity, linearity, reproducibility and long life expectancy[41, 74, 164]. Infrared sensors can be affected if the water vapour in the air condenses, e.g. if the temperature is below the dew point temperature.

The disadvantages are related to the efficiency of sensor's optical components. Optics degrades over time and the light intensity will vary slightly due to aging of the light source, resulting in significant drift in sensor output. There are several methods applied nowadays to compensate for this problem. Some sensors use a second detector tuned to a wavelength other than the target gas for a reference value and some have integrated a reference light source. In addition, some sensors have a special filter included as a mean to provide a dual wavelength operation. Another way for drift compensation is by employing an Automatic Baseline Correction, ABC, software algorithm to the sensors. This enables the infrared sensor to be automatically calibrated based on the lowest measured baseline level over certain period of time. The automatic baseline correction method requires that the building is not in constant operation, since the method resets the daily lowest measured value to an assumed outdoor CO_2 concentration, e.g. at night time.

Additionally, the infrared sensor is sensitive to ambient temperature and pressure fluctuations[94]. Since the non-dispersive infrared measurement techniques fundamentally measure the number of CO_2 molecules in a certain fixed volume, the atmospheric conditions affect the CO_2 measurement due to the compressibility of gas. If the actual measurement environment differs from the calibrating conditions, a small error will be introduced to the output signal[97]. The error in different operating conditions can be evaluated according to the equation 3.2.

$$C_S = C_{iS} \cdot \frac{p_0 \cdot T_a}{T_0 \cdot p_a} \quad \text{[ppm]} \qquad \text{(eq. 3.2)}$$

Where,

C_S corrected sensor reading of volume concentration, ppm;
C_{iS} gas concentration indicated by the test sensor, ppm;
T_a ambient temperature, K;
p_a ambient pressure, hPa;
p_0 pressure at standard/specified test conditions, hPa;
T_0 temperature at standard/specified test conditions, K.

3.3.1.4 Catalytic gas sensors

Measurement principle

Catalytic gas sensors work with the catalytic combustion principle, where a gas molecule oxidizes on the catalytic surface at a much lower temperature than its normal ignition temperature. Most metal oxides and their compounds have these catalytic properties. To enhance the reaction rate of hydrocarbons the sensing element is heated by an embedded heating wire and the surface is covered by a thin catalytic layer. When the gas burns on the active surface, the heat of combustion causes the temperature to rise. This in turn changes the resistance of the sensing element, which is measured with a specific electric circuit. The concentration of the gas readings are in direct proportion to the electrical signal.

Sensor performance and applications

This type of sensor is applied for detection of combustible gases [41], but they have also been developed for measurement of VOCs indoors[181]. The main advantages of catalytic gas sensors are that they are stable, reliable, accurate, have a linear output and are sensitive to human generated odour, cigarette smoke and emissions from building materials[41, 74]. Additionally, they are inexpensive.

The disadvantages have been reported to be their non-selectivity, sensitivity to ambient temperature and humidity, slow response and difficulty in knowing what to calibrate against[74]. Furthermore, there are some chemicals which can inhibit the sensor performance. Deterioration can also occur when the sensor is exposed to excessive concentration of gases and excessive heat. Moreover, the quality of the sensor can vary quite drastically from one manufacturer to another[41]. They have one to three years of life expectancy. Because catalytic sensors burn the gas being detected, sensor material is changed in the process and the sensor eventually burns out[41].

Developments on this sensing technology have been made during recent years. Sasahara et al.[181] developed and tested a highly sensitive sensor based on adsorption/catalytic combustion, operating in a low-high pulse heating mode. The sensor showed high sensitivity to VOCs at low concentrations. Additionally, the sensor had no considerable sensitivity to ambient temperature and humidity, because of the high absorption temperature.

3.3.1.5 Field effect transistor (FET)

Measurement principle

Gas sensitive devices based on field effect transistors are generally called GASFETs. Different types of GASFETs are e.g. MOSFET, SGFET, where the specific name denotes the gate material and/or the set-up. The MOSFET sensing element consists of a thin catalytic layer, platinum or palladium, on top of a metal oxide semiconductor field-effect transistor. All devices have a common structure: a gate on the top of an insulating layer SiO_2, a p-doped silicon channel, a n-doped source and drain[7]. In field effect transistors gas molecules diffuse into the sensing element and react at the gate of the transistor, thereby changing the current through the device[74].

Sensor performance and applications

Field effect transistors are sensitive to a broad range of hydrogen-containing compounds, e.g. VOCs. Selectivity to different gases is depending on the operating temperature, the metals chosen for the gate material and the thickness and morphology of the gate material[7, 74]. This type of gas sensing technology has been used in electronic nose applications[10]. The main advantages of the field effect transistors are fast response, good stability, low cross-sensitivity to moisture and small size[7, 74]. However, the experience with these sensors for indoor climate measurements is still limited.

3.3.1.6 Mass sensors

The mass sensors typically adsorb the gas onto the surface of the sensing element. As a result the change in mass is detected. There are two types of mass sensors: surface acoustic wave sensors and quartz crystal microbalance gas sensors.

Performance and applications of surface acoustic wave sensors
Surface acoustic wave sensors detect a gas by measuring the disturbance it causes in sound waves across a tiny quartz crystal. Typical surface acoustic wave sensor is composed of oscillators with dual delay lines/resonators and corresponding oscillator circuits. One device is coated with gas-sensitive film and the other is left uncoated for use as a stable reference. The adsorption of a specific gas onto the sensitive film modulates the phase velocity of the acoustic wave through various response mechanisms such as the mass loading effect. This results in a change of frequency at the output of the surface acoustic wave oscillator. The frequency difference between the two oscillators is directly proportional to the gas concentration[215].

These sensors can detect a wide range of gases due to the wide range of gas sensitive coatings available[10]. They are applied in detection of explosive gases[193], in electronic noses[10], etc. To achieve selectivity, several sensor devices can be combined into a sensor array. One such system for indoor air quality monitoring, based on a surface acoustic wave sensor system array, is introduced by Bender et al.[19].

The surface acoustic wave sensors have many advantages when compared to other currently available types of gas sensors. They have high sensitivity, fast response time and good stability[215]. The disadvantages include high false alarm rates, large signal evaluation errors and that the circuitry required to operate the sensor is complex and expensive[10, 215]. Additionally, temperature and humidity influences the performance of the sensors by causing shifts in the baselines. Development on this sensor technology principle is ongoing[215].

Performance and applications of quartz crystal microbalance sensors
Quartz crystal microbalance gas sensors operate with the same principle as the surface acoustic wave sensors. However, the change in mass, after the gas has been adsorbed onto the surface, is detected by the actual change in shape of the device. A membrane is deposited onto the surface of the crystal, which adsorbs gas, resulting in an increase in its mass. This increase in mass alters the resonant frequency of the quartz crystal which is used for detection of the gas[10]. Quartz crystal microbalance gas sensor is applied for detection of explosive gases [193], in electronic noses [10] and implemented in VOC measurement instruments[7]. Sensitivity and selectivity towards a certain gas is achieved through coatings with different polymers. Advantages of this type of sensor are high stability of the signal, fast response time, good operation at typical room temperature and humidity. The disadvantages include poor signal to noise performance, complex fabrication process and complex interface circuitry[7, 74].

3.4 Requirements on sensors for DCV

In order to apply the different available gas sensing technologies for indoor air quality control in a DCV system, there are certain requirements that the sensor must fulfil. This chapter describes the principal requirements that are set on sensors in building control systems. Additional, quantitative requirements on gas sensors for indoor air quality control are proposed.

3.4.1 Principal requirements on sensors for indoor air quality control

Sensors for indoor air quality control with a DCV system should give fast, stable and reliable output signals corresponding to the value for the specified quantity measured. The best controls and air distribution systems are useless hardware if the control inputs used are not valid, or are so unreliable as to make them ineffective [46] Incorrect measurement of specified reference quantities can lead to under- or over-ventilated rooms, resulting in uncomfortable indoor climate or excessive use of energy. In addition, the correct location of sensors is vital to achieve the required performance from any control system.

Based on basic requirements and general requirements on sensors applied in building control systems the sensors should have the following performance characteristics[43, 74, 84, 209]:

- Sensitivity to the measured property in question;
- Sufficient operating range for the measurement purpose;
- Good accuracy and resolution over the whole operating range;
- Good precision and reproducibility;
- Linear output signal, with minimal linearity deviation and low hysteresis;
- Low cross-sensitivity to any other property and influencing factors, e.g. other gases or environmental conditions;
- Fast response time, including sufficiently fast rise time and recovery time, compared to the time variations of the indicator of a particular application;
- Good stability with no need for manual recalibration;
- Sufficiently stable output signal with minimal noise.

Additionally the practical and economic considerations to fulfil are:

- Long life with easy operation as well as low maintenance requirements;
- Mechanical ruggedness;
- Electronic ruggedness (immunity to interference);
- Ease of installation;
- Reasonable size and weight;
- Compatibility and interchangeability with other components and adherence to relevant standards;
- Low cost, including low price and low-cost operation.

Indoor air quality control by DCV systems aims to control the concentrations of gases and particles caused by emissions that vary in time, e.g. due to occupancy, occupant related activities and processes in the room. Measurement of pollutants that remain constant in time, e.g. from building materials and furniture, with sensor methods is impractical and not efficient from the system point of view. For these emissions a constant base ventilation airflow rate should be assured. Additionally, it should be noted that selective measurement of toxic or carcinogenic substances with sensor methods seems unnecessary for continuous indoor air quality control. The emission sources for these compounds should be identified and removed.

3.4.2 Proposed quantitative requirements on gas sensors for indoor air quality control

3.4.2.1 Sensors performance based on requirements on a DCV system

There are two principally different possibilities to control indoor air quality with demand controlled ventilation:

- maintain the required minimum outdoor airflow rates;
- maintain the required concentration of a specified indicator/pollutant.

The ventilation rates required for keeping the acceptable air quality indoors are presented in the majority of ventilation standards and guidelines. For example according to the Swedish recommendations on indoor climate[203], the outdoor airflow rates should not be lower than 7 l/s per person for sedentary activities in the room. In addition a minimum airflow rate of 0.35 l/s per m^2 of floor area should be added to the total lowest outdoor airflow rate supplied to the room. This additional component is intended to dilute pollutants from other sources than people. The European standards specify minimum airflow rates based on different indoor air quality categories[64, 199].

The required minimum airflow rates can be determined with a DCV system by direct control of airflow, e.g. with occupancy sensors, when the number of people is known. However, the required airflow rates can also be indirectly determined by measuring pollutant concentrations. Based on the mass balance equation used for steady-state conditions the pollutant concentration and ventilation rate are correlated as follows:

$$\dot{V} = \frac{\dot{V}_p}{C_r - C_{sp}} \quad [\mathrm{l/s}] \qquad \text{(eq. 3.3)}$$

Where,

C_r the pollutant concentration in the room, (volume by volume);
C_{sp} the pollutant concentration in the supply air, (volume by volume);
$\dot{V}$ airflow rate, l/s;
$\dot{V}_p$ the pollutant generation rate, l/s. For example, CO_2 generation rate per person, based on age and metabolic rate for an assumed activity level. For office work the CO_2 generation rate is assumed to be 19 - 24 l/h per person[58];

It is assumed in the previous equation that the concentration in the exhaust air equals the indoor concentration, e.g. there is perfect mixing in the room.. Furthermore, the mass balance equation is valid for conditions, where the concentrations and source strengths do not vary in time and there is no mechanism other than ventilation removing the pollutant from the indoor environment[158].

The requirements that must be set on the controlling sensors can be evaluated from the requirements that are set on the airflow rate control. The Swedish guideline

VVS AMA 98[236] specifies that the biggest permissible deviation from the required airflow rate supplied to the building and to the rooms should not exceed ± 15 %. This value includes also the measurement uncertainty of the airflow rate. For evaluating the maximum uncertainty that can be required by the controlling sensors in a DCV system, similarities can be drawn from the calibration guidelines of measuring instruments. The International Organization of Legal Metrology guidelines commonly state that the measuring instruments should have an uncertainty not greater than one third of the maximum permissible error for a given measurement. This concept can be transferred to the sensors controlling the airflow rate in the system. This means that the uncertainty of the indoor air quality sensors should not lead to greater error than one third of the maximum permissible error for the required airflow rate. In this case one third would correspond to ± 5 % of the deviation in airflow rate that can be associated with the controlling sensor.

The deviation in airflow rate ± 5 % would correspond to about ± 5 % uncertainty of measurement of the concentration deviation, $\Delta(C_r - C_{sp})$, when a constant pollutant generation rate is assumed. The maximum permissible uncertainty of each concentration measurement can be estimated by a differential analysis of concentration quantities included in equation 3.3, as follows:

$$\frac{\Delta\dot{V}}{\dot{V}} = \sqrt{\left(\frac{\Delta C_r}{\left(C_r - C_{sp}\right)^2}\right)^2 + \left(\frac{\Delta C_{sp}}{\left(C_r - C_{sp}\right)^2}\right)^2} \qquad \text{(eq.3.4)}$$

Where,

$\Delta\dot{V}$	deviation in airflow rate, l/s;
ΔC_r	uncertainty of measurement of the pollutant concentration indoors, (volume by volume);
ΔC_{sp}	uncertainty of measurement of the pollutant concentration in the supply air, (volume by volume).

For each concentration measurement the corresponding uncertainty should be ≤ ± 3.5 %. This means that for keeping the airflow rate of 10 l/s within the permissible deviation the measured outdoor CO_2 concentration can have an uncertainty of 14 ppm. The room CO_2 level must be determined within the uncertainty of 32 ppm. However, it can be assumed the both sensors will have the same/similar uncertainty. Figure 3.2 shows how the uncertainty of the airflow rate is influenced by the uncertainty of each measured CO_2 concentration. The uncertainty of measurement for each sensor is assumed to be the same in absolute terms.

The figure shows that in order to fulfil the requirement of maximum ± 5 % deviation from the design airflow rate the maximum uncertainty of measurement for each CO_2 concentration should be about ± 15 ppm to ± 30 ppm depending on the set-point. It can be assumed that the outdoor concentration is about 400 ppm and the set-point value about 1000 ppm. Then the required sensor uncertainty would correspond to about ± 5 % of the lower concentration level 400 ppm and ± 2 % of the higher concentration level 1000 ppm.

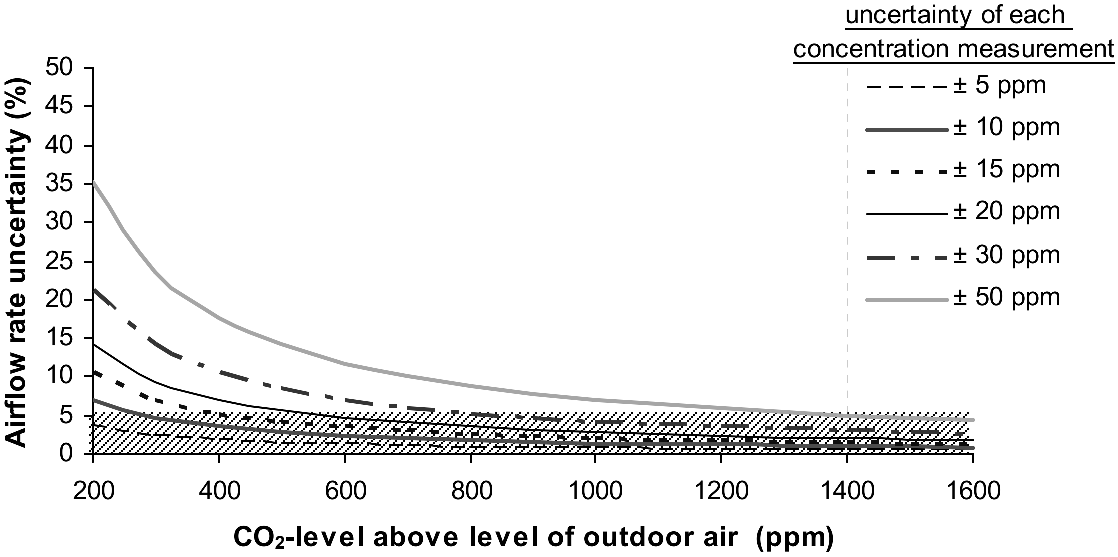

Figure 3.2. The uncertainty of the airflow rate at different CO_2 concentration deviations calculated for various uncertainties of the indoor and supply concentration measurements. The diagram is based on the CO_2 generation rate 20 l/h. The uncertainty of the CO_2-sensors should not lead to greater uncertainty in required airflow rate than ± 5 %.

An alternative way to control indoor air quality with a DCV system is to maintain the required pollutant concentration in the room. The ventilation guidelines commonly specify the required CO_2 concentrations that must be maintained indoors for keeping the air quality on acceptable level. For example, the Swedish indoor climate guideline R1 defines two different indoor air quality classes: AQ1 and AQ2[203]. For indoor air quality class AQ1 the CO_2 concentration in the room at normal room use should not exceed 800 ppm and for air quality class AQ2 this level is 1000 ppm. The requirement for a DCV system is to maintain this concentration level. The exact amount of airflow rate needed for keeping the set-point level has a secondary importance. The design airflow rates are chosen according to the maximum load and planned activity in the room and based on the requirement that the pollutant concentration should not exceed the given set-point.

In order to keep the specified indoor air quality class, a requirement is proposed that the uncertainty associated with the controlling sensor should not be bigger than one third of the difference between the two air quality classes. For example, the difference between the two air quality classes AQ1 and AQ2 is 200 ppm. To keep the required air quality class the uncertainty of the concentration measurement should be less than ± 65 ppm. This would correspond to ± 6.5 % and ± 8.1 % from the set-points at 1000 ppm and 800 ppm, respectively.

Some other standards specify the requirements on the CO_2-level above the level of outdoor air that must be maintained in the room for a given indoor air quality category[64]. In this case it is required that both the room and supply air conditions are measured. The requirements on the controlling sensors can be evaluated similarly as was done for evaluating the requirements for keeping the required set-point of CO_2 concentration. This means that compare the difference between the respective air quality categories. Alternatively, the evaluation can be based on the comfort criteria. For example, European standard EN 15251:2007[65] specifies four different indoor air quality categories. The first category is based on the 15 % of expected percentage of dissatisfied. For the second and third category this percentage is 20 % and 30 %, respectively. The indoor air quality would classify under fourth category if the expected percentage of dissatisfied is higher than 30 %.

These required CO_2 concentration levels and the minimum ventilation rates are based on comfort criteria and aim to achieve an acceptable perceived air quality for the majority of the occupants. The perception of indoor air quality is commonly expressed as percentage of dissatisfied, PD. The percentage of visitors dissatisfied with the level of body odour in a space can be expressed as a function of CO_2 concentration and airflow rate as follows[37, 78]:

$$PD = 395 \cdot e^{-1.83 \cdot \dot{v}_{olf}^{0.25}} \qquad \text{[\% dissatisfied]} \qquad \text{(eq. 3.5)}$$

$$PD = 395 \cdot e^{-15.15 \cdot (C_r - C_{sp})^{-0.25}} \qquad \text{[\% dissatisfied]} \qquad \text{(eq. 3.6)}$$

Where,

PD	percentage of dissatisfied due to indoor air quality, %;
C_r	the pollutant concentration indoors, (volume by volume);
C_{sp}	the pollutant concentration in the supply air, (volume by volume);
$\dot{v}_{olf}$	specific airflow rate, l/s per olf;

The equations 3.5 and 3.6 apply for spaces where sedentary occupants are the main pollution sources.

In order to fulfil the requirement for the given indoor air quality class, the deviation in percentage of dissatisfied should be smaller than one third of the difference between the preceding and following indoor air quality class. For example according to the indoor air quality classes specified by the European standard EN 15251:2007[65], to fulfil the first and second air quality class, the deviation should be < ± 1.6 % in percentage of dissatisfied. For the third air quality class this deviation should be < ± 3.3 %. To keep the percentage of dissatisfied within the specified deviation, the uncertainty associated with the concentration measurement can be estimated by a differential analysis of concentration quantities included in equation 3.6, as follows:

$$\frac{\Delta PD}{PD} = \sqrt{\left(\frac{\Delta C_r}{\left(C_r - C_{sp}\right)} \cdot c_1\right)^2 + \left(\frac{\Delta C_{sp}}{\left(C_r - C_{sp}\right)} \cdot c_2\right)^2} \qquad \text{(eq. 3.7)}$$

Where,

ΔPD	deviation in percentage of dissatisfied, %;
ΔC_r	uncertainty of measurement of the pollutant concentration indoors, (volume by volume);
ΔC_{sp}	uncertainty of measurement of the pollutant concentration in the supply air, (volume by volume).
c_1, c_2	sensitivity coefficients, $c_1 = c_2$

For each concentration measurement the corresponding uncertainty should be about ≤ ± 7.5 % to ≤± 9.5 %, when the two first indoor air quality categories are to be fulfilled. Figure 3.3 shows how the percentage of dissatisfied will be changed by the uncertainty of each CO_2 concentration measurement. The uncertainty of measurement for each sensor is assumed to be the same in absolute terms.

As it can be seen from the Figure 3.3, the maximum uncertainty of measurement for the CO_2 concentration should be about ± 50 ppm for the first and the second indoor air quality category, according to European standard EN 15251:2007[64, 65]. Assuming that the outdoor concentration is about 400 ppm, the described CO_2-sensor uncertainty would correspond to about ± 13 % of the lower concentration level 400 ppm and to about ± 5 % at higher concentration level 1000 ppm.

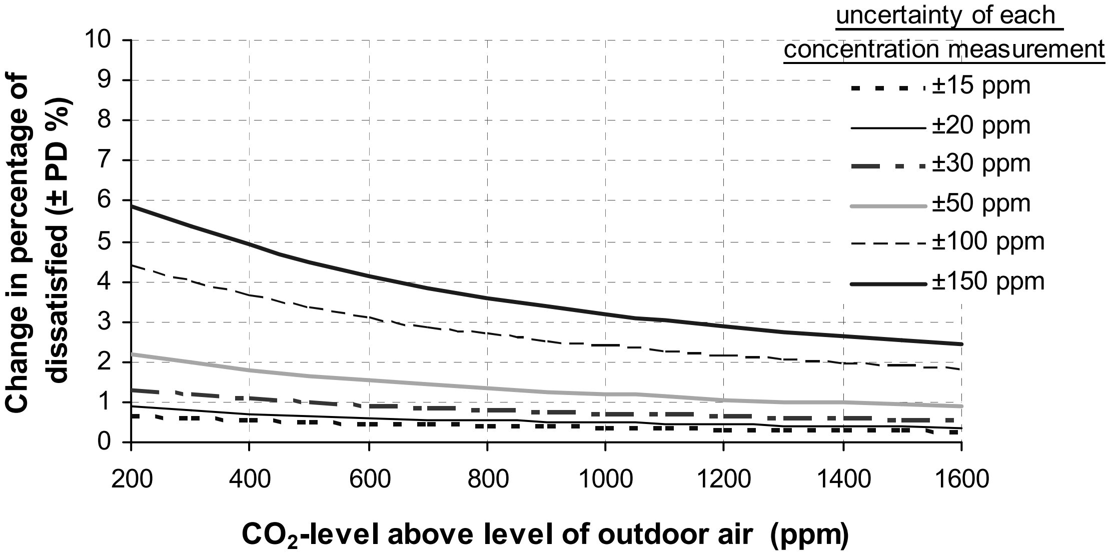

Figure 3.3. Change in percentage of dissatisfied at different CO_2- levels calculated for various uncertainties of the indoor and supply air concentration measurements. The diagram is based on the CO_2 generation rate 20 l/h. The uncertainty of the sensors should not lead to greater change in percentage of dissatisfied than ± 1.6 % or ± 3.3 %, depending on the required indoor air quality category.

The proposed requirements on the uncertainty of indoor air quality sensors are mainly applicable for CO_2-sensors. This is because there are basically no guidelines stipulating acceptable concentrations of common air contaminants for non-industrial buildings. Nevertheless, if the pollutants and their required concentrations are or can be specified, the requirement on the uncertainty of the controlling sensor should be based on the requirements on the concentration levels that must be maintained. When the variation in the given pollutant concentration in the supply air is not known the measurement of the supply air conditions is also required. This is in order to avoid the risk of using supply air with a higher pollutant concentration than the room air, hence leading to an increase in the pollutant concentration.

3.4.2.2 Proposed quantitative requirements on indoor air quality sensors

Based on the demands set on indoor air quality control in premises the controlling sensors in a DCV system should fulfil the following requirements:

- When the requirement on the DCV system is to maintain the specified minimum airflow rates for the room the uncertainty of concentration measurement should be ≤ ± 3.5 % for each indoor air quality sensor.

- When the requirement on the DCV system is the maintain the required concentration of CO_2 the uncertainty of concentration measurement should be ≤ ± 6.5 % or ≤ ± 8.1 %, when the required set-point is 1000 ppm or 800 ppm, respectively.

- When the demand is to keep the specified indoor air quality category based on the percentage of dissatisfied, the uncertainty of each sensor should be about ≤ ± 7.5 % to ≤± 9.5 %, for the specified percentage of dissatisfied of 15 % or 20 %.

- The specified sensor uncertainty should include all the possible sources of uncertainties, e.g. calibration errors, repeatability, linearity, hysteresis, stability and cross-sensitivity, etc.

- Response time less than one third of the nominal time constant of the controlled room. This would correspond to about 15 minutes for a cell office room of 10 m^2 and airflow rate 10 l/s.

3.5 Performance of commercially available sensors for indoor air quality control

This chapter describes the background and aim of the performance evaluation of commercially available sensors for indoor air quality control. First a summary of available information about the performance of commercially available indoor air quality sensors is presented. Then the aim of the sensor performance studies is described in detail. In addition, an overview of the sensor procurement and the selected test sensors is given.

3.5.1 Introduction

During the beginning of this work a sensor market survey was carried out in order to get an update about the commercially available sensor technologies for indoor air quality control. The available indoor air quality sensors detect the concentration of selected reference gases or mixture of gases. Since indoor air consists of thousands of different gases it is a challenging task to select the most representative ones and select the sensors accordingly.

Carbon dioxide is commonly used as an indicator for the sensory pollution load from people, since it is easy to measure and the concentrations vary similarly to bio-effluents generated by humans. A number of companies provide sensors for carbon dioxide measurement indoors. Although manufactures have published some information about the expected performance of their CO_2-sensors, there is a lack of literature describing the specifications and characteristics of commercial sensors. In particular, there is a shortage of independent studies.

One of the most extensive studies on DCV sensor performance was conducted more than fifteen years ago as part of the Annex 18 program[74]. In this study the two tested CO_2-sensors revealed an acceptable performance for DCV control purposes. The problems identified concerned sensitivity to humidity, temperature and tobacco smoke. Jones et al.[114] showed in sensor performance tests in a full scale test room that similar CO_2-sensor models from the same manufacturer can perform differently under steady-state and transient conditions. It was concluded that the in-situ performance of these sensors should be periodically checked in DCV applications.

Recent performance tests with CO_2-sensors revealed that the uncertainties of the tested sensors were close to manufacturers values and no drift occurred during an eight month measurement period in the field[224]. However, in this article the applied methods are not described in a clear way, raising several questions about the results. In the most recent study, where CO_2-sensor performance was evaluated directly in the field, the results showed poor sensor accuracy under tested reference conditions[237]. This can be attributed to improper calibration procedures and/or poor long-term stability of the tested sensors.

There is also a great interest to control gaseous pollutant emissions from other sources than people, e.g. processes in the room, office equipment, cleaning, etc. This is especially important in cases where people are not the main variable pollutant emission source in the room. Unfortunately there are no sensors currently available for detecting all the gases present in indoor air. Instead, mixed-gas sensors, which measure the weighted influences of various gases, have been used in several applications. For example, the mixed-gas sensors have been successfully applied in restaurant conditions[145] and in spaces with tobacco smoking[240]. The possible application of mixed-gas sensors in library and photocopying areas have been also studied[147].

Although the application of mixed-gas sensors has become of interest for the control of indoor air quality, there are several issues raised regarding their performance. One of the biggest disadvantages has been noted to be their non-specific behaviour[74]. Since the sensor reacts to a large number of substances it is difficult to distinguish between the measurand of interest and external factors. Moreover, sensitivity to ambient humidity and temperature conditions and problems with stability have also been pointed out in several reports[74, 90, 93]. Other studies have shown that it can be difficult to determine air quality by mixed-gas sensors in analogy to indoor air quality perceived by a person[25].

Performance tests with eight metal oxide semiconductor gas sensors of two different types showed that the sensors included drift in their output and a loss of sensitivity over time[182]. This would make the yearly replacement of sensors necessary, causing problems with maintenance.

3.5.2 Aim of the sensor study

According to the literature review carried out, updated information is needed on performance characteristics of CO_2-sensors and mixed-gas sensors for demand controlled ventilation applications. Hence, a study was planned with the aim to:

- test the performance characteristics of different commercially available CO_2-sensors and mixed-gas sensors in detail and evaluate if the proposed quantitative requirements set on indoor air quality sensors are fulfilled. Additionally, when possible, make a comparison with manufacturer's data.
- test the relative sensitivity characteristics of mixed-gas sensors and evaluate their application possibilities in commercial buildings;
- test the performance of CO_2-sensors and mixed-gas sensors under transient conditions in the field and evaluate the most suitable sensor location;
- evaluate the long-term stability of CO_2-sensors applied in an existing DCV system.

The study comprised the following main points:

- study of the characteristic performance of CO_2-sensors and mixed-gas sensors under laboratory conditions;
- evaluation of the performance of the mixed-gas sensors in a full scale emission free test room with different typical pollution sources;
- sensor tests in the field.

3.5.3 Sensor procurement

The tested CO_2-sensors and mixed-gas sensors were procured from seven different manufacturers. The manufacturers were identified in the sensor market survey that was carried out prior to this study. The aim of the market survey was to find and procure sensors with different technology principles and solutions.

The majority of the CO_2-sensors ordered were non-dispersive infrared sensors. The main difference between the chosen sensors is the drift compensation method included to the sensor transmitter. Some sensors have automatic baseline correction, some have a special filter technology and some use a second light source for drift compensation. The sensors ordered from the same manufacturer are based on the same technology, even though they have different model designations. The difference between the models is depending on the additional measurement options added to the transmitter, e.g. combined measurement of temperature, humidity, VOCs. The current study concentrates only on the sensor performance in terms of measurement of CO_2 and mixed-gases, whereas the performance of the two measurements was tested separately.

Besides the non-dispersive infrared sensing technology it was also possible to include electrochemical and metal oxide semiconductor CO_2-sensors in the test program. These types of sensors tested were special pre-calibrated sensor modules provided by the original equipment manufacturers. The modules had a microprocessor included for signal processing intelligence. Some of these sensors are still under the development.

The available mixed-gas sensors applied for indoor climate control are based on metal oxide semiconductor technology. However, there appears to be slight differences between the sensors in terms of gas sensitivity. In the current test program complete sensor transmitters and modules including just a sensing element and a transducer were tested. Additionally, a sensor modules incorporating a microprocessor and providing a digital sensor output were tested.

Table 3.1 shows the specification of the tested CO_2-sensors and mixed-gas sensors along with the manufacturers' stated performance characteristics. Twelve different models of CO_2-sensors and four different models of mixed-gas sensors were available for testing. In addition, two models of combined CO_2/mixed-gas sensors were tested. For some sensor models more than one specimen was ordered. All together twenty seven indoor air quality sensors were purchased. The detailed information about the tested sensors is given in APPENDIX B.

Table 3.1 Specification of the tested sensors in the study programme

Model	**Nr of sensors** [2)]	**Manu-facturer**	**Sensor type**	**Relatively sensitive gases**	**Measuring range, ppm**	**Sensor uncertainty** [1)] **< ± ppm**
S1	2	A	NDIR [3)]	CO_2	0-2000	20ppm+5%m/v [4)]
S2 [5)]	6	A	NDIR	CO_2	0-2000	20ppm+5% m/v
S3	2	B	NDIR	CO_2	0-2000	30ppm+3% m/v
S4	1	B	NDIR	CO_2	0-2000	30ppm+3% m/v
S5	1	C	NDIR	CO_2	0-2000	50ppm+3% m/v
S6 [5)]	1	C	NDIR	CO_2	0-2000	40ppm+2% m/v
S7 [5)]	1	D	NDIR	CO_2	0-2000	50ppm+2% m/v
S8	2	D	NDIR/ MOS [3)]	CO_2 / VOCs	0-2000 CO_2 n/a [4)]- VOC	50ppm+2% m/v n/a - VOC
S9	1	D	NDIR	CO_2	0-2000	50ppm+2% m/v
S10	1	D	NDIR	CO_2	0-2000	50ppm+2% m/v
S11[5)]	2	D	NDIR/ MOS [3)]	CO_2/ VOCs	0-2000 CO_2 n/a - VOC	50ppm+2% m/v n/a - VOC
S12	1	E	solid state electrolyte	CO_2	400-4000	20 % m/v
S13	1	E	solid state electrolyte	CO_2	400-4000	20 % m/v
S14	1	F	MOS [3)]	CO_2	400-3000	n/a
S15[5)]	1	E	MOS	VOC	1 - ~30	n/a
S16 [5)]	1	E	MOS	VOC	1 - ~10	n/a
S17	1	F	MOS	VOC	1-10 000	n/a
S18	2	G	MOS	VOC	350-2000	n/a

Note 1: The sensor uncertainty specified by the manufacturer at specified test conditions
Note 2: The additional specimens of a sensor model are designated with letters from A to D.
Note 3: NDIR – non-dispersive infrared sensor; MOS – metal oxide semiconductor sensor; NDIR/MOS – combined sensor for measurement of CO_2 and mixed-gases
Note 4: m/v - measured value; n/a – information not available;
Note 5: S2, S6, S7 and S11 are duct sensors, sensors S15 and S16 are sensor modules including a sensing element and transducer only.

The sensor models *S1* to *S14* have analogue output signals, which are correlated into concentration units in ppm, parts per million. Sensors *S8* and *S11* have two output possibilities: one for measuring CO_2 only and one for measuring a combined effect of CO_2 and mixed-gases. The analogue signal of the combined measurement of CO_2/mixed-gases is transformed to 0-100 % in indoor air quality ratings. The voltage outputs of sensor modules *S15* and *S16* are correlated into resistance change of the sensing element expressed as kΩ. Sensors *S17* and *S18* have digital output signal.

3.6 Characteristic performance of CO_2-sensors

This study evaluated the performance characteristics of CO_2-sensors. A comprehensive study was carried out under laboratory conditions. The sensor models tested in detail were *S1* to *S9* and *S12* to *S14,* according to the numeration in Table 3.1. The performance of the several additional models and extra specimens was verified later with the already tested model from the same manufacturer.

The laboratory tests consisted of determination of different performance characteristics of the sensors. This study is limited to the evaluation of following sensor performance characteristics: determination sensor characteristic curve, linearity, hysteresis, repeatability, short-term stability and cross-sensitivity to temperature, humidity and supply voltage change. This chapter describes shortly the methodology and provides the results and discussion of the study. More detailed description of the experimental methodology is presented in APPENDIX B. The evaluation of uncertainty of measurement is presented in APPENDIX C. More detailed information about the sensors output at different tests can be found from Maripuu[142].

3.6.1 Experimental methodology

3.6.1.1 Summary of the test set-up and measurement techniques

The tests were carried out in the laboratory of SP Technical Research Institute of Sweden. This laboratory is equipped with apparatus especially used for sensor calibration. A small-scale test chamber made of glass and stainless steel was used for CO_2-sensor performance tests. An internal volume of empty chamber is 50.9 litres and dimensions are 1005 x 250 x 220 (H) mm. The test chamber has a smaller inner chamber, with the size of 810 x 215 x 220 (H) mm, where the test sensors were placed. The chamber is built in a way that parallel gas inflow and outflow is assured through the perforated inner walls.

A high concentration CO_2 gas was used for mixing with the synthetic air in order to achieve the required concentration level. The amount of reference gas and synthetic air needed was controlled by gas flow regulators and measured with a soap bubble meter before and after each test. Additionally, a reference instrument was connected to the test chamber for comparison and evaluation of the stability of the reference conditions. Before the final mixing of the gases, the synthetic air was humidified to the required level specified by the conditions needed in the test chamber. A detailed description and schematic picture of the test set-up and measurement techniques is given in APPENDIX B.

The expanded uncertainty of determining the reference CO_2-concentration in the test chamber was in a range of ± 3.4 % to ± 4.7 %. The higher values correspond to the lower concentration levels. The calculation procedures are shown in APPENDIX C. The measurement uncertainty of reference gas concentration is dependent on the analysed gas concentrations specified by the gas manufacturer and available measurement equipment in the laboratory. The uncertainty of measurement in calibration of commercial gas sensors in the calibration laboratories is commonly in a range of ± 2 % to ± 4 %. The lower values are achieved when the reference gas is directly supplied from the gas bottle.

The reference ambient test conditions in the test chamber were: temperature +22 ± 2 °C, relative humidity 40 ± 5 % and pressure based on atmospheric conditions, with a small overpressure in the inner test chamber. The air velocities in the chamber were within the limits specified for typical indoor conditions.

The sensors were installed according to the manufacturer's instructions. Special care was undertaken in packaging and handling the sensors prior to testing. All of the sensors were connected to a logging and data acquisition system. Due to the limited number of available channels in the logging system the current test program presents the results of twelve models: *S1* to *S9* and *S12* to *S14*. The performance of several additional models and extra specimen was verified later with the already checked model from the same manufacturer.

Some preliminary tests were carried out prior to the performance tests in order to evaluate the test set-up and inspect if some malfunctioning occurs with the sensors. Considerable baseline offset was observed on some of the non-dispersive infrared CO_2-sensors during the set-up tests. This can be caused by possible transportation/installation damages. Since the sensors in question include self-adjustment systems, the occurring baseline offset was considerably decreased during the pre-heating time.

3.6.1.2 The sensor performance tests

The range of CO_2-concentrations used for testing the performance of CO_2-sensors is presented in Table 3.2.

Table 3.2 Reference concentrations applied in different tests for determining the CO_2-sensors characteristic performance

Reference gas (measurand)	**Concentration of the gas mixture (ppm)**								
	Test condition number:								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Carbon dioxide	400	800	1200	1600	2000	1600	1200	800	400

First the sensor characteristic curve was determined in a step change procedure by recording the output of the sensor for the values of the measurand as presented in Table 3.2. From the sensor characteristic curve the sensors' sensitivity and the deviations associated with linearity, hysteresis and possible calibration errors were evaluated. Some comparison was done with the manufacturer-specified data. The sensitivity has been calculated as the change in output between test conditions 3 and 4, divided by the corresponding change in input, expressed in V/ppm. The linearity of each sensor was evaluated by determining the maximum deviation between any measured value and a straight line between test conditions 1 to 5, shown in Table 3.2. These evaluation procedures are based on the sensor performance tests conducted as part of the Annex 18 program[74].

Hysteresis can be evaluated as the maximum deviation between test conditions 2 and 8, 3 and 7 and 4 and 6. However, with the available measurement techniques it was not possible to obtain exactly the same reference concentration under forward and reverse test conditions and a small error can be introduced to the results with this calculation method. Therefore, first the theoretical output of the sensor at the measured reference concentrations at test conditions 6, 7 and 8 was calculated based on the linearity equations between the tests 2, 3, 4 and 5. The hysteresis was evaluated as the maximum deviation between the measured output at reverse test conditions 6, 7 and 8 and corresponding theoretical output of the sensor. A schematic explanation of the hysteresis evaluation is given in Figure 3.4.

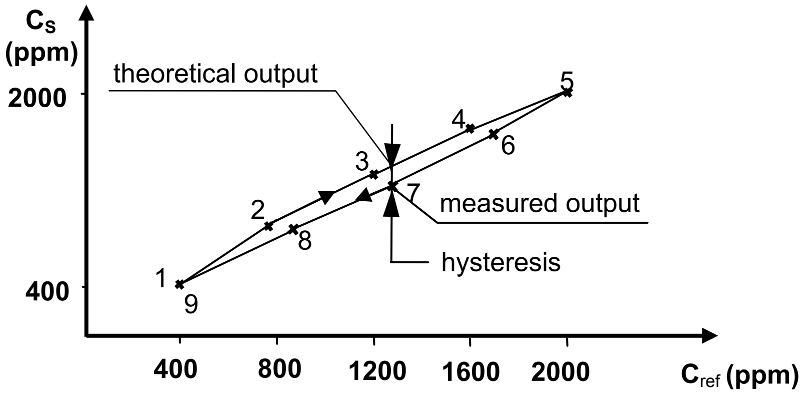

Figure 3.4 Schematic explanation of evaluation of hysteresis based on measured sensor output C_S and reference concentration C_{ref}. The hysteresis is evaluated as the maximum deviation between the measured output at reverse test conditions 6, 7 and 8 and corresponding theoretical output of the sensor at the same reference conditions. The theoretical output is evaluated according to the linearity equations between the test conditions 2, 3, 4 and 5.

For evaluating repeatability, the sensors were tested at test conditions 1 and 4 alternatively 4 times. Repeatability was evaluated by calculating the maximum deviation from the straight line between points 1 and 4, which corresponds to calculated mean values for the respective test points.

The stability study in the current test program aimed to analyze short-term stability of the sensors′ output signal. A 6-hour experiment under constant reference concentration conditions at the level of $C_{ref} = 1600 \pm 32$ ppm was carried out. The supply of reference gas was directly from a gas bottle with laboratory checked concentration.

For testing the response time the sensor input was changed from test condition 2 to test 4 and reverse. From the results time constant, rise time and recovery time were calculated. The time constant was calculated as the time until the output has changed by 63 % of difference between the steady state values. The rise time is calculated as the difference between the times when the signal crosses a low threshold of 10 % to the time when the signal crosses the high threshold of 90 %. The fall time was determined similarly to the rise time. The response time tests were carried out in a 1 litre box in order to minimize the effect from the test system. Furthermore, for conducting this experiment a specified air velocity of the gas flow rate passing the sensor should be assured. This was 3 m/s for a duct sensor and < 0.15 m/s for a room sensor. Unfortunately, with the available set-up it was only possible to test the room sensors.

The warming up time was measured after the sensors were left 24 h without the power supply. The time from switching on the power supply until the output was stable was recorded as the warming up time. The reference conditions in the test chamber were kept constant during this time, at about $C_{ref} \approx 500$ ppm level. The concentrations before and during the time the supply power was switched off corresponded to empty test room conditions.

Cross-sensitivity to varying temperature, relative humidity and supply voltage was tested by varying each quantity one at a time. The reference conditions in the test chamber were kept constant, at the level of $C_{ref} \approx 500$ ppm. Following test conditions were applied: temperature +23 °C , +30 °C; humidity 20 %, 40 % and 65 % r.h.; supply voltage $U_n = 24$ V + 20 % for sensors *S1*- *S9* and $U_n = 5$ V ± 10 % for sensor *S12*, *S13* and *S14.* Cross-sensitivity is calculated as the ratio between the change in sensor output and the change in the specific influence quantity.

3.6.3 Results

The sensor *S14* did not show any reasonable output at the reference CO_2-concentrations in any test. Variation in the output signal irrespective to the concentration pattern was indicated. This leads to the assumption that the sensor has some technical problems. The sensor module was sent to the manufacturer for inspection. No results will be presented here.

3.6.3.1 Sensor characteristic curve

The characteristic curve for each test sensor is presented in Figures 3.6 and 3.7. The results are presented in terms of the deviation of the measured value by the sensor from the reference value in the test chamber, e.g. deviation = C_S - C_{ref}, and plotted against the reference gas concentration. The results are compared with the sensor measurement uncertainty specified by each manufacturer. Furthermore, in order to make the best comparison with the available sensor uncertainty data, the output values of all non-dispersive infrared sensors have been corrected to the manufacturer specified test conditions, according to the equation 3.2 in chapter 3.3.1. The specified test conditions are conditions at which the sensor's calibration is performed in the factory. Based on the specifications, the pressure at standard test conditions for all of the non-dispersive infrared sensors is 1013 hPa. The temperature at standard test conditions is for sensors *S5* and *S6* +25 °C and for sensors *S7*- *S10* +23 °C. For sensors *S1* to *S4* the temperature dependency has been included in the claimed sensor uncertainty and therefore no temperature correction has been done to the measured values. It must be noted that the corrections are based on the theoretical influence of ambient conditions. The actual cross-sensitivity to temperature and atmospheric pressure may be different for each sensor and should be evaluated in cross-sensitivity tests[73]. Unfortunately in this study it was only possible to test the influence of temperature.

Figure 3.5 gives an overview of how the sensor characteristic curves should be interpreted. All of the diagrams show the deviations based on both the measured and corrected values. The test conditions 1 to 5 according to Table 3.2 are referred to as the forward measurements and the tests 5 to 9 as the reverse measurements. The calculated expanded uncertainties of measurement for the deviation values shown in the figures as error bars include both the measurement uncertainties of reference conditions and of sensor readings. The expanded uncertainties correspond to 95% of confidence interval. The calculation procedure for the uncertainties of measurement is presented in APPENDIX C.

The deviations based on corrected sensor output should be within the manufacturer's data lines, if the manufacturer's data is to be fulfilled. Nevertheless, this is not the only requirement to fulfil the specified uncertainty data. It is assumed that the given sensor uncertainty also includes uncertainty contributions from other sources, e.g. repeatability, stability, etc. These characteristics are also evaluated in this study and discussed in the following sub-chapter. The data about the manufacturer-stated uncertainty for each sensor was given in Table 3.1, chapter 3.5.3.

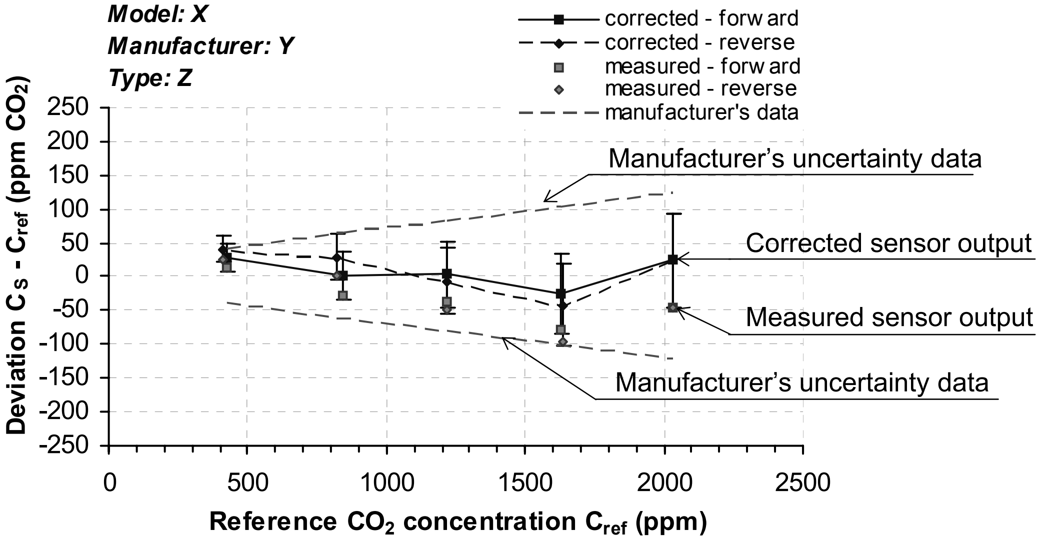

Figure 3.5 Interpretation of the characteristic curve for an example test sensor *X,* from example manufacturer *Y.* The type refers to the sensor technology: non-dispersive infrared, NDIR, or solid state electrolyte sensor. The diagram shows the deviations of the measured and corrected sensor output from the reference concentration in the test chamber, plotted against the reference gas concentration. The deviations based on the corrected sensor output should be within the area of the manufacturer's data lines. The error bars represent the evaluated expanded measurement uncertainties of the deviation with 95 % confidence interval.

The results show that deviations based on corrected values are within the manufacturer-specified uncertainty data for the majority of the tested sensors. Differences from the factory specified data can be seen from the characteristic diagram for sensor *S8.* The results for the sensor *S9* are on the very edge of the specified uncertainty. Furthermore, as it can be seen from the Figures 3.6 and 3.7, both of these sensors seem to have negative baseline offset. Sensors *S7, S8* and *S9* sensors include self-adjustment system and have a reference light source for bias/drift compensation. It can be assumed that the baseline offset is influenced by incorrect calibration of the reference light source.

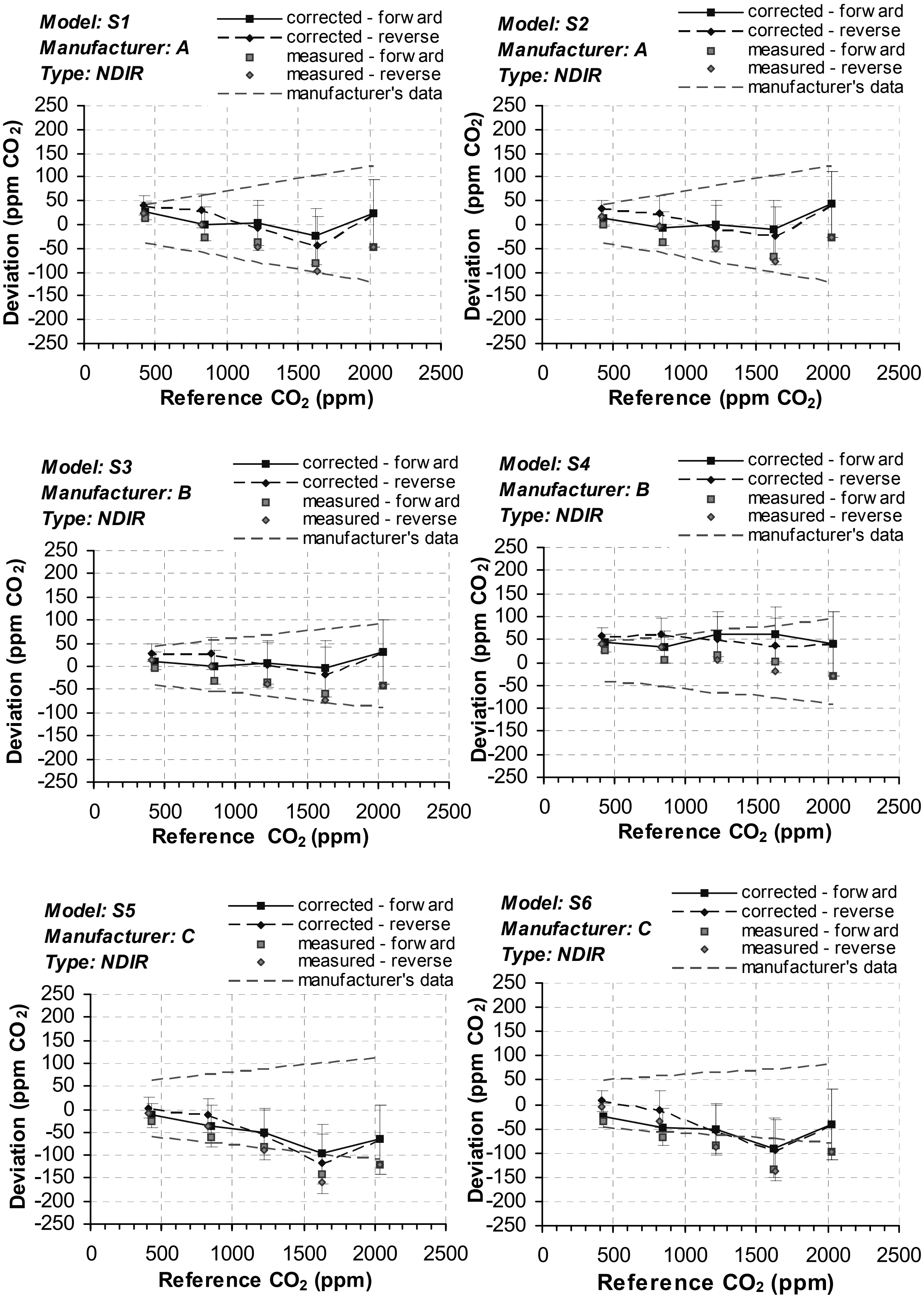

Figure 3.6 Characteristic curves for the sensors *S1* to *S6*. The error bars represent the evaluated expanded uncertainties of the deviation with 95 % confidence interval. The tests were carried under following environmental conditions, with evaluated uncertainty $k = 2$: temperature +23.2 ± 0.4 ˚C; relative humidity 39.0 ± 3.5 %, atmospheric pressure 978 ± 3 hPa.

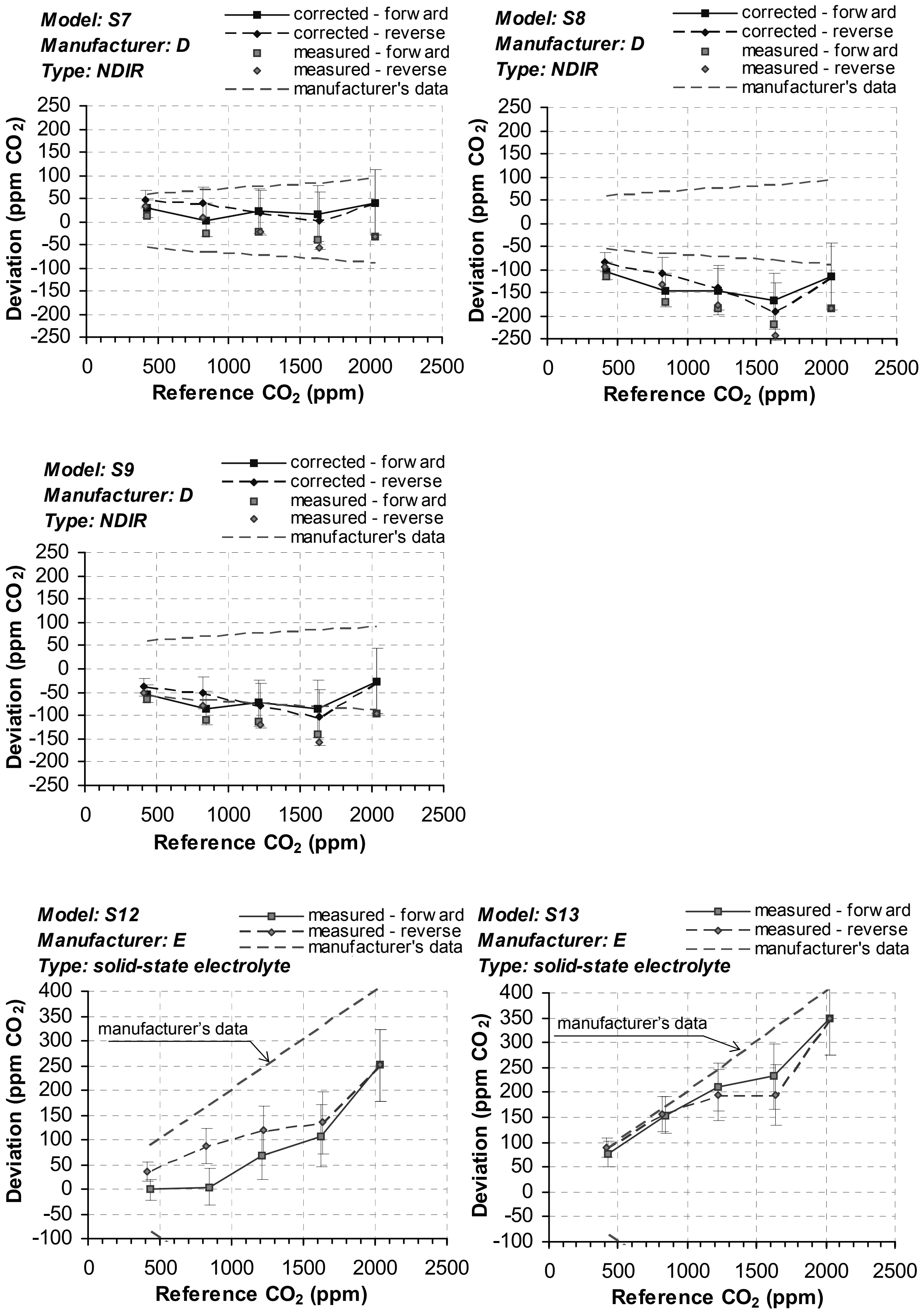

Figure 3.7 Characteristic curves for the sensors *S7* to *S9, S12* and *S13*. The error bars represent the evaluated expanded uncertainties of the deviation with 95 % confidence interval. The tests were carried under following environmental conditions, with evaluated uncertainty *k = 2*: temperature +23.2 ± 0.4 °C; relative humidity 39.0 ± 3.5 %, atmospheric pressure 978 ± 3 hPa.

The solid-state electrolyte sensors *S12* and *S13* have considerably higher deviations from the reference conditions. The measured output for sensors *S12* and *S13* were not corrected since the manufacturer specified data does not specify the conditions for given sensor uncertainty. The possible effect of environmental conditions on sensor output has been evaluated in cross-sensitivity test and will be discussed later on. However, as it can be seen from the sensor characteristic curves, the deviations are within the manufacturer specified uncertainty data. From the output of sensor *S13* some baseline offset can be observed.

3.6.3.2 Sensitivity

The evaluated sensitivities for the CO_2-sensors are presented in Table 3.3. The sensitivity has been calculated as the change in output between test conditions 3 and 4, divided by the corresponding change in input. The results are based on uncorrected sensor readings. According to the results, the sensor sensitivities are very similar for the sensors with the same measurement principle. However, it must be noted, that the sensitivity of the sensors may not be constant over the input range of the sensor due to linearity deviations. Therefore the evaluated sensitivities are different with other test conditions than 3 and 4, which are shown in Table 3.3.

The sensitivity value for the sensor is dependent on the operating range of the sensor and the corresponding range in output signal. The test sensors *S12* and *S13* have an operating range from 400 ppm to 4000 ppm, while all other sensors work in a range of 0 to 2000 ppm. Furthermore, the solid-state electrolyte sensors have an output signal of 0 – 4 V while the NDIR sensors provide analogue outputs of 0 - 10 V. Therefore the sensitivity values for the sensors *S12* and *S13* are considerably smaller. From the control point of view it is advantageous to have higher sensitivity values. For example, a CO_2 concentration change from 400 ppm to 1000 ppm would result in 2.4 V to 3 V change in output for the test sensors *S1* to *S9*. The corresponding change would be about 0.7 V for the sensors *S12* and *S13*.

Table 3.3 Measured sensitivity for the tested CO_2-sensors. The values show the change in sensor's output in response to a change in input.

Measured parameter	**Test sensor**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
Sensitivity ($\cdot 10^{-3}$ *V/ppm*)	4	5	5	5	4	4	5	5	5	1	1

3.6.3.3 Linearity and hysteresis

The evaluated linearity and hysteresis values for the tested CO_2-sensors are presented in Table 3.4. The values are based on uncorrected sensor readings. Unfortunately no manufacturer-specified data for these parameters are available for comparison.

The maximum evaluated linearity values were observed at test condition 4 for the majority of the sensors. Only sensor *S7* had the highest linearity at test condition 2. The majority of the linearity values are negative. This means that the measured values were lower than the theoretical linear line between the corresponding outputs at test conditions 1 and 5.

Table 3.4 Evaluated linearity and hysteresis values for the tested CO_2-sensors. For the best performance of the sensor the linearity and hysteresis values should be minimal.

Parameter	**Test sensor**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
Linearity (ppm CO_2)	-48	-45	-29	19	-44	-53	-28	-54	-50	-79	-48
Hysteresis (ppm CO_2)	27	29	29	27	21	33	35	33	29	83	-41

The maximum hysteresis occurred generally at point 8. Only for sensor *S13* the maximum hysteresis was observed at point 6. The hysteresis values were positive for the majority of tested sensors, meaning that the sensor output was higher at reverse test conditions than it was at forward test conditions. An exception occurred for the sensor *S13*, which had negative hysteresis at point 6.

For the best performance of the sensor the linearity and hysteresis values should be minimal. On average, the evaluated linearity values are –3 % from the measured output values at the given test point. The maximum hysteresis is on average +4 % from the measured output at the respective test point. The results are very similar for non-dispersive infrared type of sensors *S1* to *S9*. Electrochemical sensor *S12* had the biggest linearity deviation and hysteresis. However, the results for the other electrochemical sensor *S13* are comparable with non-dispersive infrared sensors.

3.6.3.4 Repeatability

The sensor repeatability has been evaluated from the repeated measurements at test conditions 1, at 400 ppm and at condition 4, at 1600 ppm. The evaluated repeatability values for the tested sensors are given in Table 3.5. The values correspond to the maximum deviation from the mean output from the repeated measurement at the respective test condition. Both the absolute values and relative values are presented.

Table 3.5 Repeatability values for the tested CO_2-sensors. The values show the maximum deviation from the mean output from the repeated measurements at the two test conditions. For the best performance of the sensor the repeatability values should be minimal.

Evaluated parameter	**Repeatability of the test sensor (ppm or % of mean value)**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
Measured value at $C_{ref} \approx$ *400 ppm (test condition 1)*											
ppm CO_2	4	6	7	5	8	11	7	8	7	11	9
% of mean	1.0	1.4	1.6	1.1	1.8	2.5	1.5	2.3	1.8	2.5	1.8
Manufacturer's value											
ppm CO_2	≤25 1)	≤25	≤25	≤25	n/a 2)	n/a	≤20	≤20	≤20	n/a	n/a
Measured value at $C_{ref} \approx$ *1600 ppm (test condition 4)*											
ppm CO_2	4	6	3	4	7	9	6	6	4	12	18
% of mean	0.2	0.3	0.2	0.3	0.5	0.6	0.4	0.4	0.3	0.7	1.0
Manufacturer's value											
ppm CO_2	≤36 1)	≤36	≤36	≤36	n/a	n/a	≤20	≤20	≤20	n/a	n/a

Note 1: For sensors S1 to S4 the manufacturer-specified data for repeatability is ± 1 % of measuring range ± 1 % of measured value;
Note 2: n/a – no information available

The tests were carried under following environmental conditions, with evaluated uncertainty k = *2*: temperature +23.1 ˚C ± 0.3 ˚C; relative humidity 43.6 ± 4.0 %, atmospheric pressure 986 ± 3 hPa.

According to the test results the repeatability, in terms of relative deviation from the mean, is considerably low at high reference concentration. At low CO_2 concentrations the relative deviations are higher. Nevertheless, all of the evaluated repeatability values are well within manufacturer-specified data.

3.6.3.5 Stability

Figure 3.8 presents the output of the selected sensors in the 6-hour stability test. The results reveal that the sensors have big variations in output signal that can be associated with signal noise. Even changes in the mean value of the output signal can be seen over time for some of the sensors.

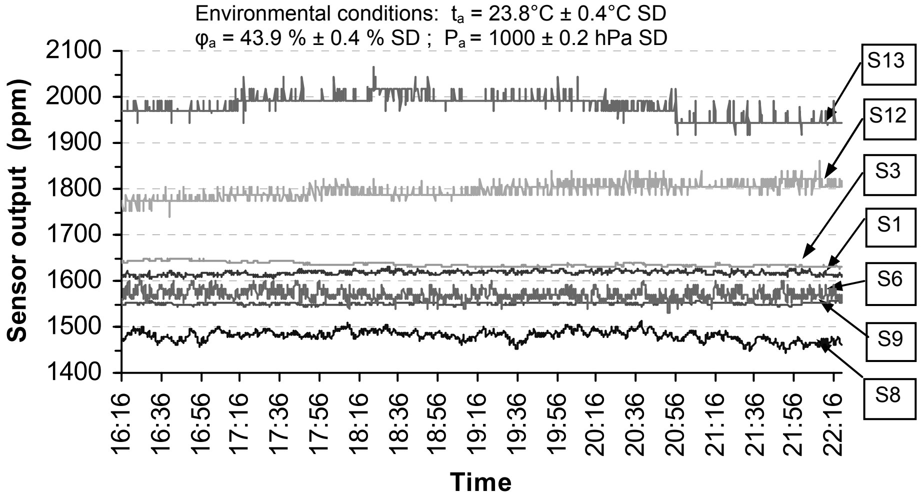
Environmental conditions: t_a = 23.8°C ± 0.4°C SD
φ_a = 43.9 % ± 0.4 % SD ; P_a = 1000 ± 0.2 hPa SD

Figure 3.8 Stability test for 6 hours under the test condition C_{ref} = 1600 ± 32 ppm. The results are presented for the sensors *S1, S3, S6, S8, S9, S12* and *S13.*

In order to evaluate short-term variations in the output signal, the measurement period was divided into 5-minute periods. For each of this period maximum deviation and standard deviation from the mean value was evaluated. Table 3.6 presents the average of these standard deviations and maximum deviation that occurred from the mean value when considering the 5-minute periods all together. For evaluating the sensor output stability over the entire measurement period the measurement was divided into 1-hour periods. The standard deviation of the average of 1-hour mean values was evaluated. Table 3.6 shows the evaluated deviations in absolute values and as a percentage from the respective mean value.

For a stable sensor output the standard deviation of the average 1-hour mean values should be close to zero. For half of the tested sensors the evaluated short-term stability values were less than 1 % from the mean values at the given test condition. The highest instabilities in sensor output signal, that can be associated with noise, were observed with sensors *S5, S6, S8, S12* and *S13.* The maximum deviation from the mean of a five-minute period was up to 3 %. This suggests that additional signal processing such as signal filtering may be required to fulfil the requirement on sensor uncertainty ≤± 3.5 %. Sensors *S12* and *S13* also had somewhat higher variations in the 1-hour mean values over measurement period.

Table 3.6 The results from the short-term stability test of CO_2-sensors under test conditions $C_{ref} = 1600 \pm 32$ ppm. The values show the deviations from the mean values evaluated over different time periods. For the stable output of the sensor the stability values should be minimal.

Evaluated parameter	Stability of the test sensor (ppm or % of mean value)										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
Signal 5 min stability											
av. SD $^{1)}$ (ppm)	2	1	1	2	14	10	1	5	1	8	9
av. SD $^{1)}$ (%)	0.1	0.1	0.1	0.1	0.9	0.6	0.1	0.4	0.1	0.5	0.5
max dev. $^{2)}$ (ppm)	10	6	6	7	45	30	5	21	5	46	64
max dev. $^{2)}$ (%)	0.6	0.4	0.4	0.4	2.9	1.9	0.3	1.5	0.3	2.6	3.2
Signal 5 min stability											
SD_{mean} $^{3)}$ (ppm)	2	3	4	3	4	4	1	7	1	14	22
SD_{mean} $^{3)}$ (%)	0.1	0.2	0.3	0.2	0.3	0.3	0.1	0.5	0.1	0.8	1.1

Note 1: Average standard deviation of 5-minute periods over the 6-hour measurement

Note 2: Maximum deviation from the mean of a 5-minute period considering all the 5-minute periods together over the 6-hour measurement

Note 3: The standard deviation of the average of 1-hour mean values

It should be noted that the instabilities are most probably smaller with lower CO_2 concentrations in absolute values, but deviation in terms of percentage from the measured value can remain the same.

3.6.3.6 Cross-sensitivity test

The results from the cross-sensitivity tests are presented in Table 3.7. The values have been evaluated as the ratio between the change in sensor output and the change in given influence quantity. In addition, the possible effect of sensor stability has been taken into account. This means that the change in sensor output to corresponding change in influence quantity should be higher than the evaluated stability values in order to experimentally certify the cross-sensitivity effect. The sensor stability corresponding to the standard deviation of the average of 1-hour mean values has been considered in comparison (see Table 3.6).

In cross-sensitivity test with temperature change the temperature was changed from +24.3 ± 0.3 ˚C to +29.7 ± 0.2 ˚C ($k = 2$). The change in the cross-sensitivity test with humidity was from 21.5± 2.9 % to 67.3 ± 2.9 %. The supply voltge was changed in a range of 19.2 V – 28.7 V and 4.8 V – 5.5 V in the test with supply voltage change.

It was preliminary assumed that the non-dispersive infrared sensors are sensitive to temperature due to its technology principle. The temperature influence was also stated in the manufacturer data of these sensors. However, cross-sensitivity to temperature was experimentally certified only for sensors *S5, S6* and *S7*. The results from other non-dispersive infrared sensors showed no effect or the change was within the sensors' stability. The electrochemical sensors *S12* and *S13* had significant cross-sensitivity to both temperature and humidity. This has been also reported in previous studies[180].

The sensitivity to relative humidity was observed to be almost negligible for non-dispersive infrared sensors. In addition, no significant effect of voltage change on output signal was observed for these sensors. Sensors *S12* and *S13* seemed to be sensitive to the voltage change. Nevertheless, no clear relationship can be drawn from the results, since the sensors output value varied a lot during the step change of supply voltage.

Table 3.7 Results from the cross sensitivity test. The values show the change in sensor's output in response to a change in a given influence parameter. For the best performance of the sensor the cross-sensitivity values should be minimal. Reference gas concentration was $C_{ref} \approx 500$ ppm

Influence quantity	**Cross-sensitivity of the test sensor (ppm/unit) or (%/unit)**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
Temperature (°C)	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-4.7	-2.1	-5.0	-$^{1)}$	-$^{1)}$	-8.4	14.5
% of reading/ °C	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-0.9	-0.4	-1.0	-$^{1)}$	-$^{1)}$	-1.6	2.7
Manuf. value % of reading	*wsu*	*wsu*	*wsu*	*wsu*	-0.4	-0.4	-0.4	-0.4	-0.4	*n/a*	*n/a*
Humidity (%)	0.1	0.2	-$^{1)}$	0.3	-0.1	-0.3	0.1	-$^{1)}$	0.1	-1.4	5.0
% of reading/%	0.02	0.04	-$^{1)}$	0.06	-0.02	-0.05	0.02	-$^{1)}$	0.03	-0.3	1.0
Manuf. value % of reading	*wsu*	*wsu*	*wsu*	*wsu*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
Voltage (V)	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{1)}$	-$^{2)}$	-$^{2)}$
Manuf. value	*wsu*	*wsu*	*wsu*	*wsu*	*wsu*	*wsu*	*no*	*no*	*no*	*n/a*	*n/a*

Note 1: The effect was too small to be experimentally certified or the change was too small to be significant
Note 2: The results were inconclusive
Note 3: wsu – within specified uncertainty; n/a – no information available

Besides the temperature influence, also changes in atmospheric pressure can affect the readings of non-dispersive infrared sensors. The calculations based on equation 3.2 in chapter 3.3.1 show this effect to be ≤ ± 4.4 % at atmospheric pressure variations between 970 hP to 1060 hPa. Unfortunately, with the available set up it was not possible to test the influence of barometric pressure.

The pre-defined requirement on indoor air quality sensors is that the cross-sensitivity should be within the maximum permissible sensor uncertainty, described in chapter 3.4.2. Calibrating the sensors at the test conditions most common for the specific application would increase the accuracy of the non-dispersive infrared sensors. For solid-state electrolyte sensors temperature and relative humidity compensation methods must be incorporated into the sensor.

3.6.3.7 Response time

The measured response times are presented in Table 3.8. For the majority of the sensors the measured rise time and response time was less than 2 minutes. The biggest response time, less than 4.5 minutes occurred with sensors *S8* and *S9*. All of the values were within the manufacturer's specified data.

According to the proposed quantitative requirements on indoor air quality sensors, the response time should be less than one third of the nominal time constant of the controlled room. This would correspond to about 15 minutes for a cell office room of 10 m^2 and airflow rate 10 l/s. The measurement results show that the tested CO_2-sensors fulfil this requirement.

Table 3.8 Response time for the tested CO_2-sensors. The response times were not measured for the duct sensors *S2, S6* and *S7.* The response time should be less than one third of the nominal time constant of the ventilation system.

Evaluated parameter	**Response time of the test sensor (min)**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
Time constant τ_{63}	1	-	1.5	1	1.5	-	-	4.5	4.5	1	1
manuf. value	*3*		*2*	*3*	*1*			*5*	*5*	*n/a*	*n/a*
Rise time τ_{90}	1	-	1.5	1	1.5	-	-	8.5	8	1	1.5
manuf. value	*n/a*		*n/a*	*n/a*	*n/a*			*n/a*	*n/a*	*1.5*	*2*
Fall time (90%)	1	-	1.5	1	1.5	-	-	7.5	7.5	1	1
manuf. value	*n/a*		*n/a*	*n/a*	*n/a*			*n/a*	*n/a*	*n/a*	*n/a*

Notes: n/a – no information available

3.6.3.8 Warming-up time

The warming-up times can be seen in Table 3.9. Many of the sensors reached relatively stable output value in a quite short period of time. However, it was observed that the mean value of the sensor output continued to increase or decrease slowly in small magnitudes up to 10 ppm, till it reached a stable level. Therefore, for evaluating the warming-up time the results are presented in three steps, which show the observed time periods for reaching 95 %, 98 % and 100 % of the final value. The final value is a 30-minute average value after 1.5 h was passed from switching on the power.

Table 3.9 Warming-up time for the tested CO_2 sensors

Evaluated parameter	**Warming-up time of the test sensor (min)**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
95 % of final value	3	1	2	1	1	4	16	1	1	-	-
98 % of final value	4	2	31	7	1	8	84	14	1	-	-
100 % of final value	40	41	94	20	3	10	130	53	9	120[1)]	121[1)]
manuf. value	*<10*	*<10*	*<10*	*<10*	*10*	*15*	*n/a*	*n/a*	*n/a*	*120*	*120*

Note 1: The value after 2 hours was stable but less than it should be according to the reference level; n/a – no information available

As can be seen from Table 3.9, the majority of infrared sensors reached 98 % of the final specified value within 15 minutes. For sensors *S3* and *S7* it took up to 1.5 hours to reach this specified level. Furthermore, there seems to be variations in the results between the sensors from the same manufacturer. In the specifications of sensors *S12* and *S13* the warming-up time was stated to be 2 hours and the sensor has a constant voltage output during this time. Based on the measurement results, the warming up time was within these limits. However, the stable mean value measured after 2 hours was considerably lower than it was commonly at the selected reference conditions. It can be assumed that the sensor output would very slowly increase in time. Unfortunately it was not possible to keep the experiment running so long as to make some more definite conclusions.

3.6.3.9 Performance test with the additional sensor models and extra specimen

The results from the performance test of additional models and extra specimen are presented in Table 3.10. All of the sensors were un-powered for four weeks before the test and switched on two days before the measurement. The results are presented as deviation in percentage of the sensor output from the reference concentration. Both the measured values and corrected values are given. The corrected values are calculated according to equation 3.2, in chapter 3.3.1. The manufacturers' data is presented in Table 3.1 in chapter 3.5.3.

Table 3.10 Results from the parallel test of additional sensor specimens. The deviation in sensor output as percentage from reference CO_2 concentrations is presented. The deviations based on the corrected sensor output should be within the manufacturer's data.

Reference concentration	**Deviation in sensor output from reference concentration (%)**										
	S1	**S1A**	**S1B**	**S1C**	**S1D**	**S3**	**S3A**	**S6**	**S9**	**S10**	**S10A**
$C_{ref} \approx 400$ ppm											
Measured	6.1	-1.2	40.0	47.4	52.9	6.9	-8.0	1.7	-8.7	41.7	-10.9
Corrected	7.2	0.6	42.5	50.1	55.6	8.8	-6.4	2.9	-7.0	44.2	-9.3
Manuf. data	*10*	*10*	*10*	*10*	*10*	*10.5*	*10.5*	*12.0*	*14.5*	*14.5*	*14.5*
$C_{ref} = 1600$ ppm											
Measured	-3.5	-5.5	13.2	16.7	19.1	-0.1	-7.0	-3.7	-5.2	13.4	-6.4
Corrected	-2.4	-3.8	15.2	18.8	21.3	1.7	-5.4	-2.6	-3.5	15.5	-4.7
Manuf. data	*6.3*	*6.3*	*6.3*	*6.3*	*6.3*	*5*	*5*	*4.5*	*5.1*	*5.1*	*5.1*

Note: The additional specimens of each sensor model are designated with letters from A to D.

As shown in the table, several extra specimens of the same sensor model had major deviation from the reference conditions. This can be linked to the baseline offset that was also observed with several test sensors at the beginning of the test program. It can be influenced by incorrect calibration of the sensor in the factory or possible transportation/installation damages. This offset will decrease in time with automatic baseline correction of some sensors. However, for some of the sensors re-calibration in the factory would be needed.

3.6.4 Discussion

The performance target for CO_2-sensors in DCV system applications is their accurate continuous measurement of carbon dioxide under normal indoor climate conditions. Sensor measurement uncertainty depends on several parameters, including uncertainty of the sensing element, resolution, linearity, hysteresis, repeatability, stability, cross-sensitivity, signal conditioning and calibration errors[43]. Several of these influencing factors are included in the manufacturer-stated uncertainty data or are listed additionally in the specifications. Unfortunately, the available information on sensors is often rather limited, which makes comparisons between sensors complicated.

In the current study the CO_2-sensor uncertainties and deviations due to possible calibration errors, linearity, hysteresis, repeatability, stability and cross-sensitivity have been evaluated. Table 3.11 gives an overview of the results of all of the evaluated sources of uncertainties and deviations at two concentration levels: 400 ppm and 1600 ppm. The values in the Table 3.11 correspond to the following:

- The corrected deviation in the Table 3.11 corresponds to the maximum deviation based on the corrected sensor output values, evaluated from the sensor characteristic curve. The corrections have done according to the measurement results from the cross-sensitivity tests. For atmospheric pressure influence the theoretical influence has been evaluated based on equation 3.2 in Chapter 3.3.1.
- The cross-sensitivity effect is given as the maximum change in sensor's output when the temperature would vary in between +20˚C and +25 ˚C, relative humidity 40 % - 65 % and pressure 970 hPa -1025 hPa.
- The total uncertainty corresponds to the maximum deviation in sensor output that would occur at given reference concentration and when the environmental conditions would vary in the specified range.

Table 3.11 Evaluated maximum deviations in sensor output from reference CO_2 concentration at 400 ppm and 1600 ppm and at environmental conditions in a range of +20˚C to +25 ˚C, 40 % - 65 % r.h. and 970 – 1025 hPa.

Source of uncertainty	**Maximum deviation in sensor output from reference C_{ref} (%)**										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S12**	**S13**
C_{ref} ≈ 400 ppm											
Corrected dev.1)	9.9	7.8	7.1	13.8	-3.6	-5.1	11.8	-23.3	-11.8	18.9	-3.1
Cross-sensitivity +/- 2)	+1.5/ -4.4	+1.8/ -4.4	+1.2/ -4.4	+2.1/ -4.4	+5.7/ -4.7	+3.2/ -5.2	+4.5/ -6.4	+1.2/ -4.4	+1.6/ -4.4	0/ -12.5	28.5/ 0
Repeatability ±	1.0	1.4	1.6	1.1	1.8	2.5	1.5	2.3	1.8	2.5	1.8
Stability ±	0.1	0.1	0.1	0.1	0.9	0.6	0.1	0.4	0.1	0.5	0.5
Total uncertainty 3)	12.5	11.1	10.0	17.1	-11.0	-13.4	17.9	-30.4	-18.1	21.5	27.7
Manuf. data ± 4)	11.9	11.9	12.4	12.4	22.0	18.5	20.4	18.5	18.5	20.0	20.0
C_{ref} ≈ 1600 ppm											
Corrected dev.1)	-2.3	-1.2	-0.9	3.8	-7.6	-5.5	1.6	-11.3	-6.1	18.4	-10.2
Cross-sensitivity +/- 2)	+1.5/ -4.4	+1.8/ -4.4	+1.2/ -4.4	+2.1/ -4.4	+5.7/ -4.7	+3.2/ -5.2	+4.5/ -6.4	+1.2/ -4.4	+1.6/ -4.4	0/ -12.5	28.5/ 0
Repeatability ±	0.2	0.3	0.2	0.3	0.5	0.6	0.4	0.4	0.3	0.7	1.0
Stability ±	0.1	0.1	0.1	0.1	0.9	0.6	0.1	0.4	0.1	0.5	0.5
Total uncertainty 3)	-7.0	-6.0	-5.6	6.3	-13.7	-11.9	6.6	16.5	10.9	19.6	19.8
Manuf. data ± 4)	12.1	13.1	12.8	6.9	12.6	11.0	9.1	9.1	9.1	20.0	20.0

Note 1: The corrected deviation corresponds to the maximum deviation in percentage from the reference CO_2 concentrations at 400 ppm and 1600 ppm, evaluated from the sensor characteristic curve. The measured output has been corrected to the manufacturer specified test conditions. For sensors S12 and S13 the factory test conditions are +20˚C and 65 % r.h.. The temperature and humidity correction is based on the measured cross-sensitivity and the pressure correction is based on equation 3.2 in Chapter 3.3.1.

Note 2: The cross-sensitivity is given as the maximum change in sensor's output when the temperature would vary in a range of +20˚C to +25 ˚C, relative humidity in a range of 40 % to 65 % and pressure of 970 – 1025 hPa.

Note 3: The total uncertainty corresponds to the maximum deviation in sensor output that would occur at given reference concentration and at the specified environmental conditions.

Note 4: Manufacturer's data is the stated sensors uncertainty including cross-sensitivity to environmental conditions. The cross-sensitivity is specified separately, see APPENDIX B.

The results show that the evaluated total uncertainty for the majority of the tested CO_2-sensors is within the manufacture-specified data. The sensors that did not fulfil the claimed uncertainty seemed to have a considerable offset from the baseline level.

Problems with the baseline offset were also identified with several other sensors at the beginning of the test program and from the performance test with additional sensor specimens. For many of the sensors that were continuously connected for weeks, this offset was decreased by automatic baseline correction applied for self-adjustment. The sensors with remaining offset are using second light source for drift compensation. It can be assumed that the second light source was incorrectly calibrated in the factory and therefore the offset was not, or will not, decrease in time.

Even if the CO_2-sensors fulfil the manufacturer-stated uncertainty, it is important to evaluate if this uncertainty is sufficient for indoor climate control with a DCV system. The proposed quantitative requirements have been developed based on the requirements on indoor air quality control specified by the ventilation guidelines and standards. When the requirement is to maintain the specified minimum airflow rate, the uncertainty of indoor air quality sensors should be $\leq \pm 3.5$ % from the concentration measurement. For keeping the required CO_2-concentration set-point the sensor uncertainty should be $\leq \pm 6.5$ % or $\leq \pm 8.1$ %, depending on the set-point, see chapter 3.4.2. Similar requirements on sensor uncertainty apply for keeping the specified indoor air quality category based on percentage of dissatisfied. This sensor uncertainty should include all the possible sources of uncertainties and deviations, e.g. calibration errors, repeatability, linearity, hysteresis, stability and cross-sensitivity, etc.

As can be seen from the Table 3.11, the evaluated total uncertainty, corresponding to the maximum possible deviation in normal indoor conditions, is higher than ± 3.5 % for the majority of the tested CO_2-sensors. However, it must be noted the evaluated reference concentrations also have an uncertainty. The estimated expanded uncertainty of determining the reference concentrations is in a range of ± 3.4 % to ± 4.7 %, depending on the concentration level. The higher values correspond to the lower concentration levels. This means that only the deviations higher than the uncertainty of the reference system can be experimentally certified. After taking into account the uncertainty of the reference system, only sensor *S3* is close to fulfil the higher requirement set on sensor uncertainty $\leq \pm 3.5$ %. Nevertheless, more than half of the tested non-dispersive infrared CO_2-sensors would fulfil the requirement on sensor uncertainty when the demand is to keep the required set-point or specified percentage of dissatisfied.

The biggest deviations in sensor output were observed from the sensor characteristic curve and from the evaluation of cross-sensitivity, see Table 3.11. The deviations indicated in the characteristic curve are influenced by the linearity, hysteresis and possible calibration errors, e.g. baseline offset. The deviations due to cross-sensitivity to environmental conditions are depending on the sensor technology and on the chosen standard test conditions in the factory calibration. Both of these deviations are systematic effects that contribute to sensor uncertainty. This means that they can be increased with the proper calibration procedures of the sensors. For the electrochemical sensors additional compensation methods should be incorporated to the sensor system for compensating for the temperature and humidity effects.

The results of this study also show that the deviations in sensor output associated with the random effects, such as repeatability and stability, were relatively small. These deviations remained within $<\pm 3.5$ % from the reference concentrations. While the instabilities in sensor output can be usually decreased by signal processing, compensating for the repeatability effects can be difficult. Therefore, repeatability can be considered as a defining parameter for the sensor uncertainty.

All of the sensors showed a reasonably fast response in the response time test. Based on the pre-defined requirements on indoor air quality sensors, these response times are sufficient for indoor climate control.

When comparing the non-dispersive infrared type of sensors with solid-state electrolyte sensors, the latter ones showed somewhat lower performance in terms of sensor uncertainty. Nevertheless, the manufacturer stated uncertainty is also considerably higher than for non-dispersive infrared sensors. According to the manufacturer-specified data the sensor uncertainty is within ± 20 % from the measured value. Although this uncertainty is clearly not sufficient for indoor air quality control with DCV systems the results are within the specifications.

3.6.5 Conclusions

For controlling the indoor air quality based on CO_2-measurement it is required that the sensors would accurately measure the target gas and would respond sufficiently fast to changes in the indoor CO_2-concentrations. In this study, twelve different CO_2-sensor models from six different manufacturers were tested in detail. The majority of the tested sensors were non-dispersive infrared type of sensors, but also two electrochemical sensors were evaluated. From the results the following was observed:

- The majority of the detailed tested CO_2-sensors fulfilled the manufacturer-stated specifications on performance

- Only one sensor is close to fulfil the higher requirement set on sensor uncertainty $\leq \pm 3.5$ % for keeping the required airflow rate. Nevertheless, more than half of the tested non-dispersive infrared CO_2-sensors would fulfil the requirement on sensor uncertainty when the demand is to keep the required set-point or the specified indoor air quality category based on percentage of dissatisfied.

- The biggest deviations in sensors outputs were indicated from the sensor characteristic curves and from cross-sensitivity to environmental conditions. Some sensors seemed to have considerable baseline offset. This can be resulted from transportation/installation problems and/or incorrect factory calibration. The uncertainty in sensor output associated with repeatability and short-term stability were relatively small.

- All of the tested CO_2-sensors have sufficiently fast response time for the indoor air quality control purposes.

- The tested non-dispersive infrared sensors have advantages in terms of accuracy over the tested electrochemical sensors. On the other hand, the tested electrochemical sensors showed somewhat faster response times.

It can be assumed that with proper calibration procedures, the commercial CO_2-sensors would perform sufficiently accurately for indoor climate control.

3.7 Characteristic performance of mixed-gas sensors

This study evaluated the performance characteristics of mixed-gas sensors in detail. A comprehensive study has been carried out under laboratory conditions. Sensors *S8, S15, S16, S17* and the two specimen of *S18* were tested in this study, according to the numeration in Table 3.1. The mixed-gas sensors were introduced in chapter 3.5.3 and are described in more detail based on manufacturer-specified data in APPENDIX B.

The laboratory tests consisted of determination of the performance characteristics of the mixed-gas sensors. This chapter describes shortly the methodology and provides the results and discussion of the study. More detailed description of the experimental methodology is presented in APPENDIX B. The evaluation of uncertainty of measurement is presented in APPENDIX C. More detailed information about the sensors output at different tests is be found from Maripuu[142].

3.7.1 Experimental methodology

3.7.1.1 Summary of the test set-up and measurement techniques

The tests were carried out in the laboratory of SP Technical Research Institute of Sweden. This laboratory is equipped with apparatus especially used for sensor calibration. A small-scale test chamber made of glass was used for the tests with the mixed-gas sensors. The internal volume of the empty chamber is 5.3 litres; dimensions are 150 (D) x 350 (H) mm.

High concentration VOC gases were used for mixing with the synthetic air in order to achieve the required concentration levels. The chosen reference gases for testing the mixed-gas sensors were toluene and acetone. The choice of the reference gases was limited by economical reasons, but also by the difficulty to find a small number of suitable VOC gases that represent the activities in indoor environment in commercial buildings. The test program aimed to choose the reference gases based on their variability in time in indoor air. Based on the literature survey toluene is the most commonly emitted compound from office equipment, but also from other processes in the room. The concentration of acetone can be related to presence of people.

The supply flow rates of the reference VOC gases and synthetic air were measured before each test in order to estimate the concentration of the mixture supplied to the chamber. Before the final mixing of the gases, the synthetic air was humidified to the required level specified by the conditions needed in the test chamber. The reference ambient testing conditions in the test chamber were the following: temperature 24 ± 2°C, relative humidity 40 ± 5 % and pressure based on atmospheric conditions.

In the majority of tests the reference VOC gas concentrations in the test chamber were determined by means of Tenax adsorption tubes. This method was found to be more suitable, since it was preliminary suspected that the plastic casings part of the sensor assemblies, emit VOC-substances to some extent, influencing the VOC concentrations in the test chamber. The Tenax tubes were analysed by Flame Ionization Detector, FID, in gas chromatography. For some of the tests, the reference concentration was evaluated based on flow rate measurement of the gases supplied. The details of measurement uncertainties for evaluating the reference concentration in the test chamber are described in APPENDIX C.

All of the sensors were installed according to the manufacturer's instructions. The sensors *S15* and *S16* are sensor modules including a sensing element and a transducer. These sensors represent the type of sensing elements that are incorporated to the commercially available sensor transmitters. For example, sensor *S8* incorporates the same sensing element as in sensor module *S15.* The measured output voltage of sensor *S15* and *S16* was correlated to sensor resistance R_s in kΩ according to the equation B.3 in APPENDIX B. From the combined CO_2/mixed-gas sensor *S8* the output corresponding to combined weighted signal was measured, which in the current test conditions is the effect of mixed-gases only. It has an analogue output signal 0-10 V corresponding to 0 - 100 % indoor air quality ratings. It is assumed that the higher values in indoor air quality ratings correspond to more polluted air.

A digital output signal was measured from the sensor *S17*, which is given as ppm units. This sensor has a resolution of 1 ppm. Sensor *S18* has also a digital output, which can be measured and monitored with the manufacturer provided data logging and monitoring system. The output can be seen as sensor resistance R_S in Ω and as a prediction of CO_2 equivalent units. In these sensors the VOCs present in the room, especially from human respiration and metabolism, are correlated to a prediction of CO_2 equivalent units.

The requirements for pre-heating time, specified by the manufacturers, were followed for all of the sensors. Some preliminary tests were carried out prior the performance tests in order to evaluate the test set-up and inspect if any malfunctioning occurs with the sensors.

3.7.1.2 The sensor performance tests

The range of reference VOC concentrations used for testing the performance of mixed-gas sensors is presented in Table 3.12. Two different gas mixtures were used VOC1 and VOC2. The VOC1 mixture was based on toluene only and VOC2 mixture included both toluene and acetone. The majority of conducted test were carried out with gas mixture VOC1.

Table 3.12 Reference concentrations applied in different tests for determining the characteristic performance of mixed-gas sensors. The values show the total concentration level of the VOC gas mixture in the test chamber

Reference gas mixture (measurand)	**Concentration of the gas mixture (ppm)**								
	Test condition number:								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
VOC1 (toluene)	0	0.1	1.0	2.0	4.0	2.0	1.0	0.1	0
VOC2 (toluene and acetone)	0	0.2	1.0	2.0	3.0	2.0	1.0	0.2	0

It must be noted that the values presented in Table 3.12 present the approximate concentration levels. The exact reference concentrations in the test chamber at each test condition can slightly vary from the presented values depending on characteristics of the gas flow system components and the reproducibility of the experiments.

The sensor characteristic curve was determined in a step change procedure by recording the output of the sensor for the values of the measurand at test conditions 1 to 9 as presented in the Table 3.12. Based on the sensor characteristic curve, sensitivity, linearity and hysteresis were determined. The evaluation procedure for these parameters is the same as in CO_2-sensor tests, described in chapter 3.6.

The repeatability of the mixed-gas sensors was evaluated by testing the sensors at test conditions 2 and 5 alternatively 4 times. Repeatability was evaluated by calculating the maximum deviation from the straight line between points 1 and 5, which correspond to calculated mean values for the respective test points.

For the sensor stability study a 6-hour experiment under constant reference concentration, $C_{ref} \approx 2$ ppm, was carried out. The current test program aimed to analyze short-term variations in the sensors output signal with no intentional changes in the input signal.

For testing the response time the sensor input was changed from test condition 2 to test condition 4 and reverse. From the results a time constant τ_{63}, rise time τ_{90} and fall time (90 %) were calculated. The response time tests were carried out in a 1 litre box made of aluminium, in order to minimize the effect from the test system.

The warming-up time was measured after the sensors were left for about 40 h without the power supply. It was first planned to do the experiment after 24 h of switching of the power supply. However, due to technical reasons this time was prolonged. The time from switching on the power supply until the output was stable was recorded as the warming up time. The reference conditions in the test chamber were kept constant, at the level of $C_{ref} \approx 2$ ppm, during the time before switching off and after switching on the power supply of the sensors.

A cross-sensitivity to varying temperature, relative humidity and supply voltage was tested by varying each quantity one at a time at constant reference concentration in the test chamber. Following test conditions were applied: temperature +22 °C and +37 °C; relative humidity 25 %, 43 % and 52 %; supply voltage: U_n= 5 V + 10 % for sensors *S15*- *S17* and U_n= 24 V ± 10 % for sensor *S8*. The two specimen of sensor *S18* had a separate power supply adaptor provided by the manufacturer. Therefore it was not possible to test the influence of supply voltage change on the sensor output. Gas mixture VOC1 was supplied to the test chamber during these tests.

3.7.2 Results

The two specimen of sensor model *S18* did not show any reasonable output signal at the reference VOC concentrations in any tests. The output values in resistance in kΩ increased to the considerably high values and did not react to the concentration changes. However, when the sensor specimens were exposed to normal indoor air the sensors seemed to correspond correctly to the indoor conditions, when considering the output in CO_2 equivalents. According to the manufacturer, the faults in signal output could have been influenced by the combination of gas mixture and sensor technology specifics. No results from the laboratory study for the sensors *S18* and *S18A* will be presented here.

3.7.2.1 Sensor characteristic curve

The characteristic curves for each tested mixed-gas sensor is presented in Figures 3.9 to 3.12. The performance of the sensors is compared in two reference VOC gas mixtures: VOC1 and VOC2. The reference gas-mixture concentrations in the test chamber were determined by means of Tenax sampling tubes. The diagrams show the sensor output plotted against the total reference gas-mixture concentration. The test conditions 1 to 5 according to Table 3.12 are referred to as the forward measurements and the tests 5 to 9 as the reverse measurements. For the sensor *S17* only results from the test with VOC2 gas mixture is presented. Problems with data saving system occurred and not data could be saved during the test with VOC1 gas mixture.

The tests with gas mixture VOC1 were carried under following environmental conditions, with evaluated uncertainty $k = 2$: temperature +26.1 ± 1.4 ˚C; relative humidity 41.7 ± 2.9 %, atmospheric pressure 980 ± 5 hPa. The test conditions for tests with gas mixture VOC2 were: temperature +22.9 ± 1.6 ˚C; relative humidity 40.5 ± 2.9 %, atmospheric pressure 971 ± 11 hPa $(k = 2)$.

The metal oxide semiconductor sensors have non-linear response characteristics with increasing gas concentration. However, there is an almost linear correlation between the logarithm of the sensor resistance, R_S and the logarithm of the gas concentration to be detected, C_{ref} for limited ranges of the concentration values. The diagrams for sensors *S15* and *S16* show log-log transformation of both reference concentration and sensor output data. In the commercial mixed-gas sensor transmitters the output is traditionally linearized with signal processing. Therefore, according to the manufacturer's data the output of the sensors *S8* and *S17* is presumed to be linear over the measurement range.

As can been from the sensor characteristic curves, the sensors behave quite similarly at the two different VOC mixtures: toluene and toluene/acetone. The small difference in sensors' *S15* and *S8* output at the two reference mixtures can be influenced by temperature conditions in the test chamber. Even though the temperature remained relatively constant at each test, small difference in ambient temperature conditions was observed between the two tests with different VOC gas mixtures. The temperature in the glass chamber was influenced by the heat emissions from the sensors themselves and by the surrounding temperature of the test chamber.

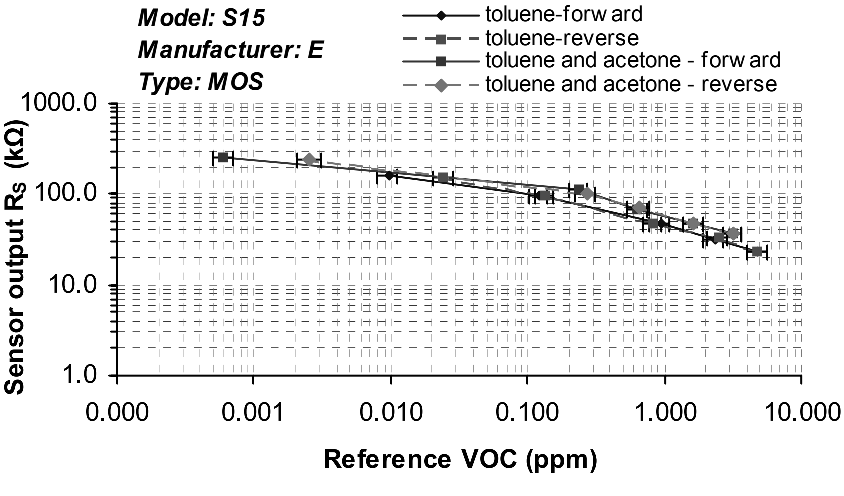

Figure 3.9 Characteristic curves for the sensor *S15* with the two VOC gas mixture conditions in a log-log plot. The error bars represent the evaluated expanded uncertainties of reference conditions with 95% confidence interval.

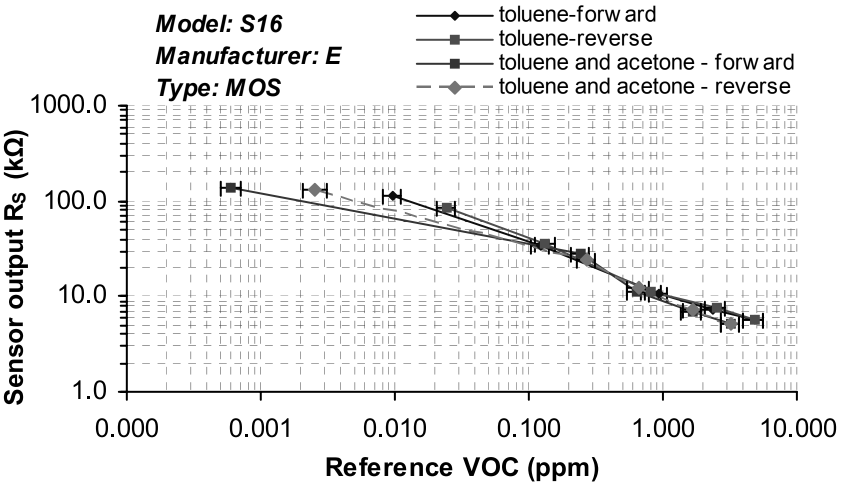

Figure 3.10 Characteristic curves for the sensor *S16* with the two VOC gas mixture conditions in a log-log plot. The error bars represent the evaluated expanded uncertainties of reference conditions with 95% confidence interval.

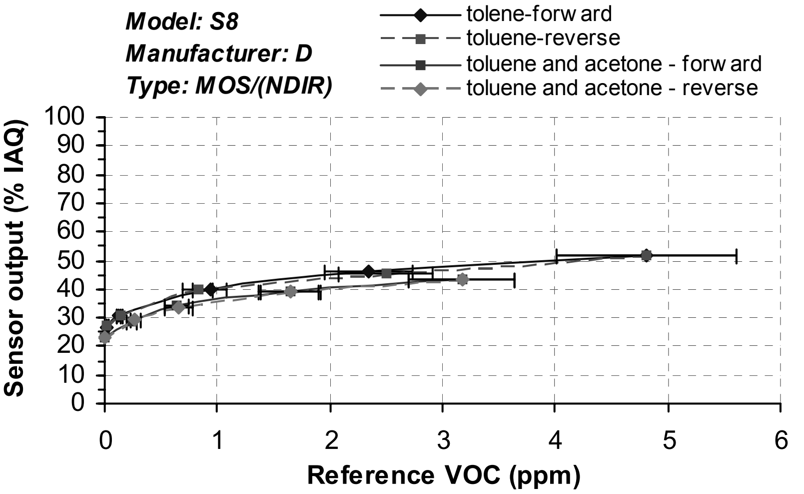

Figure 3.11 Characteristic curves for the sensor *S8* with two VOC gas mixture conditions. The error bars represent the evaluated expanded uncertainties of reference conditions with 95% confidence interval.

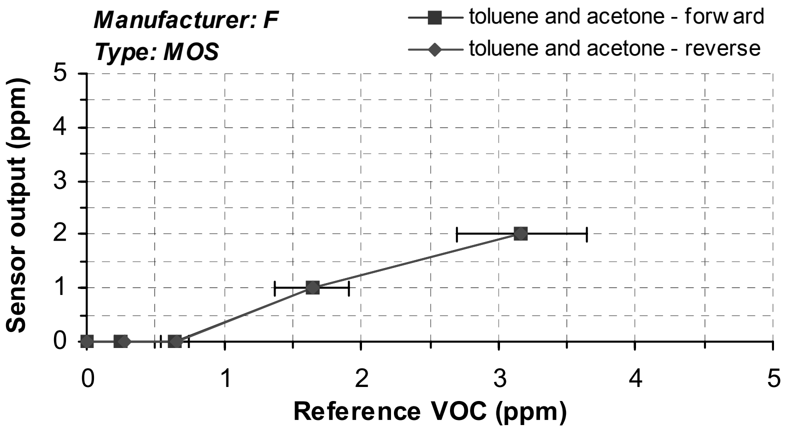

Figure 3.12 Characteristic curves for the sensor *S17* with the VOC2 gas mixture condition. The error bars represent the evaluated expanded uncertainties of reference conditions with 95% confidence interval.

In addition, it must be noted that the output of sensors *S15* and *S16* close to 0 ppm VOC gas concentration, measured at test conditions 1 and 9, should not be considered as absolute values. It was difficult to reach a steady-state baseline value for these sensors at about 0 ppm of VOC concentration, with synthetic air only. It can take many hours till the stable value is reached. After 3 hours of experiment, the sensors' output was still slowly changing. Due to economic reasons it was not possible to run the sensor for unlimited time. Furthermore, the baseline resistance of the sensor is influenced by the synthetic air used. It also contains a small amount of VOCs specified by the gas manufacturer, regardless the high purity class. Therefore, differences at sensors output can occur between the different tests with synthetic air.

It is difficult to evaluate the sensors measurement uncertainty from the sensor characteristic curves. There is very little information provided by the manufacturer about the performance characteristics of their sensors. It is not known what the output of these sensors should be with the different gas mixtures and their concentrations. This is except for sensor *S17,* which has output in ppm, which should be comparable with the reference concentrations. The manufacturer's data for sensors *S15* and *S16* provides some data about the sensitivity towards different gases. However, this data is presented as a ratio to baseline resistance R_0, which corresponds to sensor output in fresh air. The baseline resistance, however, can vary from sensor to sensor and depend on the reference fresh conditions used, e.g. in the current case on the synthetic air used.

From the results for sensor *S17* it can be observed that the output of the sensor follows the estimated reference concentrations. Since the sensor has quite low resolution, the concentrations between the full ppm levels are not detected. Therefore, it can be observed that the sensor output is 2 ppm even when the reference concentration is close to 3 ppm with the given uncertainty.

3.7.2.2 Sensitivity

Table 3.13 presents the evaluated sensitivities for the tested mixed-gas sensors. The sensitivity has been calculated as the change in output between test conditions 3 and 4, divided by the corresponding change in input. On sensor characteristic diagrams the sensitivity corresponds to the slope of the function line between sensor output and reference concentration. For the sensors *S15* and *S16* it describes the slope of the R_S curve on a logarithmic scale, for sensors *S8* and *S17* a linear output is presumed. The measured sensor sensitivities with the two reference VOC gas mixtures are almost the same, as can be seen also from the sensor characteristic curve figures.

Table 3.13 Sensitivity for the tested mixed-gas sensors with two reference gas mixtures. The values shoe the change in sensor's output in response to a change in input

Reference gas mixture	**Sensitivity of the test sensor (unit/ppm)**			
	S15 [log(kΩ)/ log(ppm)]	**S16** [log(kΩ)/ log(ppm)]	**S8** (V/ppm)	**S17** (ppm/ppm$_{ref}$)
VOC1 (toluene)	-0.4	-0.4	0.5	-[1)]
VOC2 (toluene and acetone)	-0.4	-0.5	0.5	1.1

Note 1: Problems with the data saving system occurred and no data could be saved during the experiment.

The sensitivity for mixed-gas sensors is in a great extent dependent on the gases detected with the given sensor. The sensitivity towards different gases is influenced by the deposition of semiconductor materials. Therefore, the sensitivity values given in the Table 3.13 should be considered as an example of sensor performance with the specified gas mixtures.

3.7.2.3 Linearity

The linearity in this study is evaluated as the maximum deviation of the measured output from the ideal linear line between the sensor outputs at minimum and maximum reference concentrations. As mentioned before, the metal oxide semiconductor sensors have non-linear response characteristics with increasing gas concentration. For sensors *S15* and *S16* almost linear correlation can be assumed in logarithmic scale for limited ranges of concentration values. However, evaluating linearity for these sensors based on logarithmic scale would not be that accurate method. In addition, these sensors represent the typical sensing elements incorporated to the commercial sensors, where the output is presumably linearized with signal conditioning in the sensor transmitter. Therefore, the linearity has been evaluated for sensors incorporating signal processing. Unfortunately it was possible to evaluate linearity only for sensor *S8*. The sensor *S17* has a resolution of 1 ppm, which makes it impossible to accurately estimate linearity with the current test conditions at low VOC concentrations.

The linearity values are given in Table 3.14. The biggest linearity deviation was observed at test condition 3. For the best performance of the sensor the linearity values should be minimal.

Table 3.14 Measured linearity for the tested mixed-gas sensors with two reference gas mixtures. The values show the deviation from the ideal linear transfer function line.

Reference gas mixture	**Linearity of the test sensor**			
	S15 R_s(kΩ)	**S16** R_s(kΩ)	**S8** (% IAQ)	**S17** (ppm)
VOC 1 (toluene)	-	-	8.1	-[1)]
VOC 2 (toluene and acetone)	-	-	6.7	-[2)]

Note 1: Problems with the data saving system occurred and no data could be saved
Note 2: Due to low resolution of the sensor it is difficult to accurately evaluate the linearity at tested reference VOC concentrations.

The results show that despite the signal processing inside the sensor transmitter considerable linearity deviations occur. However, as can be seen from the characteristic curve in Figure 3.11, the linearity deviations occur at lower concentrations. The sensor output is almost linear at concentrations higher than 1 ppm with the two VOC gas mixture conditions. This can be related to the optimal detection range, which is specified to be between 1 to 30 ppm by the manufacturer of the sensing element. Operating input range of the sensor specifies the range for which the sensor characteristics are maintained at stated values. However, this information is not given in the specifications of the sensor *S8* and therefore no conclusions can be made.

3.7.2.4 Hysteresis

The measured hysteresis for the different sensors is presented in Table 3.15. The hysteresis has been evaluated similarly as in CO_2-sensor tests and the evaluation procedure can be found from chapter 3.6.1. For the sensors *S15* and *S16* linearity equations based on a logarithmic function were used in the calculations of hysteresis. Unfortunately no manufacturer-specified data is available for comparison.

Table 3.15 Measured hysteresis of tested mixed-gas sensors with two reference gas mixtures. For the best performance of the sensor the hysteresis values should be minimal

Reference gas mixture	**Hysteresis of the test sensor**			
	S15 R_s(kΩ)	**S16** R_s(kΩ)	**S8** (% IAQ)	**S17** (ppm)
VOC 1 (Toluene)	2.7	2.1	1.1	-$^{1)}$
VOC 2 (Toluene and acetone)	-4.4	-1.5	0.7	0

Note 1: Problems with the data saving system occurred and no data could be saved

For sensors *S15* and *S16* the biggest hysteresis occurred at test conditions 8 with both gas mixtures. Sensor *S8* had biggest hysteresis at test conditions 7, when tested with VOC1 gas mixture and at test conditions 8 with VOC2 gas mixture. The maximum measured hysteresis for sensor *S8* was 1.1 % in IAQ ratings, which can be considered considerably low when compared to the measuring range of 0 - 100 % indoor air quality ratings. In order to compare this data with the sensors *S15* and *S16,* the hysteresis values for these sensors have been evaluated in relation to the resistance change over the measured concentration range. The measured hysteresis for the sensors *S15* and *S16* were less than 8 % from the measured range with both VOC1 and VOC2 reference gas mixture conditions, being somewhat higher for sensor *S16.* For sensor *S17,* no hysteresis can be indicated from the results. However, this is most probably due to the low resolution of this sensor and due to the tested low reference concentration values.

3.7.2.5 Repeatability

Table 3.16 presents the evaluated repeatability values for the tested mixed-gas sensors. The values correspond to the maximum deviation from the mean output from the repeated measurements at the respective test points. Both, absolute values and relative values are presented. The tests with gas mixture VOC1 were carried under following environmental conditions, with evaluated uncertainty $k = 2$: temperature +22.7 ± 1.3 ˚C; relative humidity 44.3 ± 4.0 %, atmospheric pressure 996 ± 2.5 hPa.

Table 3.16 Repeatability of tested mixed-gas sensors. The tests were carried out at the VOC1 (toluene) gas mixture. For the best performance of the sensor the repeatability values should be minimal.

Reference VOC concentration	**Repeatability of the test sensor (unit or % of mean)**			
	S15 R_s(kΩ)	**S16** R_s(kΩ)	**S8** (% IAQ)	**S17** (ppm)
$C_{ref} \approx 0.1$ ppm				
Measured value (unit)	4.9	1.9	0.2	-$^{1)}$
% of mean	4.6	6.4	0.9	-$^{1)}$
$C_{ref} \approx 4.3$ ppm				
Measured value (unit)	1.4	0.2	1.8	-$^{1)}$
% of mean	4.7	4.6	4.1	-$^{1)}$

Note 1: Problems with the data saving system occurred and no data could be saved

The results show similar relative repeatability values at the two reference VOC concentration levels for sensors *S15* and *S16*. Sensor *S8* showed quite low repeatability at the lower concentration level, which was less than 1 %. However, at the higher VOC concentration level the repeatability is similar to the sensor *S15* and *S16* and is about 4 % from the mean value. Unfortunately, no manufacturer-specified data is available for comparison.

3.7.2.6 Stability

The stability study in the current test program aimed to analyze short-term variations in the sensors output signal. A 6-hour experiment under constant reference VOC concentration was carried out. During the first measurement hour instabilities in the ambient temperature and humidity conditions occurred, which influenced the sensor readings. Consequently, the results from the first measurement hour are not included to the calculations. The tests with gas mixture VOC1 were carried under following environmental conditions, with evaluated uncertainty $k = 2$: temperature +23.1 ± 1.1 ˚C; relative humidity 45.2 ± 2.8 %, atmospheric pressure 998 ± 2.1 hPa.

The results from the stability study are presented in Table 3.17. To evaluate short-term variations in the output signal, the measurement period was divided into 5-minute periods. For each of this period maximum deviation and standard deviation from the mean value was determined. The Table 3.17 presents the average of these standard deviations and maximum occurred deviation from the mean value considering the 5-minute periods all together. Additionally, to evaluate the sensor output stability over the entire measurement period the measurement was divided into 1-hour periods. The standard deviation of the average of 1-hour mean values was calculated.

Table 3.17 The results from the short-term stability test of mixed-gas sensors under test condition of C_{ref} = 2.1 ± 0.3 ppm. The tests were carried out with VOC1 (toluene) gas mixture. The values show the deviations from the mean values evaluated over different time periods.

Evaluated parameter	**Stability of the test sensor (unit or % of mean)**			
	S15 R_s(kΩ)	**S16** R_s(kΩ)	**S8** (% IAQ)	**S17** (ppm)
Signal 5 min stability				
Average SD [1) (unit)	0.05	0.03	0.02	0
Average SD (% of mean)	0.1	0.4	0.04	0
max deviation [2) (unit)	0.12	0.05	0.1	0
max deviation [2) (% of mean)	0.3	0.7	0.2	0
Signal 1 h stability				
SD_{mean} [3) (unit)	0.41	0.06	0.12	0
SD_{mean} [3) (% of mean)	1.0	0.8	0.3	0

Note 1: Average standard deviation of 5-minute periods over the 5-hour measurement
Note 2: Maximum deviation from the mean of 5-minute period considering all the 5-minute periods together over the 5-hour measurement
Note 3: Standard deviation of the average value of 1-hour mean values

If the output is stable the standard deviation of the average 1-hour mean values should be close to zero. The percentages in the Table 3.17 show the percentage of the measured deviation from the respective mean value. For all of the tested sensors the evaluated short-term stability values were within 1 %.

3.7.2.7 Cross sensitivity test

The results from the cross-sensitivity study are presented in Table 3.18. The values have been evaluated as the ration between the change in sensor output and the change in given influence quantity. In addition, the possible effect of sensor stability has been taken into account by comparing the changes in sensor output at different test conditions with stability values. If the changes are higher than the evaluated sensor stability, the change in output is most probably due to the influence quantity tested. Unfortunately, no manufacturer-specified data is available for comparison.

Table 3.18 Results from the cross-sensitivity test. The tests were carried out with VOC1 (toluene) gas mixture. The values show the change in sensor's output in response to a change in a given influence parameter. For the best performance of the sensor the values should be minimal.

Influence quantity	**Cross-sensitivity of the test sensor**			
	S15 (kΩ /unit)	**S16** (kΩ /unit)	**S8** (%/unit)	**S17** (ppm/unit)
Temperature (°C)	-2.3	0.1	0.7	-[1)]
Relative humidity (r.h.)	-1.0	0.1	0.2	-[1)]
Absolute humidity (g/kg)	-3.2	0.4	1.0	-[1)]
Voltage (V)	22.6	-20.1	-[1)]	1.1

Note 1: The response of the sensor was too small to be significant

In cross-sensitivity test with humidity change the relative humidity was changed from 24.5± 2.8 % to 51.8 ± 2.8 %. According to the results, the increase in relative humidity about 27 % r.h. decreased the sensor *S15* output about 40 % from the initial value. For the sensors *S16* and *S8* an increase in output about 28 % and 25 % from the initial value was observed. Due to the low resolution of sensor *S17* the output showed constantly 0 ppm and no changes were registered during the different relative humidity conditions.

The cross-sensitivity test with temperature variation was carried out by placing the test chamber into a hot water basin. The temperature in the test chamber increased from +22 °C up to +37 °C. Since during this time no changes were done in the humidity settings, relative humidity decreased from 42 % r.h. down to 18 % r.h. Furthermore, it was observed during this time that the sensors' output value remained almost the same. The output changed from the initial value about 6 % for the sensor *S15*, 2 % for sensor *S16* and 0.7 % for sensor *S8*. In order to achieve the initial relative humidity values as at the beginning of this test, the humidity content in the chamber was increased. It was possible to increase the relative humidity with 10 % r.h. only, but the change in sensors' output up to 25 % from the initial value was observed. At the end of the temperature test the test chamber was removed from the hot water basin to cool down the chamber conditions.

When different influencing parameters are tested in cross-sensitivity test it is important that only that one factor is varied at the time and the other parameters are kept constant. Unfortunately, due to the specifics of the temperature test procedure and available test set up, it was not possible to keep the relative humidity values constant while changing the temperature. Nevertheless, some calculations based on initial test conditions and conditions after removing the test chamber from the water basin were done and are shown in Table 3.18. After removing the test chamber from the water basin, relative humidity conditions similar to the ones at the beginning of the test were achieved. However, due to bigger variability in the relative humidity conditions the results can be inconclusive.

From temperature test it was observed that the two parameters, temperature and relative humidity, have non-independent influence on sensor output. Therefore, these parameters should be looked together. For doing so, the influence of absolute humidity conditions have been analysed in more detail. Figure 3.13 shows the relationship between absolute humidity and sensors output measured at the temperature and humidity tests at different reference gas concentrations. A linear functional relationship between the absolute humidity conditions and sensor output can be seen from the two diagrams in the Figure 3.13. The sensitivity values can be evaluated from the model fitted to the measured data, which express the slope in the linear line. The highest values of the two fitted models have been presented as cross-sensitivity values in Table 3.18.

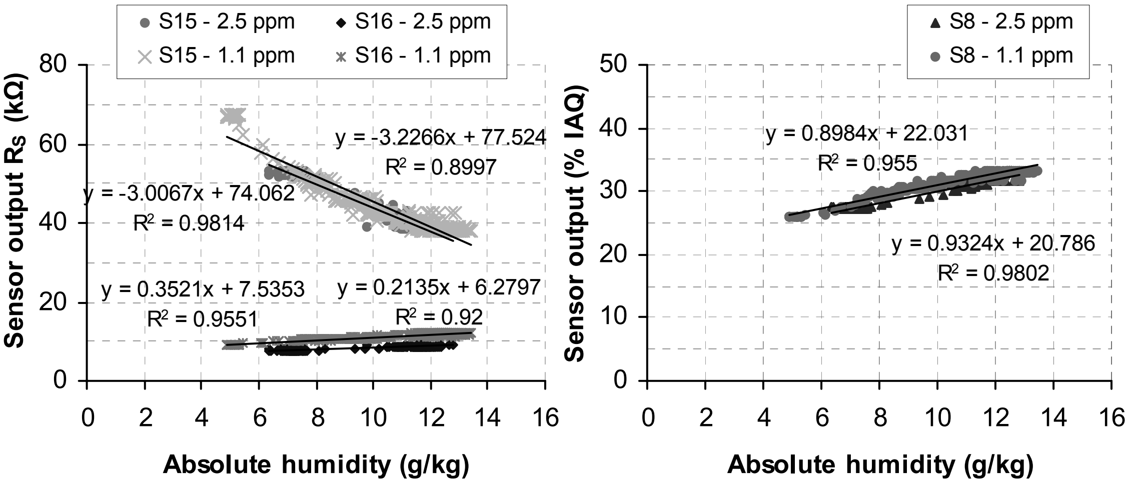

Figure 3.13 Cross-sensitivity to absolute humidity of the test sensors *S15, S16* and *S8*. The tests were carried out with VOC1 (toluene) gas mixture at different concentration levels. The diagrams present a functional relationship between absolute humidity and sensors output.

According to the test results seasonal change in absolute humidity in indoor conditions about 8 g/kg would result to a change about 7 % in IAQ ratings in the output of sensor *S8*. The influence of absolute humidity on metal oxide semiconductor sensors can be due to the absorption of water to the sensitive layer. This has been analysed in several studies and algorithms for corrections for the humidity effect have been developed that can be implemented in the sensor control electronics[85, 93].

The supply voltge was changed in a range of 21.1 V – 26.4 V and 4.6 V – 5.4 V in the cross-sensitivity test with supply voltage change.The cross sensitivity test with supply voltage change showed considerable sensitivity on the output of sensors *S15* and *S16*, which can be expected. Some influence was also indicated with sensor *S17*, but the change was negligible for sensor *S8*.

3.7.2.8 Response time

The results from the response time test are presented in Table 3.19. The time constants and rise times were less than 1.5 minutes for sensors *S15* and *S18*. Recovery times were observed to be somewhat longer than rise times, which can be related to the specifics of sensor technology. For sensor *S8* all of the response times were close to 3.5 minutes. The somewhat longer response times for sensor *S8* can be expected when compared to sensors *S15* and *S16.* The response time is affected by the housing. The sensors *S15* and *S16* had especially ordered metal boxes for housing, with the hole in the cover over the head of the sensing element. In commercial sensor transmitters the sensing element may not be close to the holes for gas diffusion.

According to the proposed quantitative requirements on indoor air quality sensors, the response time should be less than one third of the nominal time constant of the controlled room. This would correspond to about 15 minutes for a cell office room of 10 m^2 and airflow rate 10 l/s. The measurement results show that the tested mixed-gas sensors fulfil this proposed requirement. Unfortunately, problems with the data saving system for sensor *S17* occurred and no data was saved. Therefore, no evaluation on the response time of this sensor could be done.

Table 3.19 Response time of the tested mixed-gas sensors. The tests were carried out with VOC1 (toluene) gas mixture.

Evaluated parameter	**Response time of the test sensor (min)**			
	S15	**S16**	**S8**	**S17**
Time constant (63%) τ_{63}	< 0.5	< 0.5	< 3.5	-1)
manufacturers value	*n/a* 2)	*n/a*	*n/a*	*n/a*
Rise time (90%) τ_{90}	< 1.5	< 1	< 3.5	-1)
manufacturers value	*n/a*	*n/a*	*n/a*	*1 min* (τ_{80})
Fall time (90%)	< 9.5	< 3	< 3.5	-1)

Note 1: Problems with the data saving system occurred and no data could be saved
Note 1: n/a – information not available

3.7.2.9 Warming-up time

In metal oxide semiconductor sensors the sensing layer is heated by a heater structure. Therefore, some time is needed for the sensor from switching-on the power supply till the sensor reaches its chemical equilibrium. This time is specified as warming-up time, often called as preheating time. As the sensor changes temperature during this time, some chemicals will be released and some will be absorbed by the sensitive surface and conductivity will be stabilized. The longer the time that sensor has been unpowered, e.g. when stored, the longer warming-up time is required to stabilize the sensor before usage.

For determining the warming up time the sensors were left 40 h without the power supply, instead of 24 h as it was first planned. This was due to technical reasons. This test was conducted last in the experiment program in order to not to influence the results of other tests. The results are shown in Table 3.20. Many of the tested sensors reached relatively stable output value in a quite short period of time. However, it was observed that the mean value of the sensor output continued to increase or decrease slowly in small magnitudes till it reached a stable level. Therefore, for evaluating the warming-up times the results are presented in three steps, which show the observed time periods for reaching 95 %, 98 % and 100 % of the final value. The final value was taken as a 30-minute average value after approx 1 hour was passed from switching on the power supply.

Table 3.20 Warming-up time of the tested mixed-gas sensors. The tests were carried out with VOC1 (toluene) gas mixture. The values show the elapsed time from switching on the power supply till reaching a stable value

Evaluated time from the final value	**Warming-up time of the test sensor (min)**			
	S15	**S16**	**S8**	**S17**
95% of final value	< 8	< 41	< 1	< 2.5
98% of final value	< 11	< 56	< 1	< 2.5
100% of final value	< 15	< 69	< 15	< 2.5
Manufacturers value	*< 15*	*< 20*	*< 5*	*2.5*

The results of the warming up time test showed that the majority of the tested sensors reached a stable value within 15 minutes. Longer warming-up time was needed for sensor *S16.* In the manufacturer specification, an example of initial action is presented for sensors *S15* and *S16.* According to this data, the warming-up time for a sensor which is stored un-powered in normal air for 30 days and then energized, is about 15 minutes for sensor *S15* and about 20 minutes for sensor *S16.*

3.7.3 Discussion

This study aimed to analyse the performance characteristics of commercially available mixed-gas sensors. Five different types of mixed-gas sensor were tested with two different VOC gas mixtures. The results are presented for four of them. The two specimens of sensor model *S18* did not show any reasonable output signal at any test condition. The faults could have been influenced by the combination of gas mixture and sensor technology specifics. This leads to the conclusion that the available methods for sensor calibration are not applicable for these sensor models. Other methods need to be specified by the manufacturer for performance checking of these sensors if they are to be applied for ventilation control in DCV systems.

The performance target for gas sensors is their sensitivity to target gas/gases and low cross-sensitivity to any other property. Additionally, the sensors should operate in a sufficient operating range for measurement purposes with low measurement uncertainty including minimal linearity, hysteresis, repeatability and stability deviations. The proposed requirment for the response time is that it should be less than one third of the nominal time constant of the controlled room. The results from this study show that the sensors have sufficiently fast response times for indoor air quality control purposes.

However, evaluating the measurement uncertainty of the tested mixed-gas sensors can be rather complicated. The metal oxide semiconductor sensors measure non-selectively a wide range of gases and the sensor signals traditionally give no indication as to the type of gases detected or in what concentration they are present. The output of the sensing elements, incorporated to the commercial mixed-gas sensors, corresponds to a change in the resistance R_S. The two tested sensors *S15* and *S16* represent the original sensing elements. The commercial sensors, e.g. sensor *S8,* transform these signals with data processing to 0 – 100 % in air quality ratings. It is assumed that the higher values in indoor air quality ratings correspond to more polluted air. Unfortunately, very little information is available about how to interpret the output signals of these sensors. It is not known what the output of these sensors should be with the different gas mixtures and their concentrations. Therefore, it is also difficult to evaluate the results regarding sensor sensitivity towards different gases and associated measurement uncertainty.

Some assessment can be done based on measured characteristics. The measurement uncertainty should include all the different sources of uncertainties and deviations, e.g. hysteresis, linearity, repeatability and stability. The measured values for these parameters can be expressed as percentage change from the respective measurement point where the uncertainty was observed. The calculated combined uncertainty would be about 6 % for sensor *S15,* about 9 % for sensor *S16* and about 20 % for sensor *S8* from the measured value. Nevertheless, this method of uncertainty evaluation may not be that accurate. It also does not consider the cross-sensitivity to environmental conditions. Cross-sensitivity for absolute humidity was observed for sensors *S15* and *S8*, which can be related to the sensor technology specifics. The results show that the output will not be influenced considerably at small changes in absolute humidity; however seasonal variations can have significant influence on the sensors performance.

The total concentrations of the VOC gas-mixtures tested varied between 0.1 ppm to 4.5 ppm. These concentration levels are rather high compared to the traditional concentrations in indoor air. In existing offices the concentrations for acetone and toluene have been reported to be less than 0.1 ppm for both acetone and toluene. In new residential buildings these concentrations are up to 0.2 ppm and in existing residential buildings up to 0.3 ppm[92]. The reason to choose such high reference gas concentration levels was due to the specifications of the tested mixed-gas sensors. For sensor *S15* the manufacturer specifies an optimal detection range to be between 1 ppm to 30 ppm. This is presumably also valid for sensor *S8.* For sensor *S16* this range is 1 to 10 ppm. Sensor *S17* has a digital output from 1 to 10 000 ppm and resolution of 1 ppm, meaning that concentration levels less than 1 ppm would be shown as zero. For sensor *S18* no information is available. The reference concentrations in the tests had to be within the minimum presumed detectability of the sensors.

The results show that that the tested sensors behave similarly at the two different VOC mixtures. At about 4.5 ppm toluene concentration the output of sensor *S8* showed close to 50 % of the indoor air quality rating. At concentration level 3 ppm of toluene and acetone mixture the output was approx 45 % of the indoor air quality rating. This leads to a question as to how the raw signals of the metal oxide semiconductor sensing elements are translated into indoor air quality ratings 0 to 100% and how to adjust the set point levels when these sensors are used for indoor air quality control? If the sensor shows at very high toluene and acetone concentrations only 50 % of the indoor air quality rating in the output signal then the set point level must be much lower than 50 %. The value of interest regarding health and comfort considerations for toluene and acetone is about 0.1 ppm[91]. Unfortunately, no information is available in the manufacturer specified data.

Additionally, it is not known how the sensor sensitivity towards different gases and their concentration levels are weighted in the output signal. Some of the VOCs usually encountered at high concentrations in indoor environment are not harmful, while some other compounds can be toxic at very low concentration, e.g. benzene. This should be considered in the output signal, especially when the output is translated into indoor air quality levels. For sensor *S8* a shorting plug is included in the sensor for varying the VOC weighting sensitivity. It has three possible positions, corresponding to “low”, “normal” and “high” VOC sensitivity. All of the tests with this sensor were conducted with shorting plug in the “normal” position. According to the manufacturer, by selecting the “low” or “high” the signal is adjusted by ± 10 % relative to the “normal” position[243]. However, it is not clear when these positioning changes should be used and if sensitivity to some specific gases will be changed with the different options.

One of the tested sensors has a signal output in concentration units, expressed as ppm. However, it has a resolution of 1 ppm. For the indoor climate control the concentrations of interest for several gases are much lower as are also the concentration changes that should be measured. Therefore, the application of this kind of sensor can be questionable. Nevertheless, this sensor can be applied in conditions where alarm concentrations of the reference gases of interest exceed the 1 ppm level, e.g. carbon monoxide.

3.7.4 Conclusion

The performance characteristics of commercially available mixed-gas sensors have been evaluated in this study. Five different mixed-gas sensors based on the metal oxide semiconductor measurement principle were tested. The results for four of them have been presented and discussed, whereas two of them represent the original sensing elements that are incorporated into the commercial sensors. From the test results following observations and conclusions can be made:

- Similar sensor behaviour was observed at the two reference gas mixtures for all of the tested sensors. However, it is difficult to evaluate the results regarding sensor sensitivity towards different gases and the associated measurement uncertainty, since very little manufacturer-stated information is available for comparison

- It is difficult to evaluate the performance of the commercially available mixed-gas sensors, which show the output as 0 to 100 % indoor air quality ratings. The output signal has been determined empirically based on the resistance change of the sensing element. However, it is not clear how this transformation is done and where the set point levels should be for these sensors when used for indoor air quality control.

- The tested mixed-gas sensors have sufficiently fast response time for the indoor air quality control purposes.

- Cross-sensitivity for absolute humidity was observed for sensors with the same type of sensing element. Seasonal variations in outdoor humidity conditions can have significant influence on the performance of these sensors. However, short-term changes in the ambient humidity conditions do not affect the output considerably

- The specified optimal measurement range and minimum detection limit for the commercial mixed-gas sensors is at a considerably higher level than the concentrations of interest for different VOCs indoors. In different data sheets the minimum optimal detection level is reported to be 1 ppm. Considerable linearity deviations occurred for one of the tested sensors below this concentration level. The tested mixed-gas sensor with digital output expressed in ppm had very low resolution and low minimum detectability, which makes it impossible to measure changes lower than 1 ppm.

There has been a lot of discussion whether the mixed-gas sensors are suitable for indoor climate control due to their non-specific behaviour[242]. Unfortunately the results of this test program can not give any answers to this question. There are many different VOC compounds in indoor air that can be linked to the indoor activities and processes, but only two of them were tested in this study. The choice of the reference gases was limited for economical reasons. On the other hand, it is also difficult to find a small number of suitable VOC gases that represent the activities in indoor environment in commercial buildings. Since many VOC gases have a combined effect on perceived indoor air quality, it can be advantageous if the mixed-gas sensors are wide-ranging. However, it is important that they are able to detect the gases that are considered as pollutants, e.g. CO, several VOCs and that they are not sensitive to traditional compounds in the atmosphere, e.g. water vapour. Furthermore, output signal weighting of the different compounds based on their health and comfort effects would be needed. Some of the VOCs usually encountered at high concentrations in indoor environment are not harmful, while some other compounds can be toxic at very low concentration.

3.8 Sensitivity study of mixed-gas sensors in controlled environment

For the applications of mixed-gas sensors for indoor air quality control, information is needed about the sensors sensitivity to pollutants from different emission sources in room. The application of mixed-gas sensors can be wide ranging and depends on the purpose and use of the premises where demand controlled ventilation is applied. This study aimed to analyse the sensitivity of mixed-gas sensors to different pollution loads that can occur in commercial buildings. Here the term *sensitivity* is used in a quantitative concept to describe the mixed-gas sensors behaviour in different environments. In this concept a parameter *relative sensitivity* is evaluated as the relative change of the sensor output signal against the initial output signal. This study is limited to a fixed number of pollutant emission sources, e.g. new office furniture, office equipment, linoleum floor, cleaning. These sources however, do not refer to the intended application of the tested sensors.

Sensors *S8, S15, S16, S17* and the two specimens of *S18* were tested in this study, according to the numeration in Table 3.1. The mixed-gas sensors were exposed to controlled indoor climate conditions in a full scale test chamber where different internal pollutant loads were varied. This chapter describes the summary of the methodology used and the results. Additionally, discussion and conclusions are presented. A detailed description of the test set-up and measurement techniques is given in APPENDIX B. More detailed information about the sensors output at different tests can be found from Maripuu[142].

3.8.1 Experimental methodology

3.8.1.1 The test set-up and measurement techniques

The tests were carried out in a full scale test room, which is built for measurement of low emissions of gaseous and particulate pollutants from construction materials and office equipment. The test room has low background emissions of pollutants due to its specific design. It is made of brushed stainless steel walls, floor and ceiling, the connections are sealed with hidden rubber gasket to make it airtight. The dimensions of test room are: length 3.5 m, width 2.4 m and height 2.3 m, which gives a floor area of 8.4 m^2 and volume of 19.3 m^3.

The environmental test conditions in the environmental chamber were kept at the level of +22 ± 1.5 °C for temperature and 45 ± 5 % for relative humidity. The temperature and relative humidity were continuously monitored. A local air humidifier was placed in the room to keep the required humidity levels. The pressure in the test room was based on atmospheric conditions, with a small overpressure in the room. The supply air flow rate to the test room was set between 6.8 -7.1 l/s, which corresponds to 1.2 - 1.3 h^{-1}, and was kept constant at all test conditions. The outdoor air supplied to the room was filtered by a five stage filter system, including an active carbon filter. The total volatile organic compounds, TVOCs, concentrations in the supply air, after the filter system, were continuously monitored with a photoacoustic spectroscopy instrument. The aim was to evaluate the stability of the supply air concentrations.

The test sensors were all installed side by side on a small board and hanged on a metal rod. The metal rod with sensors was placed in the middle of the test room for all of the tests. The board with the sensors was at the height of 1.1 m above the floor. In addition to the mixed-gas sensors tested in this study, the CO_2-sensors *S3* and *S5* were used for monitoring the carbon dioxide concentration in the test room.

Gas concentrations in the room were in several tests determined by adsorbent sampling tubes filled with Tenax-TA. The VOCs were identified and quantified by thermal desorption and gas chromatography, using FID and MSD as parallel detectors (TD-GC-FID/MSD). FID is used for quantification and MSD for identification of individual substances. The location of the sampling point was next to the sensor stand.

3.8.1.2 The sensor performance tests

The performance of the mixed-gas sensors were evaluated with different pollutant emission sources that can occur in commercial buildings. Following pollutant emission sources were selected:

- new office furniture
- new and old personal computer with two different types of monitors
- linoleum floor
- cleaning of linoleum floor
- presence of a person

The choice of emission sources for testing was influenced by practical circumstances and the simplicity of the test procedures.

The different pollutant sources were placed in the room according to the test program, described in Table 3.21. An example of the room set up is shown in Figure 3.14. Since the test room has no artificial lighting a table lamp was placed in the room for several tests in order to observe the instruments and conditions in the room.

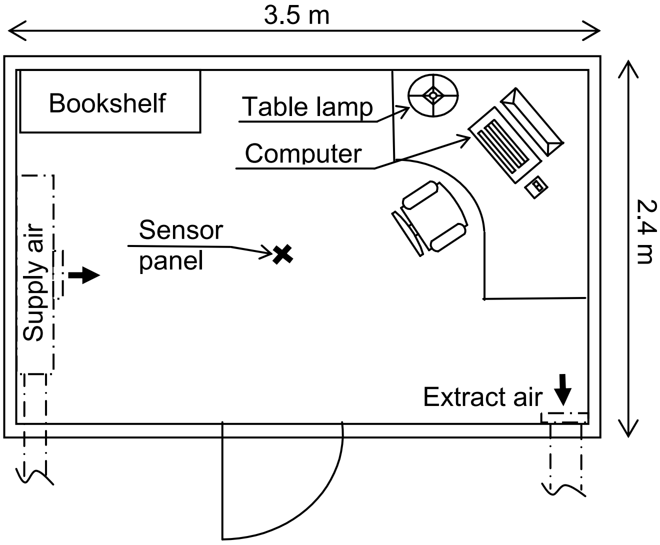

Figure 3.14 Schematic picture of the full scale test room used for sensitivity tests of mixed-gas sensors. An example of the room set-up

The sensors' output was continuously monitored before and after the different emission source(s) was/were installed to the test room. Before each test the room surfaces were cleaned carefully with a towel wetted with distilled water. The aim of this procedure was to avoid any impact from the previous test conditions.

Table 3.21 Overview of the conducted tests in order to determine relative sensitivity of the mixed-gas sensors

Test nr	Pollutant source	Test description
1	Empty test room	The aim of this test was to measure the background conditions of the test room.
2	New office furniture	The aim of this test was to evaluate the sensors' sensitivity to office furniture. New furniture including an office table, a chair and a bookshelf was placed in the room.
3	Old PC and CRT monitor	The aim of this test was to evaluate the sensors sensitivity to personal computer and older CRT type of monitor. A 5-year old PC with CRT monitor was installed in the room. The PC was set to run in a certain activity mode.
4	New PC and LCD monitor	The aim of this test was to evaluate the sensors sensitivity to a new PC and new LCD type of monitor. A new PC with LCD monitor was installed in the room. The PC was set to run in a certain activity mode.
5	New linoleum floor and cleaning agent	The aim of this test was to evaluate sensors sensitivity to floor material and cleaning activity in the room. A new linoleum floor material was installed in the room and cleaned with the cleaning-agent. The dosing of the cleaning agent/water mixture was explicitly done and documented. The linoleum floor was polished one week before installing to the test room.
6	Linoleum floor, furniture, new PC and LCD screen, 1 person	The aim of this test was to evaluate sensors sensitivity if the room is fully furnished and equipped with office equipment and at the same time a person is working in the room. All the pollutant emission sources were placed in the room and after a specified time one person entered the room to do some traditional office work, e.g. typing.

The change in the tested mixed-gas sensors' output for different emission sources was evaluated at steady-state conditions before and at certain of period of time after the emission sources were placed in the room. Relative sensitivity of the test sensor to different pollutant sources has been evaluated as the relative change of the sensor output signal divided by the initial sensor output signal, as follows:

$$S_{rel} = \frac{S - S_0}{S_0} \qquad \text{(eq. 3.8)}$$

Where,

S_{rel}	relative sensitivity of mixed-gas sensors to different pollutant emission sources;
S	output of the tested mixed-gas sensor at a given test conditions with specified pollutant source;
S_0	output of the tested mixed-gas sensor at empty test room conditions before the test with specified pollutant source

When a pollutant source is placed in the room, the concentration of different VOCs will increase. However, after the peak concentration level is achieved the concentration levels will start to decrease with time. This depends on the type and age of the pollutant emission source and environmental conditions [129, 227]. After cleaning procedure, a peak of concentration will occur minutes after the cleaning is finished and then decrease to the initial level. This can take a few hours or less. In the current test program the aim was to evaluate the peak concentrations if possible.

The study was carried out during three weeks period of time, while the sensors were continuously connected for eight weeks. The results from this study do not take under consideration sensor drift and its impact on the measured results.

3.8.2 Results

Figure 3.15 shows the evaluated relative sensitivities of the tested mixed-gas sensors at different test conditions. The results from sensor *S17* have not been included to the figure, since this sensor showed continuously zero at all test conditions.

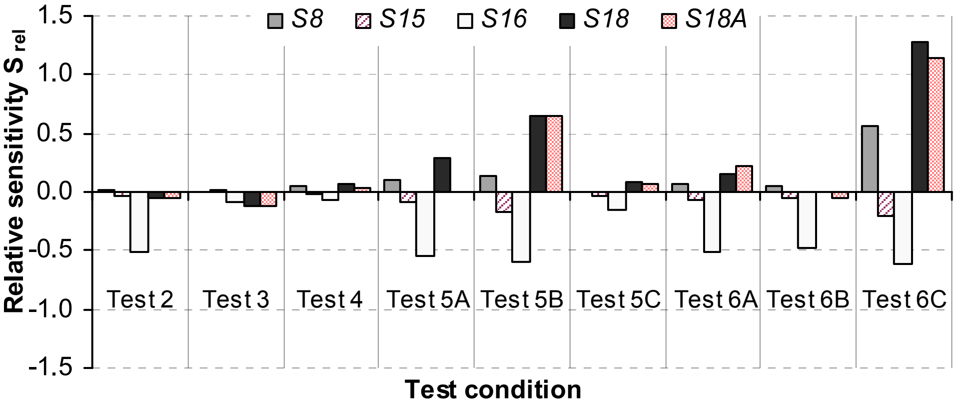

Figure 3.15 Evaluated relative sensitivity of the tested mixed-gas sensors to different emission sources. The values are calculated as the difference in sensor output between the room conditions before and after the emission sources were placed to the room, divided by the initial conditions, shown in equation 3.8. The sensor *S17* showed continuously zero at all tests and therefore the results have not been included to the diagram.

In the Figure 3.15 the test conditions correspond to the following:

- *Test 2*: new office furniture in the room. The results are based on the conditions before and 3-hours after the furniture placement.
- *Test 3*: old PC with CRT monitor. The results are based on the conditions before and 4 hours after the PC and the monitor were placed to the room.
- *Test 4*: new PC with LCD monitor. The results are based on the conditions before and 3 hours after the PC and the monitor were placed to the room.
- *Test 5A*: linoleum floor. The results are based on the conditions before and 4 hours after the linoleum floor was installed to the room.
- *Test 5B*: cleaning the linoleum floor. The results are based on the conditions before washing (the linoleum floor had been in the room for 4 days before this procedure) and 15 minutes after the floor washing was finished.
- *Test 5C*: cleaning the linoleum floor. The results are based on the conditions before washing and 3.5 hours after the floor washing was finished.
- *Test 6A*: linoleum floor, furniture, new PC with LCD monitor. The results are based on the conditions before and 4 hours after the linoleum floor, furniture and PC with LCD monitor were placed to the room.

- *Test 6B*: linoleum floor, furniture, new PC with LCD monitor. The results are based on the conditions before and 11 hours after the linoleum floor, furniture and PC with LCD monitor were placed to the room.
- *Test 6C*: linoleum floor, furniture, new PC with LCD monitor and 1 person. The results are based on the conditions before one person entered the room and 4 hours after the entering.

The negative relative sensitivity values indicate a decrease in sensor output during the specified test condition. It must be noted that for sensor modules *S15* and *S16,* the output decreases when the concentration of pollutants increases. These sensors represent the typical sensing elements incorporated to the commercial mixed-gas sensors. The measured output of these sensors is correlated to the resistance change of the metal oxide semiconductor sensing element.

3.8.2.1 Background emissions measured in the empty test room

According to the results from Tenax sampling conducted in the empty test room the $TVOC_{GC}$ concentration was approx 30 µg/m^3. This value can be considered as considerably low and is close to the minimum detection limit of the VOC measurement method[178]. The individual compounds with the highest concentration in the room at the current test condition were benzene and cyclohexane. These compounds can be associated with outdoor traffic[57].

The concentrations of indoor pollutants do not depend only on its indoor emission rate. It also depends on the rate at which it is being transported from outdoors to indoors after filtration in the ventilation system and on the rates at which it is adsorbed/desorbed by indoor surfaces. The ventilation system supplying the air to the test room in the current study has a five-stage filtering system. The filtering system includes a carbon filter which is able to decrease the concentrations of VOCs supplied to the room. In real applications, the supply air conditions would be different and the outdoor air can have bigger influence. In any case, the possible effect of outdoor pollutants on room conditions should be evaluated. In this study, the idea was to minimize the impact from outdoor sources.

3.8.2.2 Relative sensitivity to furniture and office equipment

According to the test results, the majority of the tested mixed-gas sensors have negligible relative sensitivity to furniture and office equipment. Sensor module *S16* seems to be more sensitive to the new furniture and computer sets than the sensor module *S15.* For the sensor module *S15* only few percentage of change in output signal was indicated compared to the initial conditions. Similar was also observed for sensor *S8*, which incorporates the same sensing element as in sensor module *S15.* The output of sensor *S8* increased about 1 % from the initial value after the furniture was installed to the room. During the test with new PC and LCD monitor this change was about 5 %. However, a slight change in sensors *S8* output was indicated at the test conditions with the old PC and CRT monitor. Nevertheless, this could have been affected by a small change in absolute humidity conditions or by the change in supply air conditions. The absolute humidity changed about 3 % from the initial test contition. Unfortunately, no data was saved from the reference instrument measuring the supply air conditions during the time when the emission source was placed to the room. Therefore, no final conclusion can be made.

For sensors *S18* and *S18A* the output in CO_2 equivalents decreased about 5 % from the initial value during the test with furniture and about 12 % during the test with old PC and CRT monitor. In the test with new PC and LCD monitor the value increased slightly, about 4 % and 7 % from the initial value for the respective test sensors. This is difficult to explain. The output of these sensors may have been affected by a small change in absolute humidity conditions or by possible change in supply air conditions.

The output of Sensor *S17* was continuously 0 ppm during these tests and did not show any change in respond also to other test conditions. This can be due to the very low emitted concentration levels of these pollutant sources. The sensor *S17* has resolution of 1 ppm and minimum detectability of 1 ppm.

The results from the Tenax sampling of VOC compounds and concentrations in the room at Test 2, with the new furniture, showed that the $TVOC_{GC}$ concentration was about 250 µg/m^3. The individual compounds with the highest concentrations identified were: ethanol,1-methoxy-,benzoate; ester of acrylic acid; benzene; cyclohexane; benzaldehyde; hexanal; nonanal; 3-carene and butyl acetate. The concentrations of the first five named compounds were between 6 and 15 µg/m^3 in toluene equivalents. The other compounds had concentrations less than 4 µg/m^3. As discussed before, the possible source for benzene and cyclohexane is outdoor air. The other compounds can be associated with the furniture in the test chamber[178]. It must be noted that these concentrations were measured at the new furniture conditions. The emissions from the materials and furniture will decrease in time and will be lower after several months of use.

The total VOC concentrations $TVOC_{GC}$, measured with Tenax sampling at the test conditions 3 and 4, were about 60 µg/m^3 and 110 µg/m^3, respectively. The VOC concentration levels are depending on the age of the material, from where it is emitted. Therefore it can be expected that the VOC emissions from the old PC with CRT monitor are lower than from the new PC with LCD screen.

The individual compounds identified with the highest concentrations at test condition 3, with the old PC and CRT monitor in the room, were benzene, benzoic acid, bethylcyclopentane, bonanal and siloxane D3. The concentration of majority of these compounds was lower than 3 µg/m^3 in toluene equivalents. The most probable compound from the computer set is siloxane D3, which is a common compound in plastic materials[178]. The other named compounds are most probably originating from outdoor air.

At test condition 4, with the new PC and LCD monitor in the room, the compounds with highest concentration were benzene, cyclohexane, siloxane D3, benzoic acid, ethyl acetate. The concentration of these compounds was between 3 µg/m^3 and 7 µg/m^3 in toluene equivalents. The concentration of toluene was 1.7 µg/m^3. Toluene is also one of the compounds that can be associated with the computer set[51]. However, it can also originate from outdoors[57].

3.8.2.3 Relative sensitivity to linoleum floor and cleaning agent

A somewhat higher relative sensitivity of mixed-gas sensors was indicated after placing the linoleum floor to the test room. Sensor module *S16* showed higher relative sensitivity to the new linoleum floor than sensor module *S15.* A change in output for about 8 % and 10 % was observed for the sensors *S15* and *S8*, while for sensor *S16* this change was more than 50 %. The output of sensor *S18* changed about 30 % after installing the linoleum floor.

The linoleum floor was kept in the room for 4 days before the test with the cleaning agent was initiated. During this time, the pollutant emissions had already decreased some extent. The average sensor output measured after 4 days of exposure was similar to the conditions before the linoleum installation, except for the sensor module *S16.*

After the cleaning procedure was started in the room the sensors output increased considerably. However, it can be difficult to evaluate the effect of pollutant emissions from linoleum surface and cleaning agent. The increase in sensors response is also influenced by the increase in humidity conditions and due to the presence of a person in the room during the cleaning. The absolute humidity in the room changed about 15 % compared to the initial conditions before washing. A peak sensor response was evaluated as 5-minute period average after the cleaning process was finished and the room door closed. Based on the peak response the output of sensors *S15* and *S8* changed about 17 % and 14 % respectively, compared to the sensors' output before the cleaning procedure was initiated. For the sensor *S16* this change was about 60 % and for the sensors *S18* and *S18A* about 65 %. Additional evaluation was done with the values collected 3.5 hours after the cleaning procedure. Only 1 % change in output from the conditions before the cleaning was observed for the sensor *S8* and about 7% to 8 % change for sensors *S18* and *S18A*.

The results from the Tenax tests, which were sampled 20 min after the cleaning was finished, showed that the $TVOC_{GC}$ concentration in the room was about 300 µg/m^3. The individual compounds with the highest concentrations identified were 1-methoxy-2-propanol, triethylamine, 2-ethoxyethoxyethanol, n-methyl-2-pyrrolidinone, hexanoic acid, 2-ethylhexanol, cyclohexane, ethyl acetate, diethylaminoethanol, butyric acid, methoxypropoxypropanol and heptanoic acid. The concentration of the first compound was about 115 µg/m^3 in toluene equivalents, the concentrations for triethylamine, 2-ethoxyethoxyethanol, n-methyl-2-pyrrolidinone were between 15 µg/m^3 and 34 µg/m^3 in toluene equivalents. The concentrations for the rest of the named compounds were below 8 µg/m^3. The concentration of toluene was 1.8 µg/m^3. The VOCs such as trietylamine, 1-methoxy-2-propanol, 2-ethoxyethoxyethanol and methoxypropoxypropanol can be associated with the linoleum floor polish[155, 178, 233]. Additionally, toluene has been found in cleaning agents and polishes[221, 233]. However, the toluene concentration indoors was also influenced by the outdoor air in the current test. The VOCs such as hexanoic acid, butyric acid and heptanoic acid can be associated with the linoleum floor[128, 178].

In parallel of the Tenax sampling in the room, also the VOC concentrations in the supply air were measured with Tenax sampling. The $TVOC_{GC}$ concentration in the supply air was about 60 µg/m^3. The individual compounds with the highest concentration were benzene, benzoic acid, ethyl acetate, methylcyclopentane, benzaldehyde and toluene. The concentrations for the majority of these compounds were less than 3 µg/m^3 in toluene equivalents.

3.8.2.4 Relative sensitivity to combined emission sources: linoleum floor, furniture, office equipment and 1 person

In the first stage of the Test 6 all of the previously tested emission sources were placed in the room together. The change in sensor output after 4-hours of measurement was about 6 % and 7 % for sensors *S8* and *S15.* This change was about 15 % and 22 % for sensors *S18* and *S18A,* compared to the initial value. After 11-hours of measurement the change in sensor output was less than 5 % for sensors *S15* and *S8* and less than 6 % for sensors *S18A* and *S18B*. Sensor *S16* showed in both cases about 50 % change in the output signal.

Considerably higher sensitivity of the test sensors was observed for the presence of one person in the test room. After a steady-state concentration of pollutants was observed in the room with the presence of one person, the output of the sensor *S8* showed about 56 % change from the initial value, while for sensor module *S15* this change was only 20%. This can be explained with the combined response of the CO$_2$ and VOC sensors inside this sensor module. The sensor *S8* incorporates both carbon dioxide measurement and VOC measurement. The signals from the two sensing elements are compared and weighted and a common signal is sent to the airflow controller. The sensor module *S16* showed bigger change in output in this test than sensor *S15.*

The output signal of the sensors *S18* and *S18A* changed more than 100 % compared to the initial condition. The measured CO$_2$ concentration in the test room at steady-state conditions was about 1000 ppm, according to the test sensor *S3*. The evaluated carbon dioxide equivalent level with sensors *S18* and *S18A* was about 800 ppm.

The results from the Tenax sampling at Test 6, which was performed about 4.5 hours after the person entered the room, indicated the TVOC$_{GC}$ concentration of about 140 g/m^3. The individual compounds with the highest concentrations identified in the room air were hexanoic acid, cyclohexane, benzaldehyde, hexanal, n-methyl-2-pyrrolidinone, nonanal, cyclodecane, d-limonene. The concentrations for all of these compounds were between 3 µg/m^3 and 8 µg/m^3 in toluene equivalents. The possible sources for these compounds have been discussed before. The detected VOC d-limonene can be associated with the presence of a person. Although the person in the room did not have any perfumes or deodorants with perfume on herself, the clothing and other personal care products may have given some effect. It should be noted that no acetone or isoprene compounds were identified in the room air. This can be influenced by the VOC sampling and analysis method applied[178]. Acetone and isoprene are the most common VOCs associated with the bio-effluents emitted from people[169].

Additionally the VOCs in the supply air were sampled with Tenax tubes during the current test condition. The TVOC$_{GC}$ concentration in the supply air was about 40 µg/m^3. The individual compounds with the highest concentration were cyclohexane, ethyl acetate, methylcyclopentane, toluene and benzaldehyde. The concentrations of all of these compounds were lower than 5 µg/m^3 in toluene equivalents.

3.8.3 Discussion

The results of this study provide information about the performance of some mixed-gas sensors tested in a controlled environment with a limited number of pollutant emission sources. Setting requirements on the relative sensitivity of mixed-gas sensors and on their operating range can be rather a challenging task. This is because the odour threshold levels for different pollutants are still not clearly specified. Furthermore, it is difficult to determine and evaluate which VOCs are representative for different processes in the room and which are important to control with demand controlled ventilation.

It is generally considered that building products and furniture emit pollutants that may influence the perceived indoor air quality[221, 227]. In a new or renovated building primary emissions of VOCs from building products generally dominate for a period of up to some months[232]. After the initial decay period, secondary emissions may arise, which may alter the intensity and perception of the emission on a long-term basis[129, 227]. Still, these emissions will become relatively constant in time. Therefore, controlling these emissions with sensor methods is not considered as efficient. When new equipment and furniture is bought it can be advantageous to have higher base ventilation rates rather than sensor control. From this study it was shown that the tested commercial mixed-gas sensors have very low relative sensitivity to office furniture or linoleum floor. This is advantageous for their application for activity related demand controlled ventilation.

Demand controlled ventilation aims to control the time varying loads in the room. It is a great interest to manage hygienic ventilation rates based on the processes in the room. In this study the sensitivity of commercial mixed-gas sensors towards office equipment and cleaning procedure was tested as an example. Previous studies with office equipment showed that the VOCs identified were insufficient in concentration to explain negative effects on humans during exposure[17, 133]. This suggests that other chemicals may contribute to the negative sensory perception. It was of interest to see if the mixed-gas sensors show any relative sensitivity towards pollutant emissions from computers and monitors. However, as expected due to the low emission rates from these sources, the effect on mixed-gas sensors response was too small to be experimentally certified. A slight change in sensors output was observed, which may have also been influenced by the humidity conditions in the room and by the supply air conditions.

Somewhat higher relative sensitivity of mixed-gas sensors was observed with the cleaning procedure. One of the six tested mixed-gas sensor showed about 14 % change in output, while the two other sensors had higher relative sensitivity. This could have been influenced by the elevated humidity levels in the room during and after the cleaning procedure as well as by the presence of a person. Some of the tested mixed-gas sensors are designed to be especially sensitive to the presence of people. Nevertheless, it is advantageous that the mixed-gas sensors respond to the cleaning processes in the room. During the cleaning process several primary and secondary air pollutants are emitted to the air which can have an impact on human health[155]. The emissions depend on several factors, e.g. on product composition and the concentration of the volatile constituent in the cleaning product. Only one type of multi-purpose cleaning product was tested in this study and therefore the conclusions can be rather limited. More detailed research on this subject can be useful in order to set further requirements on the mixed-gas sensors performance characteristics.

Mixed-gas sensors relative sensitivity to people was clearly indicated in the last tests with all the pollution sources, e.g. furniture, linoleum floor, PC with LCD monitor, and one person in the room. After the room CO_2 concentration increased up to about 1000 ppm, the test sensors showed more than 50 % change in their output. For the combined mixed-gas/CO_2-sensor *S8* it can be assumed that the CO_2 measurement signal will take precedence in the sensor system with the presence of people.

When comparing the basic sensing elements, represented by the sensor modules *S15* and *S16,* it can be clearly indicated from the tests that sensor *S16* is more sensitive to the different pollutant emission sources tested than sensor *S15*. The sensor module *S16* showed more than 50 % change in output signal at the presence of furniture and linoleum floor. Lower sensitivity was indicated towards PC and monitors.

Due to the low concentrations of VOCs in the test room during different tests, no change in response was indicated for sensor *S17*. This sensor continuously showed 0 ppm at all times.

3.8.4 Conclusion

This study aimed to analyse the relative sensitivity of mixed-gas sensors to different pollutant sources that can occur in indoor environments. The tests were carried out in a controlled environment with low pollutant emissions in the background and the supply air. This study was limited to a fixed number of emission sources, e.g. new office furniture, office equipment, linoleum floor, cleaning procedure and occupancy. However, these sources do not refer to the intended application of the mixed-gas sensors. The application of mixed-gas sensors can be wide ranging and depends on the purpose and the use of the premises where demand controlled ventilation is required. Furthermore, the mixed-gas sensors should be applied for control of indoor air quality in premises where people are not the primary source of pollutants.

The choice of emission sources for testing was influenced by practical considerations and the simplicity of the test procedures with these sources. It was also of interest to find out how the mixed-gas sensors would respond to the pollutant emission sources that can be considered to be relatively constant in time, e.g. building materials and furniture. From the current study, the following can be concluded:

- The majority of the tested mixed-gas sensors show negligible relative sensitivity towards the tested office furniture and very low relative sensitivity to polished new linoleum floor. This is advantageous for their application for demand controlled ventilation.

- The results showed that controlling the indoor air quality based on processes in the room, such as use of office equipment and cleaning, can be difficult with these types of mixed-gas sensors. Very small change in sensor response was indicated in tests with the office equipment. This can be due to the very low emissions from these sources. Somewhat higher sensitivity was observed towards cleaning of the linoleum floor. However, the change in sensor output could have been influenced by the increased humidity levels during the cleaning procedure as well as the presence of a person in the room.

- The majority of the tested sensors showed sensitivity to the presence of a person in the test room. One of the tested sensors incorporates both CO_2 measurement and VOC measurement. This can explain the change in the sensors output at the presence of people. Two of the other mixed-gas sensors are designed to be especially sensitive to the presence of people.

3.9 Performance of the CO_2-sensors and mixed-gas sensors in the field

The purpose of this study was to evaluate the performance of commercial mixed-gas and CO_2-sensors in the field. A study has been conducted in a meeting room in an existing building operating with a DCV system. A number of tests were carried out with the test sensors under different load conditions. Additionally, the performance all of the existing CO_2-sensors in the building was evaluated in terms of long-term stability.

This chapter describes the summary of the methodology used and results obtained. Additionally, discussion and conclusions are presented. More detailed description of the experimental methodology, including description of the reference instruments, is presented in APPENDIX B. More detailed information about the sensors output at different tests can be found from Maripuu[142].

3.9.1 Experimental methodology

3.9.1.1 The test set-up and measurement techniques

The tests were carried out in a meeting room located in an existing building in Denmark. The room is designed for maximum of 8 persons. The dimensions of the meeting room are: length 4.5 m, width 3.5 m and height 2.6 m, which give a volume of 40.95 m^3 and 15.75 m^2 of floor area. The test room has big windows on the walls facing north-west.

The ventilation system connected to the test room is based on a DCV system, where 100 % outdoor air is supplied to the room with a pressure dependent VAV diffuser in the ceiling. The designed airflow rate to the meeting room is in the range of 20 l/s to 70 l/s. The airflow rate is controlled by means of a combined CO_2/temperature sensor with a built-in controller. The sensor measures the CO_2 concentration and temperature and the highest output from the two measurements is set as a ventilation demand signal for the regulating damper in the VAV supply air diffuser. The set points set of the sensor are: minimum opening for the damper 400 ppm of CO_2 or +20 ˚C and maximum opening for the damper 1000 ppm of CO_2 or +24 ˚C. The built-in controller works as a P-controller. The existing CO_2/temperature sensor is similar to the sensors *S1* and *S3* tested in this study, except that the test sensors have no controller functions.

Some tests were also carried out under constant supply airflow conditions. The airflow rates were set constant by sending a constant input signal to the regulating damper in the VAV supply air diffuser from the voltmeter.

Following sensors were tested in the field, based on the list in Table 3.1, chapter 3.5.3: *S1, S1A, S1B, S1D, S2A, S3, S5, S6, S8, S8A, S11, S11A* and *S18.* All together thirteen air quality sensors were tested, including eight CO_2-sensors, one mixed-gas sensor and four combined mixed-gas/CO_2-sensors. The test sensors were placed to the various points in the room and to the exhaust air duct and connected to a logger located outside the meeting room. Additionally, temperature, relative humidity and CO_2 concentration were measured with reference instruments at the same locations as the test sensors as well as outdoors. The reference instruments used for CO_2 measurements work with a similar technology principle as sensors *S1* and *S3.* Figure

3.16 shows the layout of the test room and scheme of the placement of the test sensors, marked with numbers.

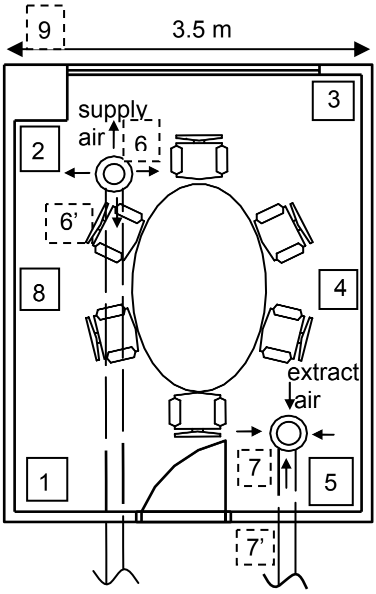

Figure 3.16 Schematic of the meeting room and the location of the sensors, marked with numbers. Points 1 to 5 and 8 were located in the room, points 6 and 7 in the duct or in the supply/exhaust air device. Measurement point 9 locates outside.

The tested CO_2-sensors and the reference instruments were checked with special zero-gas equipment before and after the test period. The results have been corrected if a baseline offset was observed. The checking of combined mixed-gas/CO_2 sensors in the field is much more complicated, since the sensor provides the output as a weighted signal from the CO_2 and VOC measurements. The baseline checking of a CO_2-measurement would not give any useful information, since it is not known which signal will take precedence in the sensor system at a given time. The outputs of these sensors were checked by exposing the sensors to the same ambient conditions. The results of this procedure showed that the sensors perform in a similar way.

At a selected room point close to the seating area, marked as room point 8, in Figure 3.16, thermal comfort parameters were monitored for determining draught rating. In addition, the concentration of ultrafine particles was measured both in the meeting room and outdoors. The supply and exhaust airflow rates were measured and logged continuously. Tracer gas measurements were carried out in the test room in order to determine the air mixing and air change rate in the room.

During the different test conditions, the main heat source in the meeting room was the presence of people and a laptop that was used for logging the data from some of the test sensors. In one test condition a person present in the room also used a laptop for his work. No lighting was switched on and the solar heat gains can be considered as minimal due to the window orientation towards north-west. The tests were carried out during a period of one week in the summer time, at the end of June.

The meeting room door was kept closed at all times when a test was carried out in the room.

3.9.1.2 Sensor performance tests in the field

In this study the output of the test sensors was observed under various load conditions and at different airflow conditions. This included a number of people in the room having a meeting, while the supply airflow rates were controlled with the sensor or set constant. The list of conducted tests is given in Table 3.22.

Table 3.22 The performed test conditions in the meeting room for the sensor performance tests in the field

Test no.	No. of people in the room	Measurement period (min) 1)	Airflow conditions	Supply airflow rate (l/s)	Airflow rate per person (l/s) 2)
1	3	60	DCV control	33	11.0
2	6	50	DCV control	34	6.0
3	6	70	constant airflow	21	3.5
4	2	60	constant airflow	21	10.5
5	5	30	constant airflow	21	4.0
6	3	70	DCV control	24	8.0
7	2	35	DCV control	24	12.0

Note 1: The measurement period correspond to the period of the meeting in the room. The meeting times at different test conditions commonly varied from half an hour to one hour.
Note 2: The airflow rate per person have been evaluated from the measured results at different test conditions and are based on the supply airflow rates (100 % outdoor air)

From the different tests the performance of the test sensors and the importance of the sensor location were studied. Additionally, the sensor output in relation to the perception of indoor air quality by room occupants was evaluated. The perception of room users towards the indoor climate was ascertained by means of a questionnaire, which was distributed to the room occupants after every test. The people were asked to evaluate their perception of different indoor climate parameters on a seven-point judgement scale. In the case of temperature, air movement and air humidity, the values 1 and 7 corresponded to extreme situations and 4 was assigned to “neutral”, which can be considered as an ideal case. The perception of air quality was judged on a scale from 1 to 7, with the ideal point of 7. Different people participated in the different tests. The questionnaire used in this study is given in APPENDIX D.

The performance of the existing DCV sensors in the case study building was evaluated in terms of their long-term stability. All together, there are thirteen combined CO_2/temperature sensors, which have been in operation for about five years. Only the performance of the CO_2-measurement of these sensors was assessed. A baseline checking with the zero-gas calibration equipment was carried out. The existing sensors are similar to the test sensors *S1* and *S3.* They include automatic baseline correction for drift compensation. There is no recorded data about the performance of these sensors at the time of installation. It is assumed that any occurring baseline drift indicated in this study has occurred during the five year period of time.

3.9.2 Results and discussion

The analysis of the results from the field test have been carried out by using the test condition 2, described in Table 3.22, as an example. However, comments about the results from other tests conditions are also given.

3.9.2.1 Output of the test sensors

According to the results, the test sensors show a distinct and good correlation to the presence of people in the room. As an example, the output of the test sensors and reference CO_2- sensors at the test condition 2 are presented in Figures 3.17 and 3.18. A scheme of the measurement points in the room and a seating plan of the persons are also shown in the figures. The meeting in the room lasted about 1 hour and six people were present in the room.

As can be seen from the Figure 3.18 the output of the tested CO_2-sensors increased from about 400 ppm to 1000 ppm in approximately 20 minutes after the meeting started. For combined mixed-gas/CO_2 sensors *S8, S8A, S11* and *S11A* this change was from 30 % to about 50 % in indoor air quality ratings. These sensors have an operating range of 0-100 % in indoor air quality ratings and it is assumed that that the higher values in indoor air quality ratings correspond to more polluted air.

The change in the airflow rates at test condition 2 is presented in Figure 3.19. The supply airflow rate increased from 23 l/s to about 34 l/s. Nevertheless, the change in supply airflow rate was indicated already 10 minutes before the room was occupied, as can be seen in Figure 3.19. The possible reasons for this are discussed further on.

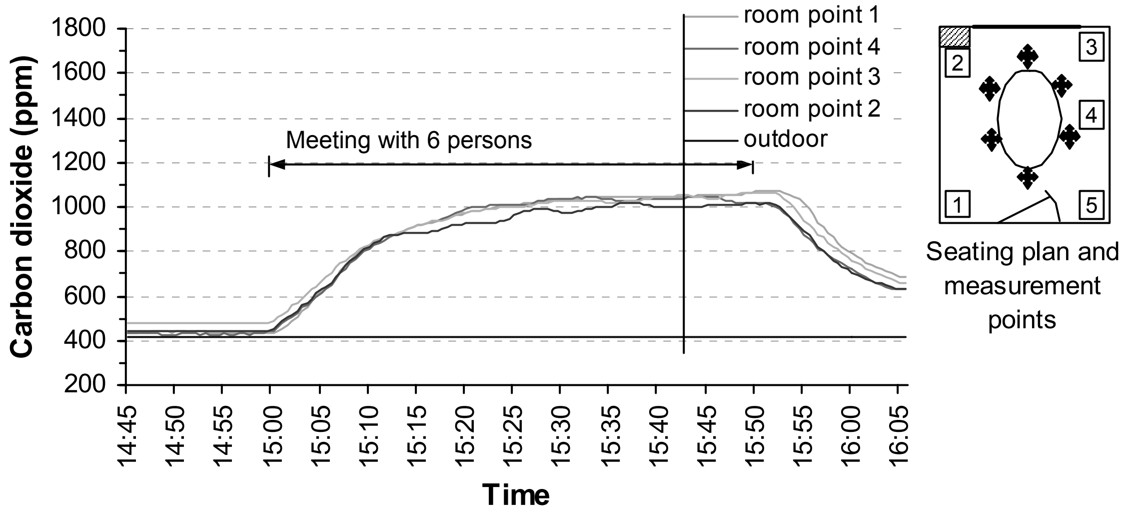

Figure 3.17 The output of the reference CO_2-sensors at test condition 2: meeting with 6 persons. The list of room points are presented according to the output lines on the diagram from maximum to minimum

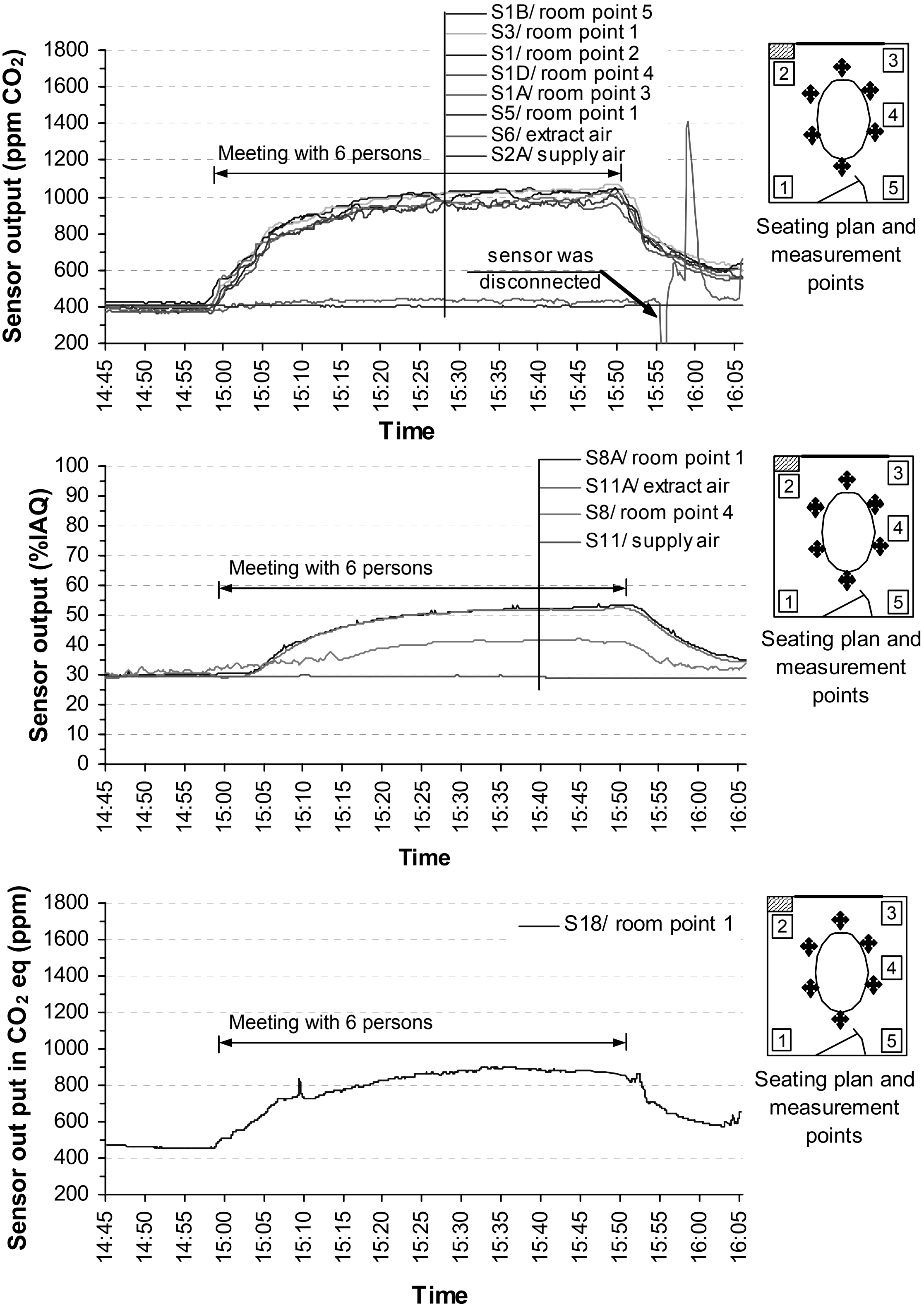

Figure 3.18 Output of the tested indoor air quality sensors at test condition 2: meeting with 6 persons. The list of sensors and room points are presented according to the output lines on the diagram at the given cross section from the maximum to minimum. The seating plan and measurement points correspond to the location of the sensors in the room and the location of the people in the room (marked with crosses).

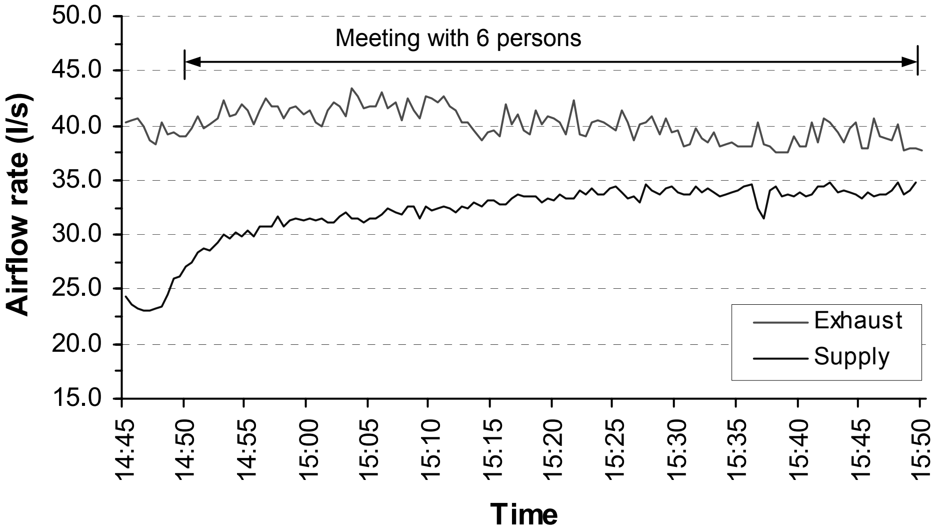

Figure 3.19 The variation of airflow rates in the test room at test condition 2. The supply airflow rate is controlled with a VAV supply air diffuser and the exhaust airflow rate controlled with central fan system according to the pressure sensor in the supply air duct.

The mixed-gas sensor *S18* showed relatively good correlation with the CO_2-sensors output at the different test conditions. At test 2 the output of the sensor *S18* was changing from 450 ppm to 900 ppm in CO_2 equivalents, while the CO_2-sensor values ranged from 400 ppm to 1000 ppm. However, some difference, up to 200 ppm in CO_2 equivalents, remained between the two different sensor technologies at all tests. In the majority of the measured test conditions the sensor *S18* showed somewhat lower values than the CO_2-sensors. Only at test 5 was the output of the sensor *S18* higher than that of the reference CO_2-sensors output.

The CO_2-sensor *S6* located in the exhaust air duct showed unreasonably low values compared to the room conditions over the entire measurement period. It was first suspected that leakage from the surroundings influenced the performance of this sensor, since it was located in the duct just outside the test room. The sensor was disconnected from the logging system for inspection and the sensor housing was carefully sealed. Very slight improvement was observed in the performance. Still, the concentrations measured with this sensor did not exceed 600 ppm with the concentration higher than 1000 ppm in the room. After finishing the test program the duct sensor *S6* was sent to the manufacturer for inspection. The manufacturer stated that no malfunctioning was observed and that the duct leakage is more probable cause for the strange behaviour that occurred in the tests. Unfortunately it was not possible to evaluate the possible duct leakage in these tests.

The performance of the test sensors have been analysed in more detail in terms of response times with the test condition 2. Figure 3.20 provides a comparison between mixed-gas sensors and one CO_2-sensor. It can be seen that the output of the sensors *S3* and *S18* started to increase immediately after 6 persons entered the room and the meeting started. About 5 minutes has passed till a change in output is observed for sensor *S8A*. Similar observation can be done also from other test conditions. The figure also shows that there is no lag time between the wall sensor *S8A* and the duct sensor in the extract air side *S11A*. Earlier studies have reported that wall mounted sensors had a delay time compared to sensors in the extract air duct[179].

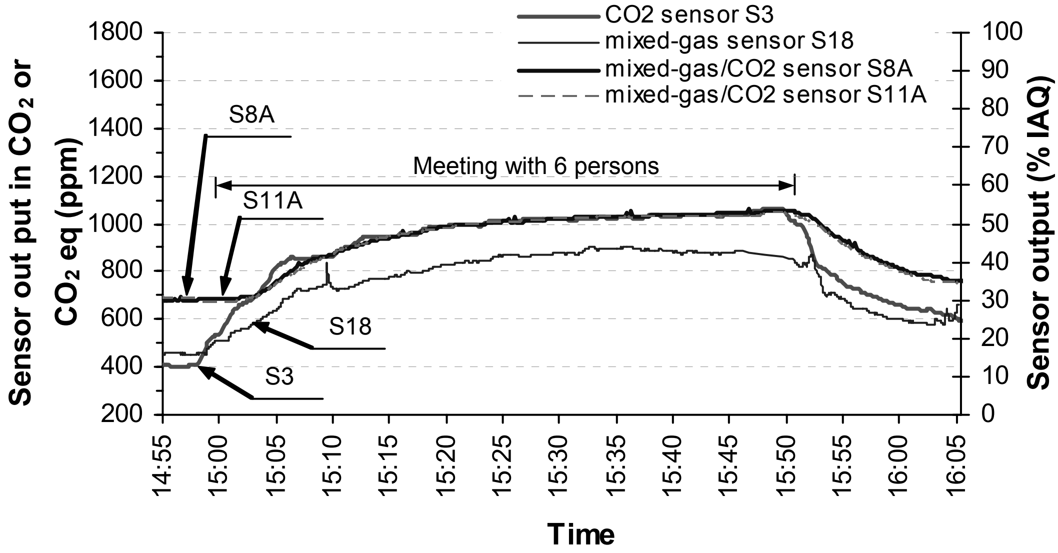

Figure 3.20 Comparison of CO_2-sensor's and mixed-gas sensors response measured at room point 1 (*S3, S8A, A18)* and in the exhaust air duct (*S11A)* at test condition 2: meeting with 6 persons.

3.9.2.2 Sensor location

The location of the controlling sensor is not so crucial when mixing ventilation is applied and if good mixing is assured. The results from the tracer gas tests indicated good air mixing in the test room. However, the results presented in the Figure 3.18 show some deviations between the sensors at different room points. For example, the lowest sensor output was indicated at measurement locations 2 and 4 and highest sensor output occurred at room point 1. Comparison with the results measured by the reference CO_2-sensors, shown in Figure 3.17, reveals that the lowest concentrations occurred at room point 2 and all other room points had similar but higher concentrations. Differences in the sensors outputs at various room points were also observed at other test conditions and often the lowest output was measured at room point 4. Nevertheless, also other situations occurred and therefore it can not be concluded that the variations followed similar pattern.

Figure 3.21 compares the highest differences that occurred between the different room points measured with the tested CO_2-sensors and reference instruments at test condition 2. The figure also presents the evaluated uncertainties for the differences, calculated according to the sensor uncertainties specified by the manufacturer. As can be seen from the Figure 3.21, the observed differences between the sensor outputs at various measurement locations are within the uncertainty of the CO_2-sensors. Somewhat higher differences that can not be related to sensor uncertainty occurred at certain time periods during the test, e.g. at the beginning and at the end of the meeting in the test room.

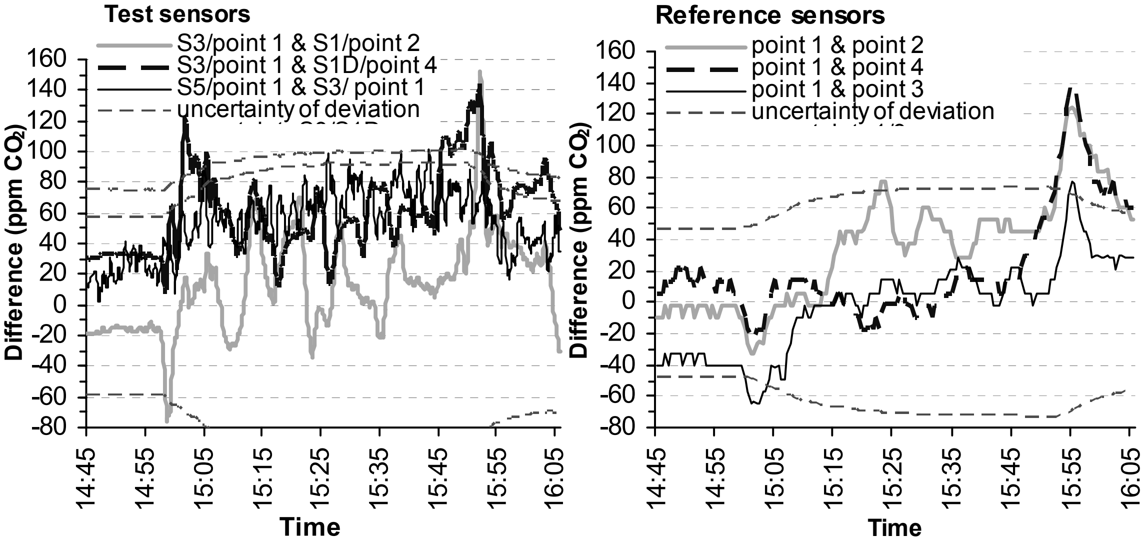

Figure 3.21 Differences between the CO_2 concentrations at different room locations measured with the test sensors and reference instruments at test condition 2: meeting with 6 persons. The evaluated uncertainties for the differences are also given in the diagrams, calculated according to the sensor uncertainties specified by the manufacturer (see Table 3.1).

The variations in the sensors output may have occurred due to specifics of the test conditions, e.g. the location of the people in the test room in relation to the sensor positions and location of the supply and exhaust air devices. According to recommendations the placement of the sensor in the room should be as near as possible to the occupied zone. Installations in the corners in the room, close to doorways and open windows, areas that receive direct sun light or are influenced by the supply/exhaust air streams and areas that are directly affected by indoor pollutant sources, e.g. breathing zone, should be avoided[12, 80, 187, 188]. All of these recommendations were followed when reference points were selected.

Even though most differences between the CO_2-sensors in the various measurement positions with test condition 2 were within the sensor uncertainties, the occurring deviations were rather big. The differences between the sensor readings can be influenced by the calibration errors and technology specifics of the sensors. The baseline of the tested CO_2-sensors was checked with zero gas calibration equipment before and after the study period. Some differences were observed between the two tests and the presented results are corrected based on the calibration data closest in time to the measurement date. Nevertheless, some uncertainty may be introduced to the results with this procedure.

The reference CO_2 instruments were checked only after all of the tests were finished. Since the CO_2 instruments incorporate automatic baseline correction, the baseline offset may have been different at the first test conditions.

The performance evaluation of combined mixed-gas/CO_2-sensors in the field is much more complicated. This is because the sensor provides the output as a weighted signal from the CO_2 and VOC signal. The baseline checking of CO_2-measurement would not give useful information, since it is not known which signal will take precedence in the sensor system at a given time. The output of these sensors was checked at same background conditions, which showed that the sensors perform in a similar way. However, this method for performance checking of these sensors may not be reliable enough.

When comparing the sensors output measured in the room and in the exhaust air duct similarities can be observed between the combined mixed-gas/CO_2-sensors. The output of the combined mixed-gas/CO_2-sensor *S11* coincided well with the similar sensor in the room, *S8A*, as can be seen in Figure 3.18. Unfortunately, no conclusion can be made from the results with the CO_2-sensors in the room and in the duct. As was discussed before, the duct sensor *S6* did not show any reasonable value during all of the tests. According to the manufacturer the possible reason could have been duct leakage. Unfortunately the CO_2 concentrations at the same location as the test sensor *S6* were not measured in order to confirm this fact.

The variations in the supply air conditions have also been studied in detail. During the day time at working hours between 8:00 till 18:00 the supply air/outdoor conditions remained relatively stable, as can be seen in Table 3.23. On the other hand, some differences can be seen in the average supply air conditions between the different days.

Table 3.23 The conditions of the supply air during the working hours measured with the test sensors *S2A* and *S11*

Measurement period	**Sensor S2A (ppm CO_2)**				**Sensor S11 (% IAQ)**			
	mean	**max**	**min**	**stdev**	**mean**	**max**	**min**	**stdev**
25 June 8:00-17:00	412	428	398	8	28.9	30.1	28.2	0.4
26 June 8:00-17:00	387	398	378	5	28.8	30.7	26.8	1.3
27 June 8:00-12:00	386	394	378	4	30.2	31.6	29.8	0.2

The results from this study will raise a question if it is really needed to have a continuous measurement of supply air conditions to control indoor air quality in the room with a DCV system. Installing additional sensors to the DCV system has economical consequences and most probably will be carefully considered in the design process. As was discussed before, the requirement to measure supply air conditions is depending on the requirements set on a DCV system, e.g. control of minimum airflow rates, required set-point or CO_2 concentration difference.

In addition, despite that the supply air conditions measured with the combined mixed-gas/CO_2-sensors were relatively stable, this type of sensor should be also installed to the supply air duct. This because it is not known which signal will take precedence in the sensor system at a given time. The variations in concentrations of mixed-gases in the supply air are not stable and predictable. When only room conditions are measured with mixed-gas sensors situations may occur that supplying more air to the room worsens the indoor air quality.

It must be also noted that the measurement period of supply air/outdoor conditions in this study was rather limited. No other information about the outdoor conditions and its variations was found for the given location of the case study building in Denmark. The previous studies conducted in Gothenburg in 1996 showed pronounced variations of outdoor CO_2 concentrations with time, with day time averages between 348 and 416 ppm[60]. From 1996 till 2009 the atmospheric CO_2 concentrations have increased about 25 ppm[160]. Therefore, nowadays the levels of variations are somewhat higher in absolute terms. However, it can be assumed that the variation intervals in outdoor CO_2 concentrations are similar nowadays in the urban areas to the variations measured in 1996. Nevertheless, long-term evaluations should be carried out about the outdoor concentrations and their stability in the location of the building where the DCV system will be applied. This information is needed in order to evaluate the need to continuously measure the supply air conditions.

3.9.2.3 Comparison of sensor output and occupant perception on indoor climate

After each test condition in this study the perception of room users towards indoor climate was ascertained through a questionnaire. Table 3.24 gives an overview of the maximum sensor output monitored in the test room under different test conditions and the perception of indoor climate evaluated by the people. It must be noted that the different people participated in these tests.

The results presented in Table 3.24 clearly show that in the test conditions where the room condition indicated by the sensors was about 1000 ppm of CO_2 or 50 % in indoor air quality ratings and below, the air quality was evaluated to be as good or neither good nor bad. People perceived this as comfortable to slightly uncomfortable. Only one case occurred, at test condition 4, where the output of the test sensors was relatively low, but the perception towards indoor air quality was not perceived comfortable and window was opened to air the room. This was most probably due to effects from the previous test in the test room, test 3, where the concentrations increased to rather a high level. After the test 3 the window was opened to air the room before the next meeting, but it seems that it was not sufficient.

The comparison of sensors output and indoor climate evaluation does not intend to give any specific guidelines for the set points to be chosen for indoor air quality control with the specific sensors. For doing so, more tests and a trained test panel is needed. These tests aimed to give some overview of the performance of the indoor air quality sensors in the field and evaluate the sensor output in relation to the perception of indoor air quality by people present in the room.

Table 3.24 Comparison of indoor climate conditions measured by the indoor air quality sensors and perceived by the people in the room under different test conditions.

Test no	**No of people in the room**	**Indoor climate parameters measured by the sensors** [1)]					**Indoor climate evaluation by the people present in the room** [2)]
		S18 $\mathrm{ppm}_{\mathrm{CO2eq}}$	**S8A** % IAQ	**CO_2** ppm	**t_{room}** ˚C	**DR** % [1)]	
1	3	886	53	1054	24.0	<6.0	Temperature was close to neutral and air movement slightly low. Indoor air quality was good and comfortable
2	6	571	40	804	23.0	<4.6	Temperature and air movement were close to neutral and comfortable. Indoor air quality was good and comfortable
3	6	n/m [3)]	71	1507	24.1	n/m[3)]	Temperature was slightly warm and uncomfortable; air movement slightly low. Indoor air quality was bad and very uncomfortable. The air was reported to be stuffy and bad air was sensed in about 30 minutes after the meeting started.
4	2	n/m	30	610	23.3	n/m	Temperature was slightly warm and slightly uncomfortable; air movement slightly low. Indoor air quality was slightly bad and slightly uncomfortable due to smell of odour in the room. Window was opened 30 min after the meeting started.
5	5	1344	n/m	1095	23.5	n/m	Temperature was evaluated as neutral, but slightly uncomfortable; air movement low and uncomfortable. Indoor air quality was neither bad nor good and slightly uncomfortable. The air was reported to be stuffy by one of the persons.
6	3	682	42	863	22.2	<6.8	Temperature and air movement were close to neutral and comfortable. Indoor air quality was neither bad nor good and slightly uncomfortable. One person reported that air was stuffy.
7	2	626	40	828	22.2	<6.3	No questionnaire was filled in!

Note 1: The values of the different indoor climate parameters are 10 minute average values measured with the sensors at the end of the test period. CO_2 concentration and room temperature are measured with reference sensors located at room point 1; draft rating DR has been evaluated from the measurement with an indoor climate analyzer, located at room point 8. According to thermal comfort standard ISO 7730 [101] the DR values should be below 15 %.

Note 2: The evaluation is based on the mean values of the answers to the different questions on a seven or five point scale. All of the people in the room answered the questionnaire.

Note 3: n/m – not measured due to problems with the logging system.

3.9.2.4 Evaluation of the existing DCV system in the test room

The current DCV system in the meeting room is based on two indicators: temperature and CO_2. These two parameters are measured with a combined sensor unit, which has also a built-in controller. The output signals from the two measurements are compared in the sensor/controller unit and depending on the defined set point a common signal is sent to the VAV supply air diffuser. Figure 3.22 presents the temperature and CO_2 concentration values logged from the controlling sensor at test condition 2. Figure 3.23 gives the comparison between the common output signal from the controlling sensor sent to the VAV supply air diffuser and the changes in supply airflow rates at the same test condition.

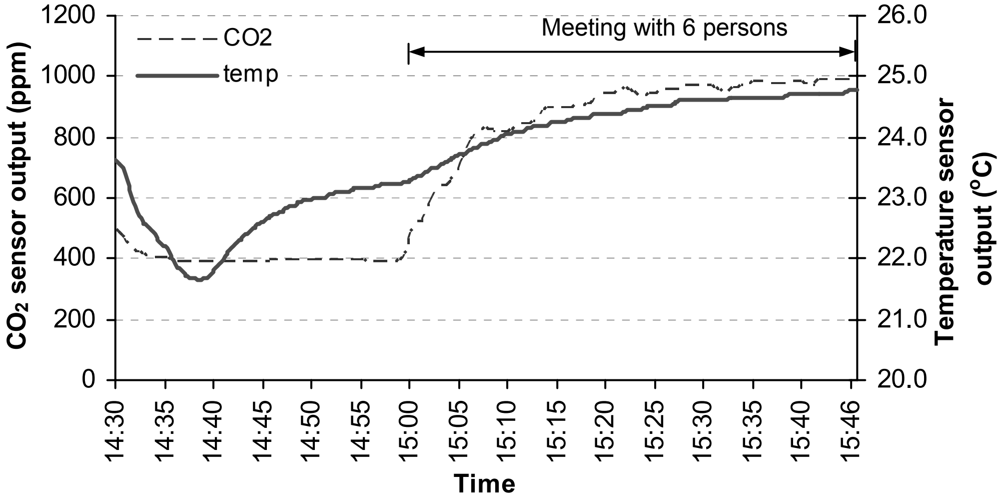

Figure 3.22 The output of the CO_2 and temperature measurement logged from the controlling sensor connected to the DCV system in the test room at test condition 2. The set point has been set at 1000 ppm and +24 °C. The supply air temperature is about +22 – 23 °C.

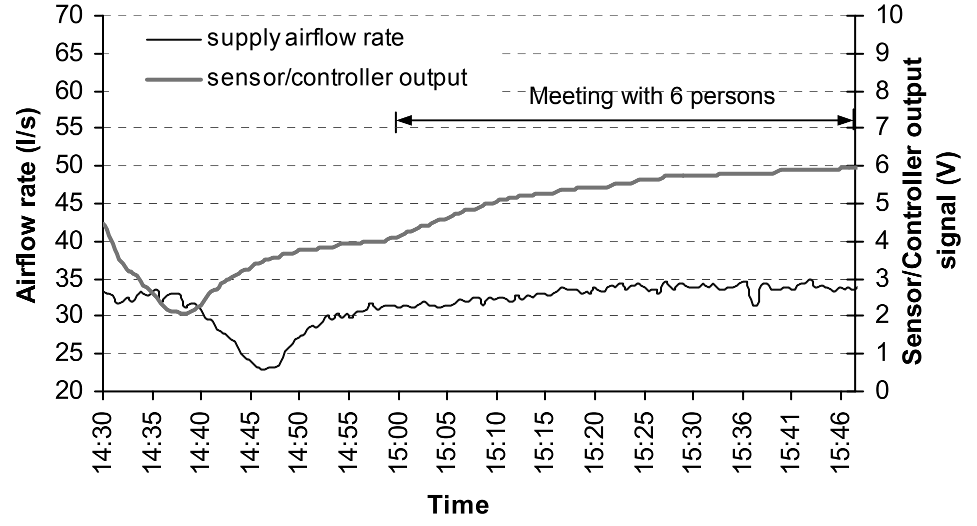

Figure 3.23 The variations in the supply airflow rate and in the common output signal from the controlling DCV sensor/controller that is sent to the VAV supply air diffuser in the test room at test condition 2. The designed supply airflow rate to the meeting room is between 20 and 70 l/s.

As it can be seen from the Figures 3.22 and 3.23, the supply airflow rates were controlled by the temperature change in the room under the described test condition. An increase in room temperature, as well as an increase in supply airflow rate, was observed already before the meeting started.

The increase in room temperature was influenced by supply air temperature, which was relatively high, around +22 – 23 °C. The reasons for high supply air temperatures were not investigated. It can be due to low occupancy level in other rooms at the times when testing was carried out. Low occupancy in rooms can lead to low airflow rates in the central ducts and loss in cooling capacity of the supply air, as was described in chapter 2.8.

It should be also noted that even though the room temperature was exceeding the higher set point value already 15 minutes after a meeting was started, the increase in supply airflow remained considerably stable after this time. The supply airflow rate did not exceed 35 l/s even though the occupancy of the room was in maximum. The average exhaust airflow rate was somewhat higher, about 40 l/s and it remained almost constant during the test period. The design airflow rate for the meeting room is 70 l/s. A similar observation can be made also from the results of other test conditions. The constant exhaust airflow rate can be due to the pressure control in the system and low occupancy of other rooms connected to the same DCV system. Nevertheless, the reasons for observed airflow variations have not been analysed in detail in the current study.

Control of airflow rates in the test room based on temperature was also observed at several other test conditions. However, in all of these cases high supply air temperatures were observed. With lower supply air temperatures the system would operate most probably according to the carbon dioxide measurement.

3.9.2.5 Evaluation of other indoor climate parameters measured in the meeting room

Carbon dioxide is commonly applied as an indicator for bio-effluents emitted from people, since the concentrations of CO_2 are predictable and easy to measure. The current sensor study has shown that also mixed-gas sensors can be applied to track the presence of people in the room. In this study also several other indoor climate parameters were monitored, e.g. temperature, relative humidity and concentrations of ultrafine particles. From these measurements, correlations to the different load conditions in the room can be evaluated. Figure 3.24 shows the variations of relative humidity and temperature in the test room under various test conditions at room point 1. In order to cancel out the impact of supply air conditions, the diagrams show the difference between the supply air and room air conditions.

It must be noted that in the current study the main heat source in the room was presence of people and one laptop. No lighting was switched on and the impact of solar radiation is considered to be minimal due to the window orientation.

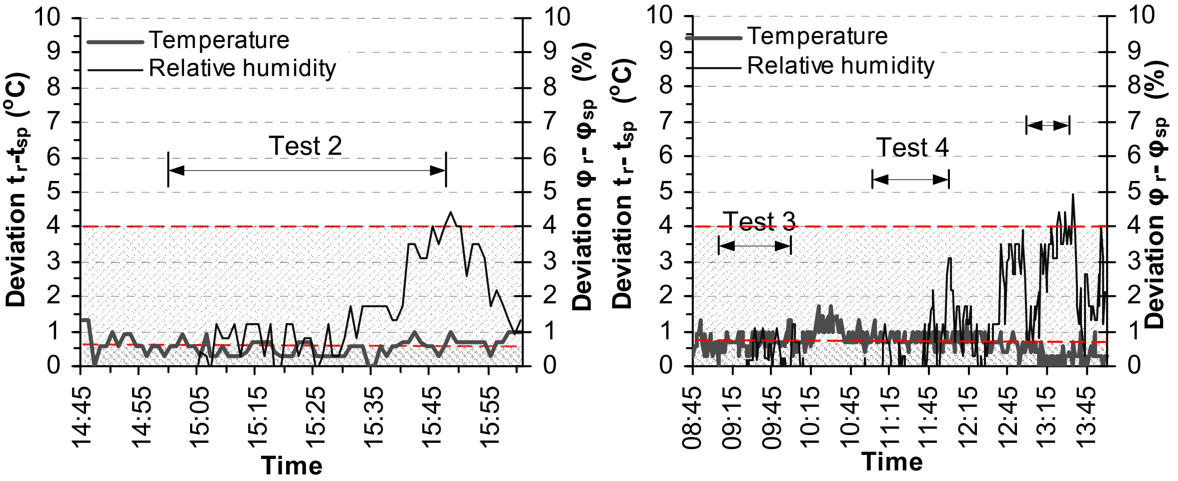

Figure 3.24 Variations in relative humidity and temperature in the room during different test conditions. The diagram shows the deviation from the supply air conditions. The shaded area marks the evaluated uncertainty for the deviation, which is ±0.5 ˚C for temperature measurement and ± 4 % r.h. for the relative humidity measurement.

As can be seen from the Figure 3.24, the changes in the temperature and relative humidity due to presence of people are small and remain mostly within the measurement uncertainties of the sensors.

Figure 3.25 presents the results of measured ultrafine particle concentrations in the room and outdoors at test condition 2. According to the results, the variations in concentrations of ultrafine particles do not show any correlation to the presence of people. The outdoor concentrations of particles fluctuated rapidly over the day. No rapid change in indoor particle levels was observed. Similar results have been reported also in one other study[144]. However, the load conditions in the room at the time of the measurement are not described in detail in the named report.

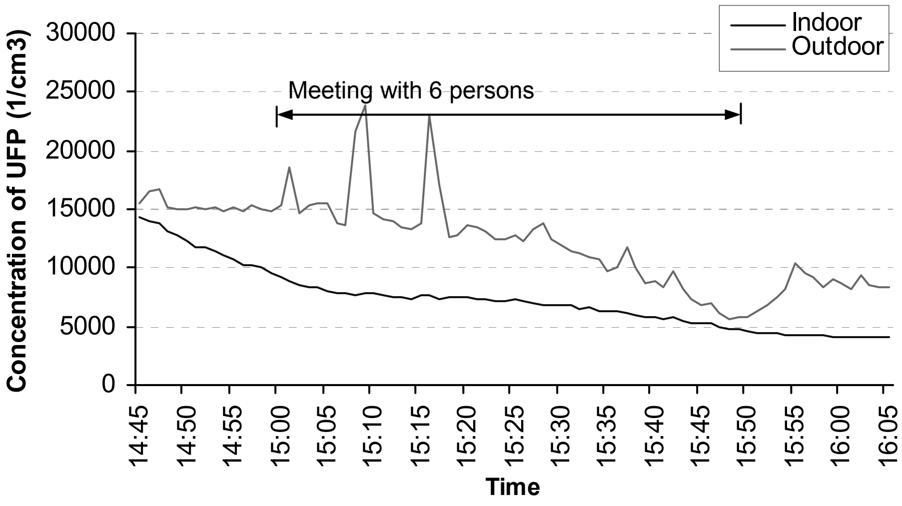

Figure 3.25 Measurement of ultrafine particles in the test room and outdoors at the test conditions 2: meeting with 6 persons

3.9.2.6 Evaluation of long-term stability of the CO_2-sensors in the existing DCV system

The long-term stability of the existing CO_2-sensors in the case study building was evaluated by carrying out a baseline checking with zero-gas calibration equipment. The results are presented in Figure 3.26. The figure gives the measured baseline offset compared to the data presented by the manufacturer.

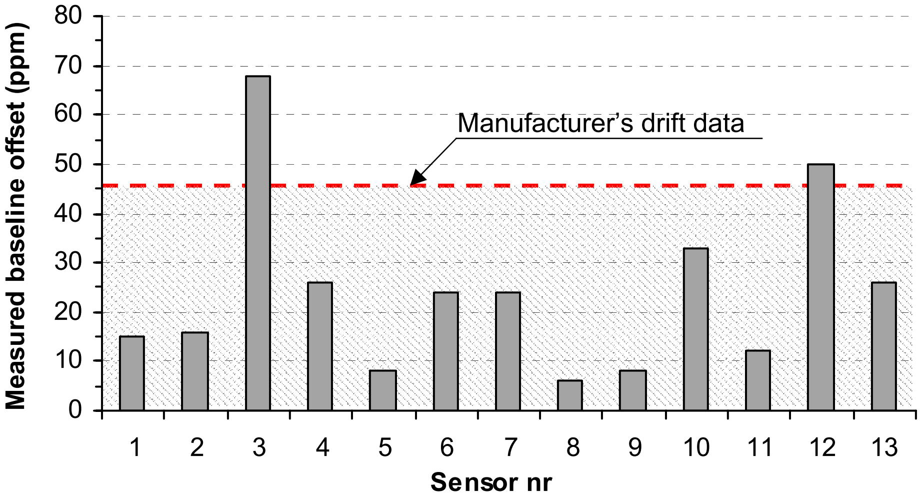

Figure 3.26 Measured baseline offset of the existing CO_2-sensors in the case study building. The baseline offset is associated with the drift in sensor output. The sensors have been in operation for about 5 years. The shaded area corresponds to manufacturers specified drift data, which is ≤± 45 ppm

The results show that the baseline offset that can be associated with the drift is less than 30 ppm for the majority of the existing CO_2- sensors. The average drift of the tested sensors was about 18 ppm. According to the manufacturer of these sensors the annual zero drift is expected to be ± 0.3 % of measurement range. This would correspond to ≤ ± 45 ppm for the tested sensors after five years of operation. Only two existing sensors showed higher offset than 45 ppm at 0 ppm of CO_2 concentration. The existing CO_2-sensors in the case study building are similar in type to the test sensors *S1* and *S3*. From the results with the existing sensors it can be concluded that this type of CO_2- sensors would have reasonable long-term stability and that the performance remains within the manufacturer specifications. Nevertheless, baseline adjustment after 5 years of operation would be recommended in order to keep the sensors within the required uncertainty.

3.9.3 Conclusions

The purpose of this study was to evaluate the performance of commercial mixed-gas and CO_2-sensors in the field. Tests with the selected sensors under different occupancy and airflow conditions were carried out. From the results, the following can be concluded:

- The tested CO_2-sensors, mixed-gas sensors and combined sensors of these two measurements show a distinct and good correlation to the presence of people in the room. A good correlation to CO_2-sensors output was observed from the mixed-gas sensor with the output in CO_2 equivalents.

- It is difficult to asses the most suitable location for the controlling sensor in the test room from the current study. More accurate calibration procedures for the gas sensors are needed for the test procedures. The test results show that the possible effect of duct leakage on sensor performance should be taken into account when duct placement is to be considered. The supply air conditions measured by the test sensors remained relatively stable during the test period. However, some difference occurred between the different measurement days. Furthermore, long-term evaluations should be carried out regarding the outdoor concentrations and their stability in order to evaluate the need for continuous measurement of the supply air conditions.

- The evaluation of the existing temperature/CO_2 controlled DCV system in the test room showed that despite the low internal heat gains in the room the existing system was controlled based on the temperature measurement than based on CO_2 concentrations. This was due to high supply air temperature.

- The variations in room temperature, relative humidity and concentration of ultrafine particles showed no correlation to the various load conditions in the room in different tests.

- The evaluation of long-term stability of the existing CO_2-sensors, similar to the sensors tested in the current test program, revealed that this type of CO_2-sensors would have reasonable long-term stability. The performance of the sensors after 5 years of operation remained within the manufacturer specifications. Nevertheless, baseline adjustment after 5 years of operation would be recommended in order to keep the sensors within the required uncertainty.

4 Occupancy in office buildings

For DCV application it is essential to have an overview of the expected load conditions and their profiles in the building. Commonly not all the rooms will be occupied at the same time. Moreover, the probability, that the peak level of occupancy in the building is the sum of all occupied rooms, is not very high. Therefore determining the actual occupancy pattern for DCV system design is in interest. The chapter describes a study on occupancy patterns in an office building. Field monitoring on occupancy conditions has been carried out in one office building for a period of one year.

4.1 Introduction

For the design of demand controlled ventilation systems it is required to know besides the expected occupancy in the building also the variations of the occupancy in time. The occupancy pattern and its profile in time influence the energy use of the system. Therefore in order to predict the possible energy savings and also to optimize the size of the system it is essential to know the average and peak occupancy factor. The occupancy factor, in some reports referred to as occupancy rate[14, 192], can be defined as the actual number of occupied rooms, divided by the total number of rooms[151]. Another report introduces a factor named “occupancy level” [111]. It is defined as the number of people that are in a building divided by the number of people that the building was designed for integrated over time and divided by the integration time.

According to the literature survey done, there are relatively few studies conducted on the actual occupancy patterns and their variations in commercial buildings. Additionally, there are very few guidelines and information about the occupancy factors to be used in the design of ventilation and air-conditioning systems. Specifying these factors can be rather challenging task, since the occupancy pattern is not only dependent on the type of building, but also on the kind of business in the building, e.g. in office buildings.

The Swedish old building code SBN 67[185] specifies the occupancy factor for office buildings for determining the outdoor airflow rates. The occupancy factor is 0.7, when the design occupancy in the building is more than 100 persons. For the design occupancy between 11 and 100 persons the occupancy factor is 0.8. For the design occupancy up to 10 people, occupancy factor 1.0 should be used.

ASHRAE/IESNA Standard 90.1-1989[14] also presents profiles for office occupancy. According to this document, the average occupancy rate is 0.76 with peak of 0.95 during weekdays between 8 a.m. and 5 p.m.

Keith and Krarti[192] reported average daytime occupancy rate in office rooms in an academic research facility to be 0.49, evaluated in the time period between 8:00 and 17:00 over a period of one month. The peak occupancy rate was 0.94 for a 10-room measurement and 0.77 for a 50-room measurement. The peak occupancy was defined as the maximum value of the quarter-hour averages during the month. A simplified prediction tool was developed to estimate peak occupancy rate in an office building from average occupancy rate and number of room within the building. A probabilistic model to predict and simulate occupancy in single person offices has been proposed also in another study[213].

Johansson[111] measured occupancy levels in three Swedish office buildings by using occupancy sensors located in cell office rooms. The studied office buildings consisted of a university building, a municipality building and an industrial office. As a result the overall average daytime occupancy level in an industrial office was 51.2 % for the daytime, ranging from 7.1 % to 88.1 %. For the university department the average occupancy level was 32.9 %, ranging from 25.8 % to 48.8 % and for the municipality planning office the average was 53.8 %, ranging from 25.08 % to 78.6 %. The specified daytime period was 8 a.m. to 6 p.m. from Monday to Friday. In this study the cellular offices were investigated without consideration of the number of people in the room. Additionally, only selected number of rooms from each building was monitored.

Halvarsson et al.[87] made similar studies in an Norwegian office building. The investigated building was a combined office and education building with two different organizations. The monitoring was done in 56 cellular offices and 2 meeting rooms during three and a half months of measurement period. All offices had an occupancy sensor installed to control the light and ventilation. The results showed the maximum occupancy factor to be 0.62 and 0.47 for the two organization office premises. In 90% of the time the occupancy factor was equal to or less than 0.35 and 0.23 respectively.

In a follow up study, carried out by Mathisen and Halvarsson[143], two more office buildings were monitored. The first building was an office building with different kind of businesses in the building. The monitoring carried out in 31 rooms showed that the maximum occupancy factor was 0.84 and average occupancy factor about 0.6 during the measurement period. In 90% of the time the occupancy factor was equal to or less than 0.65. The other building studied was a university building, where occupancy in 200 rooms was monitored. The evaluated maximum occupancy factor was about 0.3 and average occupancy factor about 0.2 during the measurement period. In 90% of the time the occupancy factor was equal to or less than 0.12.

Another study monitored occupancy in 27 different office rooms in 10 different French companies[23]. The monitoring was done with the occupancy sensors installed in each room during a two-week period of time. The results revealed the average occupancy rate in office rooms to be 40 % for the daytime, considered as 10 hours period in a day. The results from single rooms were ranging from 8 % to 70 %. The occupancy rate was also measured for 13 meeting rooms, where the number of people in the room was accounted for. The number of people in the room was evaluated by a webcam. During the daytime the occupied time was about 16 % in average. The average number of people divided by the designed number was 48 %.

Besides the studies in office buildings, few reports about monitored occupancy patterns can be found also for other building types. Von Neida et al.[235] and Maniccia et al.[140] monitored occupancy in different room types in a number of commercial buildings. The average percentage of time each room type was occupied has been presented. The day time average occupancy, measured between 6 a.m. to 6 p.m., was 40 % for break rooms, 26 % for class rooms, 20 % for conference rooms, 33 % for single person office cells and 33 % for restrooms.

Mysen et al.[151] studied occupancy density in Norwegian primary schools. The study relates the occupancy factor in schools to the occupancy in class rooms and evaluates the occupancy factor as the number of people present in the room divided by the number of pupils assigned to the class room. The average evaluated occupancy factor in all classrooms was 0.94.

Jagemar and Olsson[106] evaluated the use electricity in premises in three new office buildings. The results show that for one office building with occupancy controlled lighting the average use of lighting was 30 % - 50 % from the design lighting power density. The maximum was 70 % during the period of occupancy between 8:00 and 18:00.

From the reviewed studies it was observed that only few similarities can be found between the different occupancy studies. This is partly because there are some differences between the methods used in the studies and how the quantities describing the occupancy are defined. However, as mentioned before, the occupancy pattern and its variations in time are also in a large extent dependent on the kind of business in the building. More data on typical occupancy factors is needed to apply them in practice.

4.2 Aim and limitations of the occupancy study

According to the literature review carried out, more information is needed on occupancy patterns in commercial buildings in order to apply this data in the system design and energy use evaluations. The aim of this study was to contribute to the knowledge of occupancy patterns and its variations in office buildings.

Field monitoring on occupancy conditions has been carried out in an office building. The occupancy patterns were monitored in different types of rooms with occupancy sensors installed to the supply air devices. Additionally, the impact of the switch-off delay time of the occupancy sensors on the measured occupancy patterns has been evaluated.

However, due to the limitations in the technology of the occupancy sensors used it is possible to only determine whether a room is occupied or not. The sensors do not give any information about the number of people in the room. It is also not studied where people are when they are not in their rooms.

4.3 Monitoring occupancy in an existing office building

This chapter describes shortly the methodology used in the occupancy study and provides the results, discussion and conclusions of the study. More detailed description of the experimental methodology is presented in APPENDIX B.

4.3.1 Experimental methodology

The monitoring of occupancy patterns was carried out in a university administration building locating in Gothenburg. The same building was used in this case study as in the DCV system study, *Case study 2B,* described in chapter 2.7 and in APPENDIX B.1. The facility has 58 office rooms, 5 copy rooms, 5 meeting rooms, 5 break rooms, 3 rooms for archives and library and a few storage and equipment rooms. Some of the rooms have been rented out to other organizations than the university administration. However, their activities are related to administration in the research field.

The occupancy status in different rooms has been determined by occupancy sensors. Therefore, monitoring of occupancy was possible only in the rooms where the DCV diffusers are installed. All together there are 76 such rooms out of 83 rooms, excluding all corridor areas and toilets. The rooms without the DCV diffusers are the storage and equipment rooms, e.g. server rooms.

Due to the limitations in the technology of occupancy sensors used, it is possible to only determine whether a room is occupied or not. The sensors do not give any information about the number of people in the room. However, according to the room layouts and design, the office rooms are intended to have only one occupant. A few office rooms are bigger and have two occupants. The meeting rooms are designed for up to 10 people, depending on the room. The copy rooms and break rooms are used by the employees in the building.

The building has a central server for logging and online visualisation of the network of DCV supply air diffuser. For saving the data from the occupancy sensors the server connects to the DCV supply air devices and registers the instantaneous reading. Due to the load of the network and technical properties of the server it is not possible to connect to all of the devices in the building at the same time. The logging is set in a way that in about every 2 seconds the server connects to one device. After the data from all the devices is registered the logging starts again from the first device. All together there are 95 DCV diffusers in the case study building. The sampling interval is about 4 minutes and 20 seconds in the case study building. The registered data from the DCV diffusers contains each room's status as either "occupied" marked as "1" in the data or "unoccupied" corresponding to "0". Additionally, an associated time and date stamp of data registration is marked. An occupied event occurs when someone enters the empty room and the sensor detects motion. In total the collected data consisted of 10 million events about the occupancy condition, considering all the rooms together and the measurement period for about one year.

Commonly a switch–off delay time is applied for sensors in order to avoid false detections of room occupancy, e.g. when the person does not move in the room. The switch-off delay time is the time duration from the latest detected movement until the occupancy sensor registers that the room is unoccupied. Two different switch-off delay times are set in the devices in the study building: 5 min and 10 minutes. However, for the majority of the measurement period the devices operated with 10 minutes of switch-off time. These switch-off delay time periods have been taken into consideration in the data processing.

The occupancy in the rooms was monitored during the period of 10th of September 2007 to 11th of September 2008. Based on the measured data, the occupancy factors and periods of occupancy were evaluated. The occupancy factor is defined here as the number of occupied rooms in a given time divided by the total number of rooms in the building. The total number of rooms in the building is considered to be the number of rooms which have DCV diffusers installed. However, some errors occurred with some DCV diffusers in the building during the measurement period. Therefore the occupancy factor has been calculated based on the total number of measured rooms. In addition, as described before it is not possible to connect to all of the rooms at once. The maximum time difference in logging between the first and last room in a series is about 3.5 minutes. Therefore, the evaluated occupancy factor in this study represents the occupancy factor within 3.5 minutes time intervals. The uncertainty introduced to the results due to non-simultaneous sampling is difficult to evaluate.

The occupancy periods have been evaluated according to the registered “unoccupied” and “occupied” events. In the data analysis the time periods from the first “occupied” event till the first “unoccupied” event is considered as occupied period. The time period from the first “unoccupied” event till the first “occupied” event is considered as unoccupied period. Some uncertainty will be introduced to the evaluated occupancy periods since the exact time when the room will go from unoccupied to occupied and from occupied to unoccupied is not registered. These events take place within the sampling interval. Therefore, the uncertainty for each evaluated occupied time period is <±4.5 minutes. When considering all the “unoccupied” to “occupied” and “occupied to “unoccupied” events together over the measurement period, it is possible to evaluate the total uncertainty for the evaluated occupancy periods.

The occupancy factor and periods of occupancy have been evaluated for the normal period of occupancy, which is considered to be between 7:00 and 18:00 from Monday to Friday, except holidays. Additionally, the last week in December and the month of July have not been included in the calculations, since many people are on holidays during this time. The results are presented with and without the switch-off delay times of the occupancy sensors. This would give information about the influence of the occupancy sensors’ switch-off delay times on occupancy patterns.

4.3.2 Results

4.3.2.1 Occupancy factor for the building

The evaluated occupancy factor for all working days during one year measurement period is presented in Figure 4.1. The diagram correspond to evaluated average, minimum and maximum occupancy factor within a 5 minute interval at the given time of the day, considering all working days together. Figure 4.1 is calculated based on the processed data, where the 5/10-minute switch-off delay times of the occupancy sensors have been subtracted from the measured data. The diagram should theoretically correspond to the actual occupancy factor of the building.

As can be seen in Figure 4.1, the maximum occupancy factor occurring in the building is 0.7. This means that the 70 % of the measured rooms are occupied at the same time in the building. The average occupancy factor during normal working hours is about 0.4. The normal working hours seem to be approximately between 8:00 and 16:00 and the normal period of occupancy between 07:00 and 18:00. It takes about two hours in the morning to reach to the peak levels of occupancy. To decrease from the peak back to the minimum occupancy in the afternoon it takes about three hours. This can be explained with the flexible arrival time in the morning between 7:00 and 9:00 and flexible leaving time between 16:00 and 18:00 in the afternoon. This is quite common in many companies and institutions in Sweden. Additionally, it is a tradition in the majority of Swedish companies and institutions to have coffee breaks in the morning and in the afternoon. As can be observed in the Figure 4.1 the coffee breaks seem to be between 9:00 and 10:00 in the morning and 14:00 and 15:00 in the afternoon. It has not been studied where people are when they are not in their rooms. However, it can be assumed that even though the occupancy factor is somewhat lower during these times, the workers are still in the building and in the break rooms.

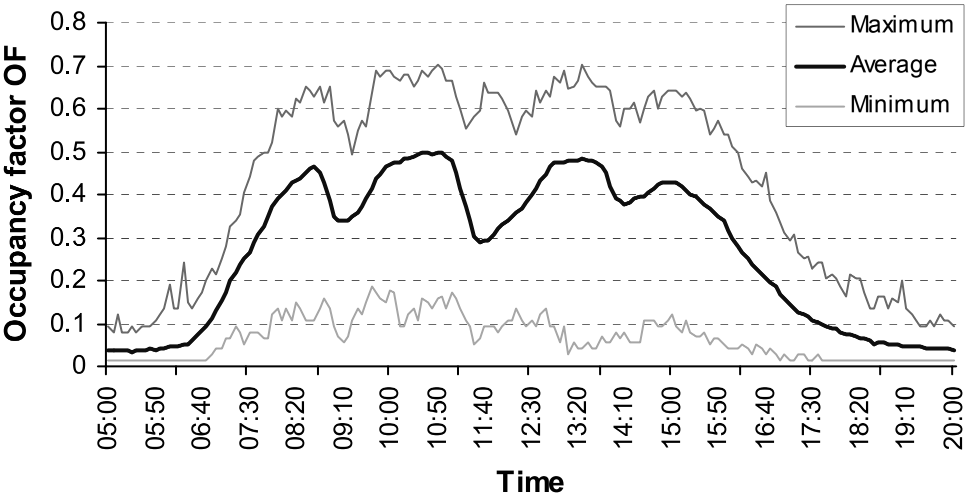

Figure 4.1 Occupancy factor for all working days over the one year measurement period for the case study building. The *OF* factors have been evaluated from the data without switch-off delay times of occupancy sensors. The occupancy factor *OF* is calculated as the ratio between the number of occupied rooms divided by the total number of measured rooms.

Figure 4.2 gives an overview of the distribution of the occupancy factors for all working days during the normal period of occupancy between 07:00 to 18:00, evaluated over the one year measurement period. During 90 % of the measured time the occupancy factor was equal to or less than 0.53. This means that during 90 % of time the aggregated occupancy is 53 % or less. During 50 % of the measured time the occupancy factor was equal to or less than 0.36.

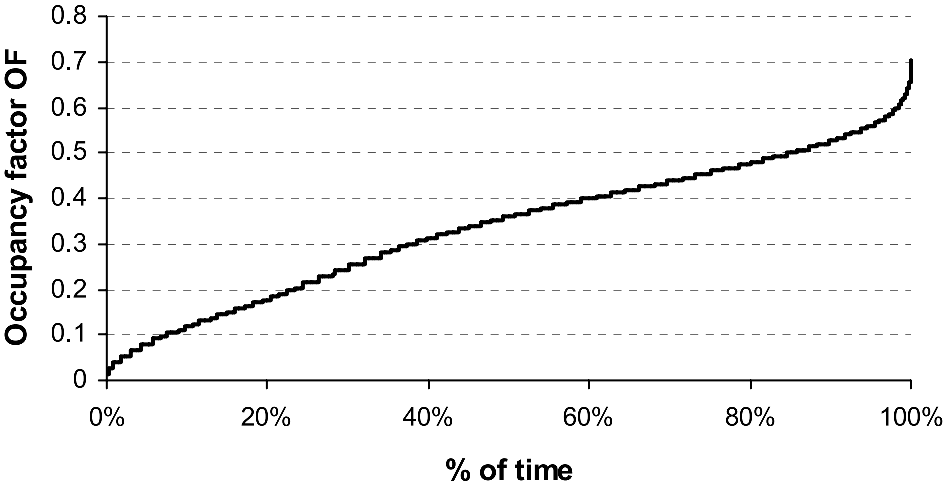

Figure 4.2 Distribution of the occupancy factor for all working days during the normal period of occupancy between 07:00 and 18:00 over the one year measurement period. The occupancy factor *OF* is calculated as the ratio between the number of occupied rooms divided by the total number of measured rooms. During 90 % of the measured time the occupancy factor is equal to or less than 0.53.

4.3.2.2 Influence of the switch-off delay times of the occupancy sensors

Commonly a switch-off delay time is applied for occupancy sensors in order to avoid false detections of room occupancy, e.g. when the person does not move in the room. It represents the time duration from the latest detected movement until the occupancy sensor registers that the room is unoccupied. The switch-off delay times set for the occupancy sensors in the case study building were majority of time 10 minutes during the measured period. For a short period, about 9 % of the total measured time, the switch-off time delay was set to 5 minutes.

These switch-off delay time periods have been taken into consideration in the data processing by subtracting these times in the data each time it has been registered from occupied to unoccupied event. The aim was to evaluate the actual occupancy in the rooms and in the building. However, it is of interest to estimate the impact of these switch-off delay times on the registered occupancy patterns.

The distribution of evaluated occupancy factors based on the measured data with switch-off delay times and processed data without these delay times are illustrated in Figure 4.3.

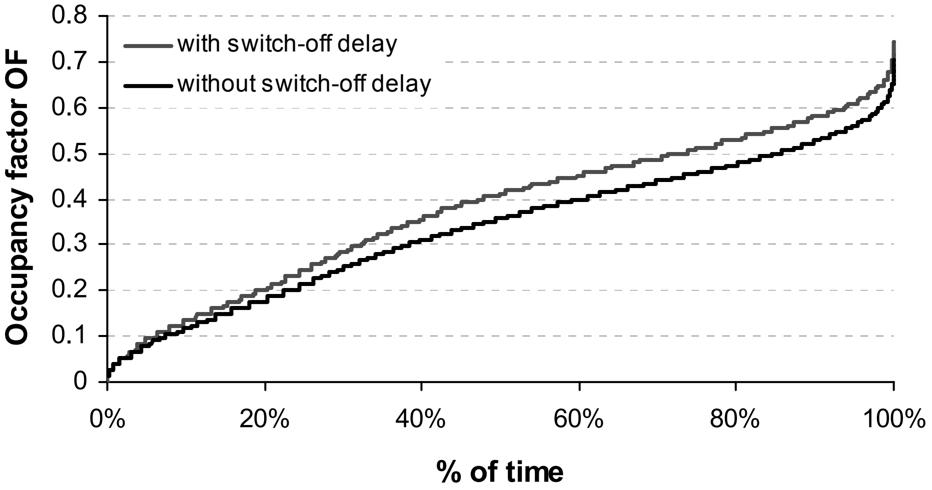

Figure 4.3 Distribution of the occupancy factor for all working days during the normal period of occupancy between 07:00 and 18:00 over the one year measurement period evaluated based on the data with and without the 5/10- minute switch-off delay time of occupancy sensors.

The maximum occupancy factor evaluated from the measured data with the 5/10-minute switch-off delay time is 0.74, compared with 0.70 without the delay time. The 5/10-minute switch-off delay time would increase the occupancy factor about 0.05.

4.3.2.3 Occupancy periods

The calculated occupancy periods as percentage of the normal period of occupancy, between 07:00 and 18:00, for different room types are presented in Figures 4.4 to 4.6. The evaluation is based on the one year measurement. The results are presented separately for office rooms, meeting rooms, copy rooms, break rooms and archives/library.

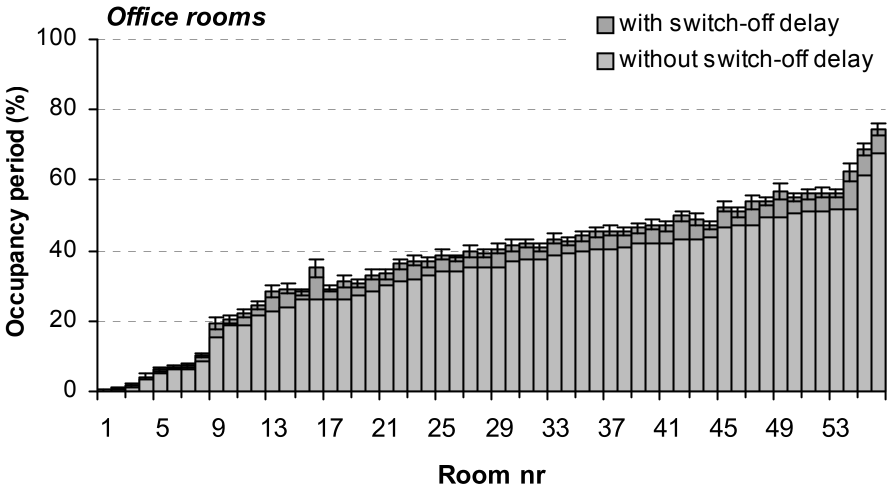

Figure 4.4 Percentage of the normal period of occupancy, between 07:00 and 18:00, that office rooms were occupied during the measurement period. The data was collected from 56 office rooms. The occupancy periods have been evaluated from the data with and without 5/10 minute switch-off delay times of the occupancy sensors. The error bars represent the evaluated uncertainties of the estimated occupancy periods.

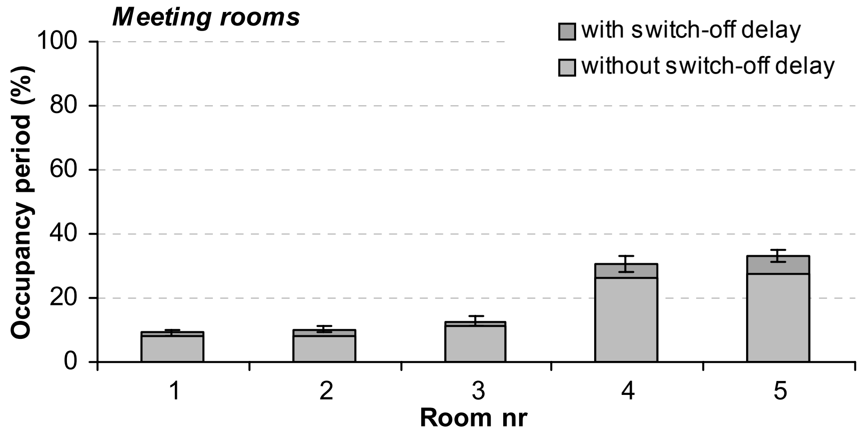

Figure 4.5 Percentage of the normal period of occupancy, between 07:00 and 18:00, that the meeting rooms were occupied during the measurement period. The periods have been evaluated from the data with and without 5/10 minute switch-off delay times of the occupancy sensors. The error bars represent the evaluated uncertainties of the estimated occupancy periods.

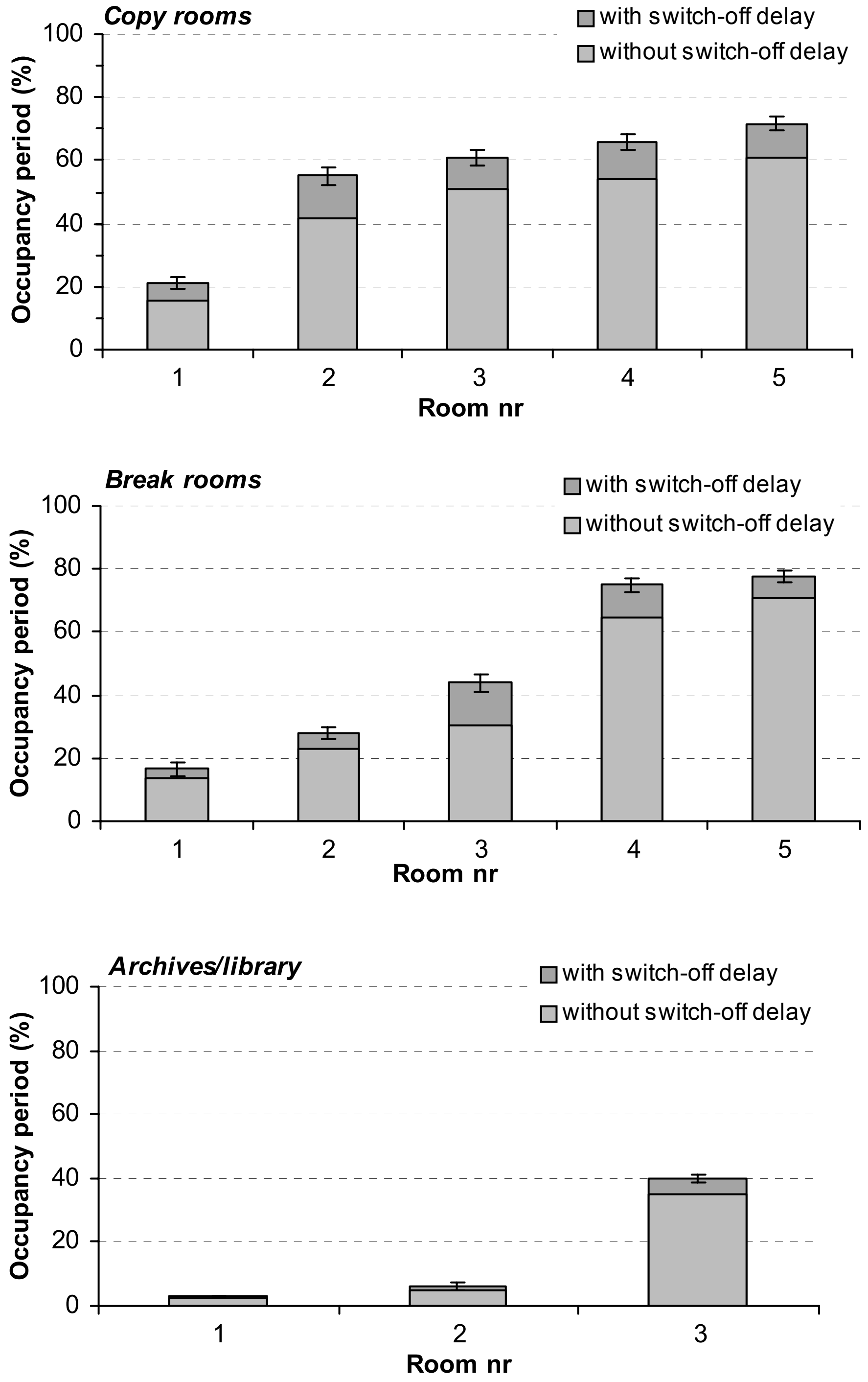

Figure 4.6 Percentage of the normal period of occupancy, between 07:00 and 18:00, that the copy room, break rooms, archives and a library were occupied during the one year measurement period. The periods have been evaluated from the data with and without 10 minute switch-off delay times of the occupancy sensors. The error bars represent the evaluated combined uncertainties of the estimated occupancy periods.

The building occupants were spending in average of 33 % of the normal period of occupancy in their office rooms, based on data without switch-off delay times. In eight office rooms out of fifty-six the occupancy period was 4 % in average. The maximum evaluated occupancy period occurred in one office room, which was 68 % of the normal period of occupancy, between 07:00 and 18:00. From the Figure 4.4 it can be seen that the 5/10-minute switch-off delay time would increase the occupancy period about 5 % of the normal period of occupancy.

For meeting rooms the average percentage of occupancy period was 16 % and maximum 28 %. The copy rooms and break rooms had somewhat higher occupancy period. For copy rooms the average was 45 % and maximum 61 %; for break rooms the average was 41 % and maximum 71 %. The copy rooms and break rooms have somewhat higher influence of the 5/10-minuter switch-off delay time than office room and meeting rooms. With the delay time of the occupancy sensors the occupancy period is increased up to 13 % of the normal period of occupancy in both room types. The bigger difference can be explained by the more frequent entries to these rooms and that the periods of occupancy are shorter.

The occupancy period for the archives and a library were 14 % in average and 35 % as maximum. The occupancy period was longer for the library room, room number 3 on Figure 4.6, which can be expected.

It must be noted that some uncertainty is introduced to the evaluated results for rooms which have more frequent and short period of occupancy, e.g. copy rooms, break rooms. For the occupancy sensors it takes 10 minutes till the unoccupied event is registered from the last detected movement. In the data processing, the switch-off delay time periods have been subtracted from the data each time it has been registered from occupied to unoccupied event. However, the changes were not done if this subtraction would lead to only unoccupied events during the time in question. Therefore somewhat higher period can be expected in the results if the room had many entries and very short periods of occupancy.

4.3.3 Discussion

This study aimed to contribute to the knowledge of occupancy patterns and its variations in office buildings. The occupancy patters were monitored in an office building used by a university administration. Due to the limitations in the technology of the sensors used for monitoring the occupancy in different rooms it is possible to only determine whether a room is occupied or not. The sensors do not give any information about the number of people in the room. It is also not studied where people are when they are not in their rooms.

In order to evaluate the simultaneous use of the building, an occupancy factor was calculated for the different times over the measurement period. The maximum evaluated occupancy factor during the working days in the building was 0.7. This means the maximum aggregated occupancy was 70 % during the one year measurement period. In 90 % of the measured time the occupancy factor was equal to or less than 0.53. This also explains the low measured total airflow rates in the *Case study 2B* building in the first study, described in chapter 2.6. The energy and airflow monitoring carried out in this case study building showed that the ventilation system had low use of energy. On the other hand, the system hardly ever reached its designed values for airflow rate.

However, some uncertainty is introduced to the evaluated results due to the measurement methods and techniques. Due to the specifics of the data acquisition system it was not possible to sample the information about the occupancy in different rooms at the same time. The data from different rooms were registered within 3.5 minutes of time. The possible uncertainty introduced to the results is difficult to estimate.

The building occupants spend in average of 33 % of the normal period of occupancy in their office rooms, based on data without switch-off delay times. In eight office rooms out of fifty-six the occupancy period was only 4 % in average of the normal period of occupancy. The maximum evaluated percentage of occupancy period, which occurred in one office room, was 68 %.

In this study it was also observed that the 5/10-minute switch-off delay times of the occupancy sensors increased the evaluated occupancy factors in the building 0.05 and occupied periods in the office rooms about 5 % of the normal period of occupancy. Somewhat higher influence of switch-off delay times on evaluated occupancy periods was observed in copy rooms and break rooms. It is assumed that the influence of the switch-off delay times on the registered occupancy periods is bigger in rooms where more entries and short occupancy periods are expected. In the current case the switch-off delay time was set to 10 minutes for the majority of time. This delay time can be somewhat longer in other buildings, e.g. 20 minutes[143]. Occupancy monitoring carried out in office buildings in Norway showed that that 20-minute switch-off delay time doubled the evaluated occupancy factor and occupancy period during the measured period[143]. However, the evaluated occupancy factors were also considerably smaller and the periods of occupancy shorter in these buildings.

The occupancy patterns and their variations are dependent on the organizations that are using the building. The studied office building is used by university administration. It can be assumed the working tasks for the employees would require less moving around. However, during 90 % of the time the occupancy was relatively low. On the other hand, the evaluated occupancy factors are somewhat higher than indicated in the previous studies, where university and educational buildings were monitored[87, 111].

Low level of occupancy in a building gives a great potential for energy savings with a DCV system compared to a CAV system. Additionally, information about most probable/predicted occupancy patterns would be an important input in the design process and would help to optimize the size of the components in the DCV system. A simultaneous factor is used to express the simultaneous air flow needed at a given occupancy and base airflow rate. From the evaluated occupancy factors, an example of a simultaneous factor for the building can be calculated according to the equation proposed by Mysen et al.[151]:

$$s = OF + b - b \cdot OF \qquad \text{(eq. 4.1)}$$

Where,

s	simultaneous factor;
OF	occupancy factor;
b	the ventilation rate for a unoccupied office divided by the ventilation rate for an occupied office

For example in the current building the minimum ventilation airflow rate in the office room without any occupancy is 7 l/s. When someone enters the room the airflow rate is increased to 10 l/s. Based on the maximum evaluated occupancy factor 0.7 the simultaneous factor would be 0.91. When the occupancy factor 0.53 is used the simultaneous factor would be 0.86. It must be noted that the evaluated simultaneous factors are applicable only when the DCV system is designed to control indoor air quality. In the current case study building the DCV system is also used for assuring the required thermal comfort. This means that the actual system size and airflow rates are determined by the cooling demand rather than by the demand for hygienic airflow rates.

Additionally, when optimizing the size of the ventilation system for indoor air quality control based on the most probable/predicted occupancy factors, it is also needed to take into account the energy use of the system. Decreasing the size of the system components, e.g. the air-handling unit and main ducts, would decrease the initial investment cost. However, smaller ducts would increase the pressure drops in the system and hence the energy use for the fan operation. In order to find the most optimal size of the components from the investment and running cost point of view, more detailed analysis should be carried out. This will be part of the future studies.

4.3.4 Conclusions

For DCV application it is essential to have an overview of the expected load conditions and their profiles in the building. It is doubtful that all of the rooms will be occupied at the same time. Therefore determining the actual occupancy pattern for DCV system design is a question of interest.

From the field monitoring of occupancy patterns and their variations in an office building following conclusions can be made:

- During 90 % of the measured time the occupancy factor was equal to or less than 0.53. The maximum occupancy factor occurring was 0.7.
- The average occupancy period for office rooms was about 33 %, for meeting rooms about 16 %, for copy rooms about 45 %, for break rooms about 41 % and for archives/library 14 % during the normal period of occupancy between 07:00 and 18:00 on weekdays.
- The 5/10-minute switch-off delay time of the occupancy sensors increased the evaluated occupancy factors in the building 0.05 and occupied periods in the office rooms about 5 % of the normal period of occupancy. The evaluated occupancy period was up to 13 % higher in copy rooms and break rooms with the switch-off delay time. The bigger difference can be explained by the more frequent entries to these rooms and that the periods of occupancy are shorter.

5 Discussion and conclusions

This thesis concentrates on demand controlled ventilation systems applied in commercial buildings. Such systems are considered as energy efficient solutions for air-based cooling and indoor air quality control. Considerable energy savings can be achieved when the airflow rate is continuously adapted to the actual load condition. However, the more complex design of DCV systems requires careful commissioning and maintenance in addition to a proper design and installation. It is also essential to know the requirements that the DCV system and its components should satisfy in order to assure that the desired performance of the system is delivered.

The objective of this work has been to clarify the requirements for a well functioning DCV system. To achieve this objective, experimental evaluations, have been carried out in real buildings as well as in a laboratory. These evaluations provide information on whether the pre-defined requirements are fulfilled by commercially available components. A special focus here has been on uncomplicated DCV system solutions that are possible to implement in existing buildings as well as in new ones. Demands on system components for one proposed system solution have been analysed regarding indoor climate, energy use and technical aspects.

Most of the DCV system evaluations and DCV system experimental work were carried out on solutions for thermal comfort control. Many of the system and design aspects, however, are general and independent of the DCV system application. Furthermore, additional focus regarding applications for indoor air quality control has been on performance of air quality sensors. Such sensor-based control of the hygienic airflow rate at varying load conditions in commercial buildings is becoming of increasing interest. The requirements for sensors applicable to indoor air quality control have been analysed and experimentally evaluated.

This thesis also provides some input regarding the actual occupancy and its variation in a commercial building in operation. For this purpose, occupancy was monitored in an office building during approximately one year.

5.1 Functional requirements on a DCV system

The fundamental requirement on a DCV system is to assure a good indoor climate with reference to indoor air quality, thermal comfort and acoustic environment. In addition, this should be achieved cost-effectively and with a minimum of purchased energy.

The essential technical properties for a DCV system for fulfilling the indoor climate demands were identified. When doing this one goal was to look for an uncomplicated system solution, which should be possible to implement both in existing buildings and in new ones. One criterion of an uncomplicated system is that the number of controlling components is minimized. A possibility for building up a DCV system with VAV supply air diffusers for airflow control and without active control dampers in the duct system has been considered.

In order to assure good indoor climate and energy efficient performance of such a system configuration the following requirements must be set on the VAV supply air diffusers and the duct system:

- The supply airflow rate must be independent of the pressure variations in the duct
- The VAV supply air diffusers should manage a pressure drop of at least 100 Pa over the diffuser without a disturbing generation of noise
- The VAV supply air diffuser should have a stable air movement pattern, which must be independent of the supply airflow rate. This means that neither at high air flow rates, nor low airflow rates, should there be any risk for cold supply air dropping into the occupied zone
- The VAV supply air diffuser should control the airflow rate within a wide range
- It should be possible to supply air with a low supply air temperature without any risk of draught
- The duct system must manage the varying airflow rates with low supply air temperature without any considerable heat gains

In order to test such an uncomplicated DCV system configuration, a type of supply air device, that seemed to fulfil the above requirements, was evaluated under laboratory conditions and studied in plants in function. A case study was carried out in two office buildings, one existing and one new. The tests were focusing on indoor climate and the need of energy. The results from the laboratory and field studies with the proposed DCV system configuration indicated the following:

- It is possible to fulfil the requirements set on the pressure independent VAV supply air diffuser in order to apply it in a wide airflow range and at low supply air temperatures.
- In the laboratory study, the evaluated risk of draught was quite low despite high airflow rates and low supply air temperatures, about +15 °C.
- The field study verified that the indoor climate demands with the proposed system configuration are essentially fulfilled. No risk of draught was indicated in measured room at high airflow rate conditions and with +15 °C supply air temperature. In addition, the noise levels were on the acceptable level. The sound pressure level in the measured rooms was lower than 30 dB(A) even when the pressure drop over the device was around 100 Pa.
- The tested DCV system configuration applied in the case study buildings for thermal comfort control showed that the system works energy efficiently. Due to the low supply air temperatures, about +13.5 °C to +14 °C from the central air handling unit, the heat recovery system accounts for almost all the heating of air needed. There was no need for additional heating with the heating coil during the measured period. Due to the low supply air temperature, the airflow rate regulation versus heat load is effective. This contributes to a low average airflow rate, and therewith the energy need for air distribution becomes relatively low.

The studies verify that the system configuration, without controlling dampers, functions as expected from thermal comfort and energy point of view. Although the tests have been carried out with a specific diffuser, the results are general in the sense that they show that high requirements on VAV supply air diffusers can result in products which fulfil them.

The current work also evaluated the heat gains in the air distribution system under varying airflow conditions and low supply air temperatures. The worst cases occur when the devices are running with minimum airflow rates. As a result, a risk of not maintaining the required room temperature may occur due to decreased cooling capacity of the supply air. From the results of the simulations done with the test system, some methods were recommended that could be applied in order to maintain the required supply air temperatures. The focus here was on insulating the main ducts with bigger insulation thickness, since this can give a much bigger effect than increasing the insulation thickness on connection ducts.

5.2 Applying DCV systems for indoor air quality control

Control of indoor air quality with a DCV system aims to manage the time varying pollutant emissions from activities and processes in the room. Nevertheless, control of indoor air quality with sensor methods can be more complicated than control of thermal comfort.

First, it can be difficult to define the reference parameters influencing indoor air quality that the sensors must measure. There are no sensors that measure the “quality” of air. Instead, quantitative parameters, as the composition of air in terms of gases and particles, can be measured and linked to the air quality. However, in many cases the link between the perception of air quality, the concentration levels of various substances and their influence on comfort and health is still not fully defined and known.

Secondly, the available sensing technologies set the limits. The indicator/pollutant chosen to control indoor air quality is in a great extent dependent of the possibilities to measure this parameter. The sensors applicable for indoor air quality control are based on measurement of gaseous compounds only. Furthermore, the gas sensors can measure selectively only one gas or non-selectively a wide range of gases, so called mixed-gas sensors. The mixed-gas sensors do not give any indication to the type of gases detected or in what concentration they are present.

Thirdly, if there are available technologies for measuring the required parameter, the sensor must fulfil certain requirements in order to be applicable for ventilation control. These requirements were identified in this work.

The sensors for control of indoor air quality and airflow rates should have the following principle performance characteristics:

- Sensitivity to measured property and low cross-sensitivity to any other property and influencing factors;
- Sufficient operating range for the measurement purpose and good resolution over the whole operating range;
- Good accuracy and reproducibility;
- Stable output signal and good long-term stability;
- Fast response time.

This work also proposes quantitative requirements on sensors uncertainty for indoor air quality control with a DCV system. These requirements have been developed based on the requirements set on indoor air quality control in premises according to the ventilation guidelines and standards. Guidelines are well established for applying CO_2 as indicator for controlling the pollutants emitted from people and their activities. However, very few guidelines exist on acceptable concentration levels for common air contaminants in non-industrial buildings. This means that it is rather complicated to set quantitative requirements for sensors other than for measurement of CO_2.

Therefore the proposed quantitative requirements are mainly applicable for CO_2-sensors.

According to the proposed requirements, the uncertainty of concentration measurement should be as follows:

- When the requirement on DCV system is to maintain specified minimum outdoor airflow rates the uncertainty of concentration measurement should be ≤ ± 3.5 % for the sensor in the supply air and in the room/exhaust.
- For maintaining the required indoor concentration of CO_2 the uncertainty of the sensor should be ≤ ± 6.5 % or ≤ ± 8.1 %, when the required set-point is 1000 ppm and 800 ppm, respectively.
- When the demand is to keep the specified indoor air quality category based on the percentage of dissatisfied, the uncertainty of each sensor should be about ≤ ± 7.5 % to ≤ ± 9.5 %, for the specified percentage of dissatisfied of 15 % or 20 %.
- A response time less than one third of the nominal time constant of the controlled room is additionally proposed.

The specified sensor uncertainty should include all the possible sources of uncertainties, e.g. calibration errors, repeatability, linearity, hysteresis, stability and cross-sensitivity, etc.

A detailed sensor study was carried out in order to test if the commercially available sensors for indoor air quality control can fulfil the above described requirements. The performance of twelve different models of CO_2-sensors and four different models of mixed-gas sensors were evaluated under laboratory conditions and in the field.

The performance tests of commercial CO_2-sensors revealed the following:

- Several of the tested CO_2-sensors would fulfil the requirements on sensor uncertainty if the requirement on the DCV system is to keep the required concentration level or the specified indoor air quality category based on the percentage of dissatisfied. However, only one CO_2-sensor is close to fulfil the requirement on sensor uncertainty when the demand on the DCV system is to keep the required airflow rate.
- All of the tested CO_2-sensors are influenced by the environmental conditions, e.g. atmospheric pressure, temperature, humidity, to a certain extent, depending on the sensor. In addition, some CO_2-sensors seemed to have considerable baseline offset. This can be due to transportation/installation problems and/or incorrect factory calibration. It can be assumed that with proper calibration procedures, the commercial CO_2-sensors would perform sufficiently accurately for indoor air quality control.
- The tested sensors have sufficiently fast response time for indoor climate control
- The evaluation of long-term stability of CO_2-sensors in an existing building, which are similar to some of the types tested in the current study, showed that the majority of the tested CO_2-sensors have reasonable long-term stability. Nevertheless, baseline adjustment after 5 years would be recommended in order to keep the sensor uncertainty within the specified requirement.

The higher requirements on sensor uncertainty also necessitate higher accuracy for the reference system. To be able to evaluate if the sensor uncertainty is within ± 3.5 %, as required for maintaining the required airflow rate, the measurement uncertainty of the reference system must be considerably lower than that, about one third of it. The measurement uncertainty of reference gas concentration in the current tests was in a range of ± 3.4 % to ± 4.7 % from the measured concentration. It was depending on the analysed gas concentrations specified by the gas manufacturer and available measurement equipment in the laboratory. Lower uncertainties can be achieved when the gas is supplied directly from the gas bottle. The uncertainty is then decided by the gas manufacturer. Reference gases with relative uncertainty of ± 2.0 % are commonly used in calibration laboratories. It is possible to also order calibration gases with uncertainty of ± 1.0 %. However, the cost of the bottled gas would be considerably higher, which in turn would also increase the cost for calibration of CO_2-sensors.

The performance tests of commercial mixed-gas sensors showed the following:

- The tested mixed gas sensors have sufficiently fast response time for indoor climate control.
- It is difficult to evaluate the characteristic performance of mixed-gas sensors in terms of sensitivity towards different gases and associated measurement uncertainty. Very little manufacturer-stated information is available for comparison.
- Some of the tested sensors are influenced by the changes in absolute humidity
- The optimal measurement range for the majority of tested mixed-gas sensors seems to be at a considerably higher level than the concentrations of interest for different VOCs indoors.
- In a full scale test chamber with different pollution sources it was observed that the majority of the tested mixed-gas sensors have negligible relative sensitivity towards the tested office furniture and very low relative sensitivity to polished new linoleum floor. This is advantageous for their application for demand controlled ventilation.
- Controlling the indoor air quality based on processes in the room can be difficult with the tested mixed-gas sensors. Very small change in sensor response was indicated in tests with the office equipment.
- Somewhat higher sensitivity was observed towards cleaning the linoleum floor. Nevertheless, the change in sensors output could have been influenced by the increased humidity levels during the cleaning procedure as well as the presence of a person in the room.
- The tested mixed-gas sensors showed good correlation to presence of people.

Nonetheless, the application of the tested mixed-gas sensors for indoor air quality control with a DCV system is undecided. The tested mixed-gas sensors cannot be used to maintain the required minimum outdoor airflow rates. In addition, air quality control based on a required set point can be rather complicated. It is not clear how the output of mixed-gas sensors should be interpreted. Furthermore, it is not clear how to adjust the set point levels when these sensors are used for indoor air quality control. No manufacturer-stated information is available for comparison or guidelines for their calibration.

The limitations for their application are also related to the lack of available standards describing the acceptable concentrations for common air contaminants for non-industrial buildings. Further developments are needed to make the output of mixed-gas sensors more quantifiable as well as developing air quality standards that can be used as reference for these sensors.

One of the tested mixed-gas sensor models uses CO_2 as an equivalent to correlate the changes in its output signal. The concept of carbon dioxide as an indicator for indoor air quality is well established. Still, further studies are needed with this type of sensor to evaluate its performance in different environments. Additionally, guidelines for calibration are needed, since the applied methods for the sensor performance checking in the laboratory were not applicable for this type of mixed-gas sensor.

5.3 Occupancy patterns in office buildings

For DCV application it is essential to have an overview of the expected load conditions and their profiles in the building. The current work evaluated the occupancy patterns in an office building for about one year period of time. According to the results, during 90 % of the time the aggregated occupancy in the building is equal to or less than about 50 %. The maximum aggregated occupancy was about 70 %. The average occupancy period in office rooms was 33 %, in meeting rooms 16 %, in copy rooms about 45 %, in break rooms about 41 % and in archives/library 14 % of the normal period of occupancy. The evaluation is based on the normal period of occupancy between 07:00 and 18:00 on weekdays.

Information about the most probable/predicted occupancy would contribute to the most optimal size of the components for the DCV system for indoor air quality control. Decreasing the size of the system components, e.g. the air-handling unit and main ducts, would decrease the initial investment cost. However, smaller ducts would increase the pressure drops of the system and hence the energy use for the fan operation. In order to find the most optimal size of the components from the investment and running cost point of view, more detailed analysis should be carried out.

5.4 Recommendations for further work

It is hoped that this work contributes to the greater knowledge of the functional requirements on components of a DCV system and lead to further product development for the purpose of a well-functioning DCV system. This work, however, has mainly been limited to requirements on some DCV components. Further work is needed to clarifying the requirements for the DCV control system in general to assure the best possible performance of the DCV system.

Additionally, based on the results of this study further analysis should be carried out to evaluate the control parameters and control strategies resulting in the most energy efficient operation of DCV systems. The impact of the performance of the controlling sensor on the energy use of the DCV system should be evaluated.

Based on the results from the occupancy study in this work, more detailed analysis should be carried out to find the most optimal size of the DCV system components from the investment and running cost point of view.

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APPENDIX A

A DEMAND CONTROLLED VENTILATION SYSTEMS: STATE-OF-THE-ART REVIEW

This chapter gives an overview of the development and applications of DCV systems. A state-of-the-art review has been carried out. A special focus here has been DCV systems based on indoor air quality control. This is partly because in the past DCV has been defined and related to indoor air quality control and the available literature is based on this ideology. DCV systems based on temperature control have been traditionally related to as VAV systems. A number of studies and reviews have been conducted on VAV systems, including performance, design and control issues. For the review of references on temperature controlled DCV systems see Sheperd[192]. Therefore, temperature controlled DCV systems will be not covered in the literature review of this study. However, some technical issues related to application of DCV systems are discussed which also apply for temperature controlled DCV systems.

A.1 Introduction

Demand Controlled Ventilation systems based on indoor air quality (IAQ) control have become in interest as a result of more strict hygienic ventilation requirements indoors. One of the first extensive reviews on indoor air quality based DCV systems was conducted for more than 15 years ago for the Annex 18 program of the International Energy Agency[152, 153, 173, 174]. The specific objective of the Annex 18 was to develop guidelines for indoor air quality based demand controlled ventilating systems. Later on, also some other reviews on indoor air quality based DCV systems have been issued[8, 50, 62, 63, 237]. However, the majority of these reviews are mainly about DCV systems based on carbon dioxide as an indicator.

Despite the fact that the DCV systems are recommended by many guidelines and it is known concept, the acceptability of a DCV system still remains controversial. There is no single common reason for this, but more likely a combination of reasons. Few of the reasons are the higher initial cost of equipment and higher maintenance costs needed. For example the sensors for indoor air quality control have been relatively expensive. Additionally, the performance of many of these sensors has been inadequate, requiring frequent need for sensor calibration and maintenance. Other constraints for widespread application of DCV are related to more advanced and complex control system, which necessitates skilled system installation and operational personnel [52]. Furthermore, since the system and its control are more complex than in a CAV system, problems with the system performance can occur. This is mostly due to lack of knowledge of the system operation and its components. More information is needed regarding the technical performance of the system components and the application of the DCV approach itself.

The purpose of this review is to summarize the literature on the current technology and application of Demand Controlled Ventilation systems in non-industrial buildings. This report covers primarily the application of indoor air quality based DCV systems, since temperature controlled DCV systems have been studied already to a great extent. The review is primarily based on the scientific literature published after the ANNEX 18 reports. In addition, this review is based on the most important findings from the published data.

The review is divided into three parts. First the factors influencing the indoor air quality in the buildings are discussed and an overview of current standards and guidelines are given. Additionally, the selection of indicators for a DCV system is analyzed. Secondly, a summary of the available sensor technology and sensor performance is provided. Thirdly, the performance and application issues of DCV systems are overviewed.

A.2 Indoor Air Quality in Buildings

This chapter gives an overview of the available information about the different pollutants in indoor environments that have possible impact on perceived indoor air quality. Additionally, the health and comfort criteria for indoor air quality specified in the different standards and guidelines are discussed. At last, the possible control parameters and indicators applicable for indoor air quality control with DCV system are overviewed.

A.2.1 Previous indoor air quality studies

The term “air quality” refers to the condition of air as perceived by humans and it depends both on the substances in the air and the individual persons exposed to the substances. The “quality” of air can not be measured. Instead, quantitative parameters, as the composition of air in terms of gases, particles etc, can be measured and linked to the perception of air quality.

It is generally assumed that indoor air pollution, one way or another, causes an increase of indoor complaints [232]. There is a wide variety of both gaseous and particle substances in indoor air, which have different potential effect on building occupants. Some pollutants may adversely affect the health of the occupants, such as allergenic, toxic and carcinogenic substances. Others may just influence the perceived air quality by causing sensory effects, e.g. eye and airway irritation and odour annoyance. Nevertheless, for many of the pollutants occurring indoors, the risk to human health and comfort is almost totally unknown and difficult to predict. This is because of lack of toxicological data and information on the dose-response characteristics in humans or animals models. The term “Sick Building Syndrome” has been in use for at least the last decade to describe building related health and comfort symptoms which cause is difficult to identify but can be associated with indoor air quality.

The possible pollutant emissions and their sources have been discussed in detail in the literature and constant research is ongoing to better characterize the different contaminants and their effect on human health and comfort. A great attention has been focused on the possible contribution of VOCs to the increase of complaints indoor health and comfort. Nevertheless, there is still no evidence that supports a cause-effect relationship between typical indoor VOC concentrations and eye/airway irritation in case of low formaldehyde levels[232]. In many buildings where the complaints of sensory irritation occur, the sum of detectable VOCs may be lower than thresholds required for eye/airway irritation[234]. For example, the results from the full scale test rooms with office equipment have shown that the VOCs identified were insufficient in concentration to explain negative effects on human during exposure [17, 133]. This suggests that chemicals other than those identified by the analytical method used, may contribute to negative perception by people exposed to office equipment [17]. The question “Are we really measuring the relevant indoor air pollutants?” has already been raised in previous studies[229].

Several hundreds of organic compounds have been identified in the indoor environment[226]. The concentrations of single VOCs are generally below 50 $\mu g/m^3$, with most below 5 $\mu g/m^3$[232]. Some recent comparative studies of VOC levels indoors in different types of premises have been conducted by Bornehag and Stridh[27], Brown[30], Hodgson and Levin[92], Zuraimi et al.[244], Loh et al.[136], Edwards et al.[57]. The difficulty to make a comprehensive review arises from the fact that no generally accepted measure for exposures to the VOC compounds have been defined [154]. The number of observed and identified VOCs is directly related to the performance of the analytical method[227]. In addition, potential chemical reactions taking place indoors can influence the concentrations of some organic compounds[234]. There are also other limitations for the review of the possible pollutant emissions. When pollutant loads and their sources are evaluated, the information about the ventilation conditions is often not provided in the report, or not even evaluated in the conducted research. This makes the results difficult to compare and analyse. The pollutant loads are influenced besides the strength of the pollutant sources also by the ventilation airflow rate.

One possible explanation for the cause of indoor complaints is believed to be the potential chemical reactions taking place in the room between some unsaturated VOCs and oxidants like ozone and nitrogen oxides. This is referred to as “the reactive chemistry” hypothesis[232]. As a result a variety of organic compounds are produced that may act as airway irritants. For example, formaldehyde levels can increase due to reactions between ozone and toner powder VOCs, e.g. styrene, and human exhalation of isoprene[230]. Also the reactions between terpenes and Ozone can result in gaseous products which are sensory irritants[206]. However, the health implications of indoor chemistry are still largely unknown and under study.

Besides the possible contributions of VOCs to indoor air quality, the effect of indoor particles has been of great interest. Moreover, since no cause relationship between typical indoor organic compounds and occupant complaints has been found, it is believed that concentrations of particles can have a great impact. Indoor air dust levels are affected by penetration of particles from outdoor air and generation from indoor sources. Ultrafine particles can also be generated as a by-product of chemical reaction between ozone and terpenes, such as pinene and limonene. In recent years, exposure to fine and ultrafine airborne particles has been identified as an important factor affecting human health[137, 190]. Several researchers have assumed that an increased mortality rate is associated with the particle levels prevailing in urban air[53, 107]. Dust contains also components that can cause allergy. Peak concentrations may be more important for health effects than long-term concentration averages[83].

Indoor air quality is traditionally determined based on the levels of pollutants present. However, research has shown that it is not just the chemical composition of the air that influences the perception of air quality. The elevated humidity and temperature levels can deteriorate the immediate perception of indoor air quality, even if the chemical composition of the air is constant and the thermal sensation for the entire body is kept neutral[33, 75]. On the other hand, too low relative humidity can affect the sensory perception in the long term basis[231]. This is important to consider when sensory pollution loads are measured and evaluated[216]. Nevertheless, the influence of relative humidity on the combined impact of VOCs, Ozone and particles on the indoor air quality is complex and far from well understood.

A.2.2 Health and comfort criteria for indoor air quality

The ventilation airflow rates supplied to the room must be based on both health and comfort criteria. However, in most cases the health criteria will also be met by the required ventilation for comfort. This is because the estimated pollutant concentrations for sensory effects are orders of magnitude below those levels where toxic effects occur. Nevertheless, any health risk should be considered separately from the sensory effects since some harmful pollutants are not sensed at all by humans, although they have negative effects on health[216]. Examples are radon and carbon monoxide.

The threshold levels for several known allergens and toxic compounds are specified in different indoor air quality standards throughout the world. The guideline values are given for a number of compounds on the basis of health impact criteria, describing concentrations at which adverse effects are observed. These compounds include nitrogen dioxide, sulfur dioxide, carbon monoxide, particulate matter, ozone, Formaldehyde and for some VOCs like Styrene, Toluene, Benzene and Naphthalene (e.g. see WHO[222, 223], U.S EPA[210], R1[172]). Guideline values are also provided for radon[172, 222]. Many of these substances originate mainly from outdoor sources and affect the indoor concentrations through ventilation and infiltration. Differences exist between the guidelines not only in terms of maximum concentration values, but also in terms of exposure time. The exposure limit values are usually given over a specified time period.

Unfortunately very few guideline values exist for comfort levels of the different pollutants. The exposure limit value for a commonly known airway irritant such as formaldehyde is defined clearly. Besides its sensory effects, such as airway irritation, long term exposure to formaldehyde can lead to acute health problems. However, for the rest of the compounds the possible sensory effects are not clearly defined and threshold values for sensory irritation and odour annoyance are still under the development. Some overview of the estimated pollutant threshold levels for sensory effects can be found in Hodgson and Levin[91], Cometto-Muñiz et al.[45] and Wolkoff[234]. The estimated sensory irritation thresholds are generally orders of magnitude higher than their corresponding odour threshold levels. In addition, there are big differences between the reported thresholds of different compounds. The latest reported odour thresholds of many organic compounds appear to be considerably lower than previously reported[234]. This can due to the difficulties that can occur when determining the odorous substances in ambient air by analytical methods. Several organic compounds that are responsible for odour can be present in the air in such low concentrations that they cannot be collected or identified by the standard techniques[234]. Moreover, odours in the ambient air frequently result from a complex mixture of substances and therefore it is difficult to identify the individual ones.

The majority of current ventilation standards specify directly the minimum ventilation rates required for keeping the specified air quality indoors, e.g. the European standard EN 15251: 2007, ASHRAE Standard 62.1-2004. The established ventilation rates are commonly based on comfort criteria and aim to achieve acceptable perceived air quality for the majority of occupants, e.g. ASHRAE Standard 62.1-2004, EN 15251:2007. However, there is no general agreement on how different sources of emissions, which may lead to sensory effects, should be added together.

Carbon dioxide can be used as an indicator for human bio-effluents that cause sensory pollution load, such as body odour. Therefore, the ventilation guidelines commonly specify the required carbon dioxide concentrations that must be maintained indoors for keeping the air quality on acceptable level. These values are based on studies of the relationship between CO_2 concentration and body odour acceptability. For example, Swedish indoor climate guideline R1 defines two different indoor air quality classes: AQ1 and AQ2 [203]. For indoor air quality class AQ1 the carbon dioxide concentration in the room at normal room use should not exceed 800 ppm and for air quality class AQ2 this level is 1000 ppm. The European standard EN 15251:2007 recommend CO_2 concentrations above outdoor concentration for the different indoor air quality categories are: 350 ppm, 500 ppm, 800 ppm and > 800 ppm. Finnish guideline FiSIAQ[81] recommends values of 700, 900 and 1200 ppm for the three different quality classes respectively.

A.2.3 Selection of indicators and control parameters for a DCV system

The choice of an indicator/control parameter for a DCV system is dependent on the purpose of the ventilation system for a given space. Besides assuring the required indoor air quality in the room the conditioned air could also be used for maintaining the required thermal comfort. It is necessary to analyse all the different loads affecting the indoor climate in the room, including their source of origin and variation in time. The application of a DCV system is advantageous mainly when the pollutant/heat sources are varying in time and there are considerable differences between the peak and minimum load conditions.

Control of air humidity can be an important from indoor air quality perspective and as a prevention measure for moisture damages in buildings. Increased moisture levels in buildings have shown to increase the prevalence of both fungi[156] and house dust mites[130], which can increase the risk for allergy and other health problems[26]. Elevated humidity levels are common in residential buildings due to high production rates of water vapour from showering, washing, cooking, etc. According to the ANNEX 18 final report[152, 153], the humidity problems, such as moisture, mould growth, destruction of walls, etc., were the main concern in dwellings. Therefore, humidity can be an effective indicator for demand controlled ventilation in these premises[3]. Since the humidity level reflects the occupancy level in a poor manner, it is not recommended as a single decision variable for demand controlled ventilation systems. According to studies by Pavlovas[167], relying on humidity only to control the ventilation rate does not necessarily result in satisfactory indoor air quality.

The preferred indicator for controlling the gaseous and particulate substances depends on the pollutants of concern in a given space. This is dependent on the activities and purpose of the building, e.g. office premise, school, auditorium, restaurant, department store, etc. Pollutant emissions from building materials and products have received a lot of attention [227]. For a new or renovated building, the primary emission of VOCs from building products generally dominates for a period of up to some months[232]. A number of international Indoor Climate Labelling schemes and guidelines/standards have been established to limit these emissions[228]. However, secondary emissions may arise after the initial decay period, which may alter the intensity and perception of the emission on a long-term basis[129, 227]. Still, these emissions will become relatively constant in time and can be managed by assuring the required constant base ventilation. Therefore, using the emissions from building materials for controlling the ventilation is not considered an efficient method for DCV systems.

Both the presence of occupancy and occupant related activity, e.g use of office equipment and cleaning, lead to variable emissions of gaseous and particulate substances. Unfortunately there is no suitable equipment currently available for detecting particles for continuous monitoring in terms of size and price[29]. Therefore, the measurement of gaseous compounds has been the primary interest. The sensory pollution load from people, the body odour, is a mixture of odours from a wide range of organic gases[216]. Carbon dioxide is commonly used as a surrogate for these compounds in order to evaluate and control the ventilation rates. The rate of generation of carbon dioxide by occupants is nearly proportional to the rate of other bio-effluent generation: both are generated at the rate proportional to the number of people, their body size and their activity level. Nevertheless, it must be pointed out that even though CO_2 levels have been correlated to comfort complaints indoors, carbon dioxide is not a pollutant of concern in buildings. Carbon dioxide does not influence the perception of the air quality in the concentration levels arising in ventilated rooms. It is used as an indicator for tracking the pollutants emitted by people, which can cause the indoor complaints.

The main advantages of using carbon dioxide as an indicator are the following: CO_2 concentration in indoor and outdoor air can easily be measured; CO_2 the concentration generated by human beings is predicable; CO_2 does not react with other gases; CO_2 does not penetrate surfaces enveloping a room. Furthermore, a relationship between the simultaneously measured levels of CO_2 and coarse particulate matter (PM_{10}) in mechanically ventilated spaces has been indicated[59], see Figure A.1. These results were obtained from measurements in a class room and it can be assumed that the particulate matter can be associated with human activities in the class room.

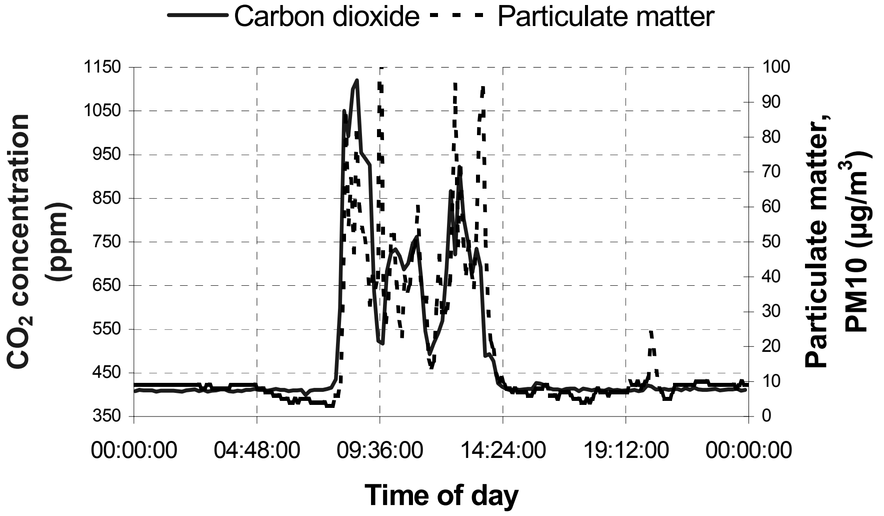


Figure A.1 Simultaneously measured carbon dioxide and particulate matter in a mechanically ventilated classroom [59]. The air change rate was 4,9 h^{-1}.

Many discussions concern the question whether the DCV control strategy based on carbon dioxide correctly corresponds to the number of people in the room in real time[8]. Carbon dioxide behaves like any other pollutant and thus for a given level of occupancy and rate of ventilation, its concentration will asymptotically rise to a "steady state" value. Therefore, very often the steady-state relationship is used to evaluate the concentration change and hence the ventilation need. However, in non-steady state conditions, which are typical for real-world applications, CO_2 concentration will generally lag behind changes in the actual number of occupants in the zone and changes in the ventilation rates. Nevertheless, according to a report by Taylor[96], even though the rate of air supplied using the steady state equation will not exactly track the source strength of bio-effluents due to transient effects, it should maintain an acceptable bio-effluent concentration.

Another option used to control the occupancy based pollution is to apply the presence of people as an indicator. This strategy is very often referred to as occupancy based DCV, where the ventilation system will be triggered directly when people enter the room, providing the exact ventilation rate per person needed to dilute the pollutants from people to the required levels. Since the traditional occupancy sensors indicate only occupied or unoccupied situations, the occupancy based DCV approach can be mainly applied when the exact number of people occupying the room can be predicted. However, more advanced sensors with occupancy counting capability have already become available in the market[22].

In general, the application of carbon dioxide or occupancy as the single indicator is recommended when there are no other strong indoor pollutant sources than people in the room. When the main pollutions sources that vary in time in the room are not just the presence of people other indicators should be included for controlling the indoor air quality. The measurement of VOCs has become of interest due to the considerable amount of different organic compounds emitted from different sources indoors.

Measuring VOCs in indoor environments is certainly extremely challenging due to the large number of VOCs present and their temporal and spatial variability. Moreover, it can be difficult to identify the VOCs originating from the specified sources and find the reference compounds that need to be controlled based on the health and comfort effects on humans. According to field studies, about 100 different VOCs have been identified in the emission testing of cleaning agents[233]. Studies with office equipment showed that the VOCs identified were insufficient in concentration to explain negative effects on humans during exposure[17, 133]. This suggests that other chemicals may contribute to the negative sensory perception. Selecting an indicator for controlling these pollutant emissions can be difficult. However, when the suitable reference organic pollutants and their emissions can be identified, the DCV system based on VOCs as an indicator can be advantageous. Meier[145] reported that VOCs can provide a good reference variable for DCV in restaurant conditions. The concentration of VOCs has been used for indoor air quality control in a space with tobacco smoking[240]. There are also other premises where the control of VOCs can be useful and needed. For example, elevated VOC concentrations have been indicated in department stores[136, 216], where the sensory pollution load is in a great extent dependent on the merchandise.

There are also other indicators used for a DCV system. For example, carbon monoxide could be used as a control parameter for ventilation in a space like a garage. However, it is not a good indicator for control of indoor air quality in other premises.

One prerequisite for ventilating with outdoor air is that it must be cleaner than indoor air. However, quite often the emissions from outdoor air, e.g. vehicle traffic and combustion, can cause the problems of air quality indoors. Based on the VOC source identification studies done in Helsinki by Edwards et al.[57], the workplace VOC concentrations were dominated by compounds associated with traffic emissions. When systems are designed, the conditions of outdoor air should be checked. This should be done in order to avoid situations where the VOC levels indoors, which actually are originating outdoors, are tried to be diluted by supplying more outdoor air. Pollutants which originate from outdoor air can to a great extent be controlled by air cleaning in a central air-handling system.

A.3 Sensors for DCV applications

This chapter describes the available sensing technologies for DCV systems. The types of sensors commonly applied in DCV systems are:

- Temperature sensors
- Humidity sensors
- Carbon dioxide sensors
- Mixed-gas sensors
- Occupancy sensors
- Combined sensors

This review is limited to control of indoor air quality with DCV systems. Therefore the sensors applicable for indoor air quality control are described here in detail. In addition, a short overview of the sensor market today and new possibilities in sensor technology is presented.

A.3.1 Carbon dioxide sensors

The carbon dioxide sensors are commonly based on non-dispersive infrared detection principle. Every gas absorbs light at specific wavelength and the infrared CO_2-sensor calculates the gas concentration by measuring the absorption of infrared light by CO_2 molecules.

The advantage of infrared detection of CO_2 is the sensors low cross-sensitivity, low hysteresis and reasonable uncertainty and linearity[74]. Disadvantages have been associated with long-term stability. Previous studies have also reported that the tested non-dispersive infrared sensors were sensitivity to relative humidity, temperature and tobacco smoke[74].

The sensor drift in these types of sensors were common to occur because of the particle build-up in the sensors and/or aging of the light source[187]. Photo-acoustic sensor accuracy can also be affected by vibration and atmospheric pressure changes. However, improvements have been done in the sensor design during the last 15 years and integration of microprocessor control have led to new sensor models with better accuracy and long-term stability. Particle build up have been minimized by use of gas permeable membranes, which permit gas diffusion but block larger particulate matter, or by hermetically sealing the optical system from dust particles[187]. There are also several ways to minimize the aging of the infrared source, e.g. use of a second detector tuned to a wavelength other than CO_2 for a reference value, integrating an additional reference light source or applying a tuneable infrared filter as a mean to provide a dual wavelength operation[132]. Another approach for drift compensation involves using a special software algorithm called Automatic Baseline Correction (ABC), which enables CO_2-sensors to automatically adjust themselves on a nightly basis when the space is unoccupied and inside levels drop to the baseline outdoor level. However, applying sensors with ABC algorithm requires that the building is not in constant operation, since the method resets the daily lowest measured value to an assumed background (outdoor) CO_2 concentration.

Recent studies with the CO_2-sensors with self-adjustment methods have shown contradicting results. Villenauve et al.[224] and Bernard et al.[23] conducted performance tests with five CO_2 sensors in laboratory and field conditions. The accuracies of tested sensors were close to manufacturers values and no drift occurred during an eight month measurement period in the field. However, in another study the results showed that the accuracy of CO_2-sensors used in commercial buildings is frequently less than is needed to measure peak indoor-outdoor CO_2 concentration differences with less than 20 % error[237]. This study evaluated the uncertainty of 44 "self-adjusting" non-dispersive infrared CO_2-sensors located in nine commercial buildings. Moreover, Apte[8] describes in his review the results obtained from a long-term test made with three "self-adjusting" non-dispersive infrared CO_2-sensors operated side by side. Considerable positive baseline offset was observed for one of the tested sensors.

Carbon dioxide sensors based on metal oxide semiconductor (MOS) and electrochemical sensor technology have also recently appeared in the market for the application of indoor air quality control. The MOS sensors are commonly used for sensing VOC gases and sensitivity of traditional MOS sensors towards carbon dioxide has been low. However, in new MOS types now available in the market the sensitivity to carbon dioxide is increased by doping Lanthanum into tin oxide.

The electrochemical sensors are reported to have shorter lifetime and lower stability than infrared sensors. Moreover, the baseline drift necessitates regular calibration[84]. Saffell and Iredale[180] conducted detailed performance and environmental tests with one type of electrochemical CO_2-sensor and compared the results with traditional non-dispersive infrared CO_2-sensors. It was concluded that the non-dispersive infrared sensors have the advantage of better accuracy, while the electrochemical cell has a faster warm up time and is better suited for dusty or damp environments. Nevertheless, there is still very little experience in using this type of sensor to measure carbon dioxide in the described application.

A.3.2 Mixed-gas sensors

The commonly available mixed-gas sensors for indoor air quality monitoring, often referred to as "VOC sensors" or "air quality sensors", are based on metal oxide semiconductor technology. In this study the term "mixed-gas sensors" is used and considered to be most correct, since with this technology principle it possible to measure also other gases than volatile organic compounds, VOCs. The metal oxide semiconductor sensor are based on the principle, where the target gases react with the oxygen on the sensing elements surface and hence changing the resistance of the sensing layer. Different response characteristics can be achieved by the deposition of semiconductor materials, use of different operating temperatures and by operating the sensors in fast pulsed temperature mode[41, 84, 239, 241].

The metal oxide semiconductor sensors measure non-selectively a wide range of gases, e.g. VOCs emitted by building occupants and their activities, tobacco smoke and building products. Traditionally the sensor signal gives no indication to the type of gases detected or in what concentration they are present. In the commercially available mixed-gas sensors the output signal is made proportional to "air quality ratings" of 0-100 %.

The advantage of mixed-gas sensors is their fairly competitive price. However, the common problem has been their non-specific behaviour. Since these sensors reacts to a large number of substances it is difficult to distinguish between the measurand of interest and external factors. Moreover, sensitivity to humidity and temperature and problems with stability have also been pointed out in several reports[74, 90, 93]. Saude et al.[182] carried out sensor performance tests with eight MOS mixed-gas sensors of two different types. The results showed that the tested mixed-gas sensors included a random drift in their basic voltage and a loss of sensitivity over time. This would make annual replacement of sensors necessary, causing problems with maintenance.

In addition, mixed-gas sensors are manufactured by several companies, but the majority of them use sensing elements from the same manufacturer. Even though different sensors are using the same sensing elements, the measurement results can differ due to different electronics in the transmitters[74].

There has been a lot of discussion on the applications of these sensors for controlling pollutants from occupancy related activities and whether mixed-gas sensors are sensitive enough for sensing the presence of people in the room[90]. Ruud et al.[179] conducted sensor tests in a conference room and found the mixed-gas sensors to be sensitive to the presence of people, tobacco smoke and other contaminations produced in the room. Positive correlation between the number of people and VOC levels have also been found in restaurant conditions[145], in an entertainment club[16] and in library conditions[147]. Furthermore, in the restaurant study done by Meier[145] it was additionally concluded that the mixed-gas sensors are suitable to correspond to food smells and tobacco smoke that were present in the restaurant. Similar results were indicated also by Huze et al.[95].

A.3.3 Humidity sensors

Humidity sensors in DCV applications are commonly used in dwellings to control the humidity levels in bathrooms, laundry rooms and kitchens. The humidity sensors traditionally used for DCV systems are following: hair and polyethylene-strip hygrometers, capacitive hygrometers, conductance-film hygrometers and lithium chloride sensors[173].

Since the humidity sensors are commonly applied in HVAC applications, a number of evaluations have been carried out about the performance of these sensors. The sensor tests part of ANNEX 18 program concluded that capacitive humidity sensors are well suited for the control of humidity levels in buildings[74]. The combined error of linearity, hysteresis and repeatability was below 5 % r.h. at +20 °C or even less for some sensors. The cross-sensitivity to variations in the ambient temperature and power supply were acceptable and cross sensitivity to hydrocarbons, carbon dioxide and tobacco smoke was negligible. Plastic strip humidity sensor tested in this study proved to be less suitable due to excessive hysteresis and linearity error.

Joshi et al.[116-118] carried out the experimental tests with capacitive and resistive type of duct mounted humidity sensors. Three duct mounted humidity sensors from each of six different manufacturers were tested and evaluated to determine the sensor uncertainty and to provide a comparison with manufacturer specifications. A total of

18 sensors were tested, nine of them were capacitive-type of sensors and nine were resistive-type of sensors. The evaluation results indicated that at 25 ˚C, two of the six humidity sensor models were within manufacturer-specified uncertainty of ± 3% for the entire relative humidity range of 10 % to 90 %. The third sensor model did not meet the manufacturer-specified uncertainty ± 3 % at any humidity level tested. The remaining three sensor models met the specified uncertainty of ± 3 % for only part of the humidity range. All of the sensors had positive hysteresis, with maximum less than 3.2 %, for all temperature and humidity levels. The largest nonlinearity -3.8 % r.h. occurred only with one sensor model. In a more recent report Joshi et al.[119] describes the evaluated response time for three capacitive type and three resistive type of duct-mounted humidity transmitters. The experimental test results revealed significant variation in the average response times, with fastest being 7 seconds and slowest being 96 seconds. Furthermore, the test results show that the tested capacitive-type of humidity sensors had faster response times compared to resistive-type of sensors.

A.3.4 Occupancy sensors

The traditional application of occupancy sensors has been for the control of lighting. However, nowadays the occupancy sensors have become more interesting for controlling the ventilation airflow rates in a DCV system. In DCV applications the occupancy sensors can be used for control of indoor air quality when the number of occupants during the period of occupancy is relatively stable and known, such as in a class room.

Most occupancy sensors applied in commercial applications use passive infrared or ultrasonic motion-sensing technologies. Some use also hybrid or dual-technologies, which combine the mentioned two technologies in one sensor[159]. The commonly available occupancy sensors provide information only about whether the room is occupied or not. However, a few people-counting types of occupancy sensors employing dynamic infrared imaging hardware and software have recently become available[22]. This kind of sensor can be more desirable for DCV application since it can provide the overview of the people entering the room and send signals to the control system to adjust the airflow accordingly. According to the conducted review by Apte[8], counting accuracy of these devices can be quite good and these devices do not suffer from the signal delay problems of the CO_2 sensing approach. Nevertheless, relatively few data exist about applying the occupancy counting sensors for ventilation control.

The performance of occupancy sensors has been studied to a great extent for applications of lighting control. However, there are many common requirements for sensor performance that should be applied also for occupancy controlled DCV systems. For example, for the desired performance of occupancy sensors it is necessary to correctly choose the coverage area of the sensor and properly adjust the sensor sensitivity. Improper adjustment and selection of these properties can lead to cases, where sensors do not correctly respond to occupancy or are not sensitive enough to detect smaller movements such as hand or wrist movement, and therefore lead to false detection of room occupancy[139]. Maniccia and Luan[139] discussed the methods to use to correctly evaluate the performance of occupancy sensors. Test methods for carrying out sensor performance tests are also described in other reports[22, 159]. Applying a switch-off delay time to the occupancy sensor is a commonly used method to avoid false detection signals of “no movement” when the activity level of people is low in the room. The chosen switch-off delay time to can have a great importance on the system performance and energy use and is discussed in several studies [140, 176].

A.3.5 Other sensors

In many applications more than one parameter is needed to be controlled in order to assure the required indoor climate. Combined sensors, often called multi-sensors, have become available in the market. This provides the possibility to monitor and control several parameters in the room, e.g. temperature/CO_2, CO_2/mixed-gases. Very often the available multi-sensors just combine the different measurements into one transmitter and no further processing of the different sensor signals is done in the sensor per se.

However, there are also more advanced multi-sensors developed, where the sensor system is combined with more complicated signal evaluation methods integrated into a microcontroller. These sensor arrays traditionally consist of several individual sensing elements based on different technology principles such as electrochemical sensors, mixed-gas sensors, different optical filters in a photo-acoustic instrument and humidity sensors[84]. Ivanov et al.[103] describe a prototype of a wall mounted multi-sensor module for residential buildings. The sensor module enables to measure different gases (CO_2, CO, O_3, H_2, H_2S), dust particle concentration, air temperature, relative humidity and it can be used also for smoke detection. The necessary signal processing is carried out by a cheap microcontroller.

The most sophisticated sensor arrays are the so-called “electronic noses”, which utilize integrated sensor arrays in combination with neural network or other advanced signal evaluation methods. The objective is to simulate the human olfactory system in a simplified form. The algorithms used for signal evaluation need a calibration to detect certain gases in the environment. On the other hand, these electronic noses can be calibrated to the human odour perception by comparisons with test persons[84]. Wenger et al.[220] showed in a study with a sensor array including sensors for temperature, dew-point and different gas concentration measurements, that the array does not require an excessive number of sensors, yet provides substantially better correlation with *decipol* than any single sensor measurement.

Different “electronic noses” are already available in the market. They are mainly applied in other fields than indoor climate control, e.g. food industry, medical industry. The use of electronic noses for indoor climate control is still under development and only few evaluations of this kind of sensor arrays for indoor air quality control purpose have been conducted. Zampolli et al.[241] developed a miniaturized electronic nose for monitoring the compounds of interest for indoor air quality control. The sensor performance was validated by using CO and NO_2 as target compounds. The results indicated that low cost real time detection for various gaseous contaminants is feasible. The sensor system was able to identify the presence of target pollutants at concentrations lower than the threshold values. Wolfrum et al.[225] demonstrated a metal oxide sensor array which is able to detect, differentiate and quantify different VOCs at ppb concentration levels, which are typical of indoor environment.

A.3.6 Sensor market today and possibilities in sensor technology

In ANNEX 18[173] at the beginning of 1990-s a prediction for the future sensor market was done. A high development potential for MOS and MOSFET sensors was expected, which would be sensitive, selective, stable and durable against chemical, mechanical and thermal influences and inexpensive. Also the development of integrated multi-sensors for combined measurements for temperature, humidity, CO/CO_2 and other needed parameters were predicted. The main requirements for the sensor development were to have sensors which are inexpensive, easy to check and calibrate, stable and have a long service life[153].

Even though no selective metal oxide semiconductor sensor with required performance properties has been developed so far, there has been a great development of other sensors. The prices of CO_2 sensors for DCV have dropped by about 50 % since 1990 and as the market penetration increases they are expected to fall further[80]. Moreover, the accuracy and long-term stability of the sensors have been considerably improved. Sensors with self-adjustment features are already available and continuous development is done for improving the sensor performance even more.

Additionally, multi-sensors with combined measurement abilities have become available in the market, providing more flexible and intelligent solutions for indoor climate control. The technologies of combined sensors is striving towards system solutions which are inexpensive, easy to install, flexible, maintenance-free and reliable with long battery life. By using MEMS technology (Micro Electro Mechanical Systems) a variety of indoor air quality related measurements can be conducted with small and compact sensor system[55, 218]. Feasibility studies on developing such advanced multi-sensors for indoor environment control have been initiated by Nordic Innovation Centre[55]. The technology platform for described multi-sensors has already been established. However, important performance improvements are still required.

In addition to the quality improvements of sensors, simplified installation is required. One of the largest cost components for sensors is the cost of installation. Installation of wiring can represent 20% to 80% of the cost of a sensor point in an HVAC system[126]. Moreover, as the number of sensors in buildings increases, methods for networking the system of sensors is needed and interoperability and self-identification will be important[29]. Therefore, efficient schemes for powering the instruments and advanced communication modes must be developed. New opportunities of wireless sensor technology can significantly reduce the wiring costs, improve the flexibility of sensors and extend the functionality of an indoor climate control system[29]. A few sensor systems with wireless communication have already become available in the market and proven to be deployable[125]. However, since these systems are relatively new in the building automation field, confidence needs to be gained that wireless sensors and controls are reliable and perform as designed. Moreover, the cost of wireless sensors and networks should be reduced in order to be cost competitive with wired sensors.

A.4 Application of DCV systems

This chapter reviews the studies on performance and application of DCV systems in different types of premises. Additionally, issues related to the design and control of DCV systems are discussed.

A.4.1 Performance evaluations of DCV systems

Here the application of DCV systems in different types of buildings is discussed. DCV systems have been used in many projects in a variety of applications including offices, schools, conference rooms/auditoria, dwellings, restaurants and entertainment clubs.

A.4.1.1 Office buildings

Only a few experimental studies of DCV systems based on indoor air quality control applied to the office buildings are reported in the literature. Haghighat and Donnini[94] studied the performance of a CO_2-controlled ventilation system installed on one floor in an office building in Montreal. A comparison in terms of indoor air quality and energy demand was done with a conventional ventilation system. The results showed 12% of less energy demand for CO_2 controlled ventilation system as compared to the traditional constant air volume flow system. Moreover, the decreased average outdoor airflow rates did not worsen the quality of indoor air and thermal comfort. However, both of the systems compared were double duct constant air volume flow rate systems, where the amount of outdoor air was varied but the supply airflow to the room was kept constant. In Northern Europe, this kind of system with recirculation air is not common at all.

Other studies carried out computer simulations in order to evaluate the performance of a DCV system based on carbon dioxide as an indicator[35, 61, 123]. A number of studies discuss the concern of increase in non-human generated pollutants when DCV based on carbon dioxide is applied in office environments[35, 61, 168, 191]. Obviously, controlling the airflow rate based on carbon dioxide will keep the required indoor air quality when there are no other strong pollutant sources present than people. Other control strategies must be involved where the non-occupant generated pollutants is a concern. Assuring the minimum constant base ventilation airflow rate is a commonly used strategy to keep the pollutants that remain constant in time on an acceptable level.

Mui and Chan[148] studied the application of carbon dioxide based DCV systems in an office building and presented a method to determine the minimum fresh airflow rate needed in the system. In this study, radon was used as a reference gas, since it is a common pollutant embedded in the building materials of high-rise buildings in Hong Kong. The provided method was based on pollutant concentration, outdoor air damper opening and air change rate.

The highest benefits of carbon dioxide based DCV systems can be expected mainly when the occupancy is unpredictably variable. This can be in some extent observed in open space offices, where the exact number of people occupying the room is unpredictable in time. The occupancy level in office rooms is strongly dependent on what kinds of organizations are using the building. Therefore using CO_2 as an indicator can be justified for indoor air quality control. However, the effectiveness of applying a CO_2 based DCV system in cell offices can be questionable. In cellular offices the occupancy can be variable in time. Nevertheless, the number of people occupying the room can be predicted to a great extent. Therefore just occupancy controlled DCV systems can provide more efficient solution.

A.4.1.2 Conference rooms/auditoria

Public buildings with more variability in occupancy, e.g. as cinemas, theatres, auditoria, churches, lecture halls and conference rooms are good candidates for DCV systems and tend to realise the largest savings when compared to the traditional CAV system. Since such areas are usually non-smoking, at least in Nordic countries, carbon dioxide is commonly used as an indicator for pollutants that are related to the presence of people. Very often also a combination of carbon dioxide and temperature control is applied when the purpose of ventilation is both to control the thermal comfort and the indoor air quality.

Chan et al.[42] investigated the indoor air quality and energy savings of a lecture theatre at Hong Kong University. A demand control strategy using both carbon dioxide and radon gases as control parameters was proposed. A series of conducted demand control ventilation simulations showed that with a DCV system the average radon and CO_2 levels inside the lecture theatre were kept under recommended guideline values. In a further study this control strategy was additionally developed. Two different operation modes, such as a real time modulation mode for the times for occupancy and purging mode for non-occupied hours were proposed[40]. The field measurements indicated that the expected performance was achieved with such a system in terms of indoor air quality and energy use.

A French study aimed to investigate the performance of two different DCV systems in two meeting rooms[20]. An occupancy based DCV system was installed in a small meeting room for 10 persons. The presence of people was detected with occupancy sensors, which are able to evaluate the number of occupants in the room. The other system was a carbon dioxide based DCV system, which was installed in a large meeting room for 30 seated persons and up to 50 standing persons. The author concluded that both systems react correctly to the real occupancy.

A.4.1.3 Schools

Another big potential for the use of DCV systems is in school premises. The majority of the schools in Scandinavia operate with constant air volume (CAV) flow ventilation systems. However, due to the relatively high occupancy and its variability over the day, DCV systems have become more commonly applied in several schools in Scandinavia and other countries.

Davanagere et al.[48] used computer simulations to investigate the impact of the American standard ASHRAE 62-1989[11] on a typical elementary school located in Florida cities. Since Florida has a hot and humid climate, the primary concern is indoor relative humidity levels about 60 % and the potential for mould and mildew growth. The results of the simulation study showed that conventional HVAC systems will have problems maintaining proper indoor humidity levels in schools with ventilation rates prescribed by the ASHRAE Standard. For this study, the DCV strategy was modelled by adjusting the ventilation rate based on the selected occupancy schedules. The author concluded that DCV system was able to provide a lower humidity level compared to the conventional ventilation system.

In another research, Mysen et al.[151] estimated the average airflow rate needed for different ventilating strategies and the corresponding energy savings with carbon dioxide based DCV and occupancy based DCV compared with a CAV system. The estimation was based on the data on actual occupancy density and the time-of-use.

This was obtained from 157 inspected classrooms occupied by fourth-grade pupils at 81 randomly selected schools in Oslo. The average CO_2 concentration was below 900 ppm when 22 occupants were present in the classroom. The comparison of the performance of the two DCV systems reveals that less average airflow rate is needed for carbon dioxide based DCV systems than for occupancy based DCV system. The use of CO_2 or occupancy sensor controlled DCV systems can reduce the energy use 38% and 51 % respectively of the corresponding energy use for a CAV system, in the case for 10 hours of operation. However, both energy use and profitability of the two systems is to a great extent dependent on the occupancy pattern in the class rooms and on the operation period. Occupancy sensors are considerably cheaper than CO_2 sensors and easier to maintain. The author concludes that if a school has full classes and negligible absenteeism, then the occupancy based DCV system would be more profitable and vice a versa for CO_2 based DCV system.

A.4.1.4 Residential buildings

The application of DCV systems in residential buildings has in a great extent concentrated on humidity control in these premises. According to ANNEX 18 final report[152, 153], the humidity problems, such as moisture, mould growth, destruction of wall, are the main concern in dwellings. The general trend was that if ventilation is appropriate to control the humidity aspects then the other pollutants are correctly dealt with too. However, there have been different opinions regarding if humidity controlled ventilation provides the required indoor climate in dwellings. In one of the earlier studies, Parekh and Riley[165] found that controlling the ventilation based on relative humidity may not be sufficient enough to maintain the required indoor climate. This is because it did not appear to track the levels of normal human activity accurately. Instead a combination of CO_2 and relative humidity sensors is recommended for providing good air quality and moisture control in dwellings in cold climates.

Jardinier[108] describes that even though a clear link between the increase of CO_2 and increase of absolute humidity in kitchens, bathrooms and toilets has been indicated, there is a clear trend that humidity control is more suitable than CO_2 control in these rooms. A link between the variation of occupancy and humidity was also detected in other rooms, such as bedrooms. However, as the average relative humidity will vary according to the seasons, the basic air flows will be decreased during winter time when absolute outside humidity is lower. Therefore a control of ventilation in these rooms can not rely on humidity alone.

Heinonen and Seppänen[88, 89] carried out an experimental research with a combined DCV system in full-scale dwelling model in a laboratory. In this DCV system the supply and exhaust airflows of the bedrooms were controlled by a CO_2 sensor and the exhaust airflow of the bathroom by a relative humidity sensor. The results showed clearly that it is possible to control the exhaust and the supply air of the room spaces at a wide range. It was concluded that good indoor air quality can be achieved by the DCV system presented in this paper.

Recommendations for combined DCV systems have also been provided by Pavlovas[166], who carried out simulations of different DCV systems applied to a typical Swedish multifamily building. The performance of different DCV system strategies, where the air outlet vents in the kitchen and in the bathroom were controlled by humidity, CO_2 or occupancy, was analysed. Simulation results showed that both CO_2 and the occupancy control result in a similar air quality. However, both strategies increase the risk for high humidity levels in comparison to the reference case with open doors. Therefore a combined humidity control and CO_2/occupancy strategy is recommended. Application of the humidity controlled DCV strategy was able to keep the CO_2 levels below 1200 ppm when the apartment was occupied. Nevertheless, increased risk for poor indoor climate may occur during the winter time when the exhaust air flow is low due to the low outdoor humidity conditions. The energy use simulations revealed that both CO_2 and the relative humidity control strategy may result in higher than 50 % reduction of the annual heat demand for ventilation, when compared to the reference CAV system. With the occupancy control the reduction is about 20 %. Nevertheless, when applying this strategy the occupancy schedule must be precisely determined in order to achieve the minimal energy use of the system.

Savin et al.[183] investigated the humidity controlled hybrid ventilation in 55 occupied dwellings in France for two years. In this ventilation system the fresh air is provided by humidity sensitive air intakes located above the windows in the main rooms, such as bedrooms and a living room. The exhaust air is managed from the sanitary rooms by humidity sensitive exhaust grilles and from the kitchen hood. The results showed that the humidity controlled system guaranteed good indoor air quality, erased the condensation risk and limited the thermal losses by balancing the airflow between the floors.

A.4.1.5 Other premises

Controlling the outdoor airflow rates by mixed-gas sensors was carried out in an entertainment club by Atkinson [16]. A mixed-gas sensor was used to mitigate the effect of pollutant emissions from allowed tobacco smoking in the tested premises. The sensor was installed into the exhaust air duct. The author concluded that the multi-gas VOC indoor air quality sensor appeared to react favourably to human load in a space with tobacco smoking.

A performance of CO_2 and mixed-gas sensors in restaurant premises was compared by Meier[145]. The measurements showed that both types of sensors are suitable for registering changing occupancy and can provide the reference variable for DCV. However, it was found that the mixed-gas sensors are more suitable to correspond to food smells and tobacco smoke that were present in the restaurant.

Another study deals with simulations of energy savings of CO_2-based DCV in a Bingo hall[217]. A pre-simulation was carried out to determine the relationship between CO_2 concentration, ventilation rate and the occupancy pattern. Three scenarios were tested, such as fixed maximum ventilation, fixed minimum ventilation and CO_2-controlled ventilation. The results indicated that with DCV based on carbon dioxide the CO_2 concentration in the Bingo hall did not exceed 1000 ppm. However, the scenario with DCV system resulted in a slightly higher mean temperature than the fixed maximum ventilation scenario, due to synchronization of the ventilation with the occupant variation in time.

A.4.2 Feasibility studies

From the results of different studies it is commonly concluded that a DCV system spends less energy than other conventional systems. Obviously the main energy savings are achieved due to the decrease in airflow rates at low pollutant/heat load conditions in a building. The more the loads are varying in time, the more energy savings can be expected. The energy use of a DCV system also depends on many other parameters, such as outdoor climate, system design, hours of use, use of heat recovery, pollutant set point, control strategy, and on a reference case used as the baseline for estimating the savings. It must be mentioned that a significant shortcoming of several reviewed reports is the inclusion of little or no information about these parameters. Therefore, careful consideration should be done when drawing general conclusions from the results presented in different studies.

Meier[146] estimated potential energy savings for typical DCV applications based on the work reported by the IEA Annex 18 and the experiences of control companies. The reported energy saving range for restaurants and lecture halls is 20-50 %; open plan offices with low average occupancy about 20-30 %; open plan offices with high average occupancy about 3-5 %; entrance halls, booking halls, assembly halls, airport check-in areas, theatres, cinemas about 20-60 % and exhibition and sport halls 40-70%. Similar evaluations were also carried out by Sørensen[205]. In this study comprehensive DCV models were developed to estimate the range of energy savings compared to CAV systems in different case study conditions.

For estimating the energy use and potential energy savings of a DCV system it is essential to correctly evaluate the real occupancy of the building. It is widely believed that the actual occupancy is significantly lower than the design occupancy levels. Drangsholt[54] made full scale trial tests in an auditorium room and found that the average occupancy rate, defined in this study as the ratio between monitored occupancy and maximum allowed occupancy during the working period of the week, was in a range of 22-51 %. Mysen et al.[151] studied the occupancy in primary schools in Norway and showed that on average only 74 % of the classroom's design capacity is utilized. In cellular offices the average daytime occupancy has been reported to be in a range of 15 % to 80 % [21, 87, 111]. The occupancy level in office rooms is to a great extent dependent on what kind of organizations are using the building. The occupancy rate is consequently low in buildings where the employees have work tasks that require them to be away from the office for long periods of the day.

Besides the energy use of the system, the economic profitability of a DCV system is also affected by the initial investment costs and the policy of an energy price. In general the costs for controlling sensors and airflow rate control equipment can make a DCV system initially more expensive than a CAV system. These extra initial costs must be recovered by a decreased energy demand of the system. Sensor maintenance should be also considered as a significant criterion affecting the economics of a DCV system. When selecting sensors it is important to consider how the sensor deals with calibration, since maintenance requirements for low cost, poorly performing sensors can far exceed any energy savings generated[186]. In any case, the cost effectiveness of a DCV system for different applications needs to be assessed individually. Some studies have evaluated the profitability of CO_2 based DCV systems for certain applications and found the pay-back time period to be up to 3 years[54, 90].

For smaller spaces such as office cells, the economics of a DCV system can be more stringent. Mysen et al.[151] evaluated the possible profitability of an occupancy controlled DCV system in office cubicles in Norway. The results suggest the maximum profitable investment in DCV equipment to be about 400 EURO per cellular office if central installations and technical areas can be reduced as a result of installing a DCV system. This investment in DCV must cover all extra costs attributable to DCV. Johansson[112] analyzed energy use and life cycle costs for different ventilation systems in dwellings. The analysis was done for with and without variable airflow rate for multifamily apartments and detached houses. The results indicated that from a life cycle cost perspective a ventilation system with variable airflow rate and heat recovery was the most beneficial. The author also reports that it takes a little less than ten years to benefit from heat recovery and around 15 years to benefit from variable airflow rate.

A.4.3 Design issues of DCV systems

This chapter gives an overview of the typical issues related to the design and control of DCV systems that are discussed in the literature. First the different control strategies applicable for DCV systems are described. Additionally, the issues related to the placement of the controlling sensor are discussed.

A.4.3.1 Control strategies for DCV systems

The control strategy involves instructions and rules that are implemented into a control loop. It is essential for the control system to be stable, accurate and work with sufficient speed in order to assure minimum lag time when controlling the processes in the room. For example, an inherent sensor lag time exists with carbon dioxide as an indicator of occupancy. This is because it relies on a rise in concentration greater than the natural noise of the sensor signal and concentration fluctuations[8]. The rise and decay of CO_2 concentration can have lag time from many minutes to many hours, which depend both on air exchange rate and applied control strategy. There are number of control strategies available to compensate for the lag times.

The control algorithms applied commonly in control of HVAC systems are proportional (P), proportional-integral (PI) and proportional-integral-derivative (PID) control. The application of the different algorithms for airflow control in a DCV system is discussed in different articles. Proportional control is recommended to a wide range of occupant densities and patterns[188]. However, even though a pure P controller has proved to be sufficient in many cases, the lack of integral function of the local zone controllers have shown as an offset[205]. To account for the offset the integral term should be utilized also to local control. Both PI and PID control have an advantage in applications that have extremely low occupancy or have high densities and large air volumes, e.g. auditoriums, large conference areas. These control approaches will introduce higher outdoor airflow rates sooner, as pollutant concentrations start to rise and can ensure shorter lag times[5, 188]. Nevertheless, according to studies conducted auditorium conditions by Drangsholt[54] the difference between the PI- and PID controller is small. The author concludes that the control performance is not significantly improved by activating the derivative effect.
Vaculik and Plett[211] describes a control strategy which accounts for differences between CO_2 concentration at the measurement location and the critical location in the building. The control set point is adjusted according to the differences between the measured concentration and the set point. The results from controller operation simulations showed that the pollutant concentrations were kept on acceptable level with no major overshoots and that the sufficient outdoor air was provided at all times.

Most control systems applied to airflow control in a DCV system is related to the automatic feed-back loop strategy, where the calculation of the control signal is based on measurements of the controlled input, e.g. pollutant concentration, temperature. A complementary way for feed-back control is feed-forward control. A feed-forward control needs information regarding the occupancy load before the correct ventilation rate is set. With this control approach it is possible to eliminate a disturbance before it really affects the output signal of a process[195]. Moreover, applying a feed-forward control approach enables to optimize the lag time of a DCV control system, since the airflow rates are corrected based on the evaluation of actual occupancy. The actual occupancy load in the space can be evaluated by measuring airflow rates and pollutant concentrations, such as CO_2, in the supply and room air. Different occupancy detection algorithms have been discussed in several studies[123, 196, 214]. For accurate occupancy detection the algorithms applied for flow controllers should consider transient conditions in the room. Therefore dynamic detection methods are applied.

Federspiel[212] proposed a feed-forward control strategy which provides outdoor air at an airflow rate proportional to the occupant density under transient conditions. Simulations with a single-zone system showed that the new strategy responds faster to a change in the occupant density compared to a feed-back DCV strategy with PI control and keeps the concentration below the threshold. Another kind of feed-forward control algorithm was developed by Sørensen[205]. The control algorithm uses measurements of the CO_2 level and ventilation air flow rate to calculate an estimate of the occupant load in the room, represented by the *decipol* level. The *decipol* level can then be regulated to a specified set point by controlling the airflow rates. The simulations showed that this DCV control strategy can assure good indoor air quality. However, compared to pure CO_2 based DCV, a *decipol* DCV triggers a larger ventilation flow rate and a larger minimum flow rate. This means lowered room temperature levels during warm periods, but also decreased profit of the DCV system, especially during cold outdoor conditions.

A.4.3.2 Sensor location

Several reports have discussed the issue of sensor placement but only few of them have been analysed it in detail. In general, the sensor must be located in a place where it best represents and correctly responds to the measured indicator. Most commonly the sensors for DCV application are duct mounted or wall mounted. The single sensor placement in the common exhaust duct is very often favoured in order to reduce first cost, maintenance cost and complexity[150]. However, the opinions seem to differ whether the sensor placement in the exhaust air system is the appropriate location or not. There are guidelines stating that the sensors in exhaust air ducts are not allowed. This is because they can result in under-ventilation due to the measurement error caused by short-circuiting of supply air into exhaust air grilles and/or leakage of outdoor/exhaust air from other spaces into exhaust air ducts[38]. Other drawbacks with duct mounting can be that the sensor value in the duct will represent the average value of the pollutant concentration over the controlled zones. This however may not be representative of what is actually happening in a particular space[187]. According to an evaluation done by Mumma[150], in different building zones with different occupancy, employing a single sensor in the common exhaust air duct resulted in under-ventilation of the critical zones. However, several studies have discussed the adjustment of the set point value with the sensor located in the duct and providing correlations between the pollutant concentration at the exhaust air and at the breathing zone[175, 189]. In general, the installation of a controlling sensor in the duct system is recommended in conditions where the airflow control system serves a single zone or when the zones served by the airflow control system have similar occupancy patterns[36, 110, 187].

The sensor location is not so crucial when mixing ventilation is applied and if a good mixing is assured. In this case both room and duct installations can be recommended. Ruud et al.[179] carried out experiments in a meeting room with mixed ventilation and studied the work of a CO_2 and temperature controlled DCV system. The results indicated no substantial differences between measured CO_2 in the duct and at the wall. However, the wall mounted sensor had a 2-min delay compared to the sensor in the return air. Analysis of sensor placement in auditorium conditions was also conducted by Fehlmann et al.[79]. In this study the CO_2 concentration was monitored both in the centre of the room and at the lectern. The results revealed minimal differences in the concentrations at the two locations.

In the case of displacement ventilation the sensor location can be more difficult to choose, depending both on the occupancy and the geometry of the room[153]. In auditoriums and assembly rooms with displacement ventilation, the highest CO_2 concentrations appear in the upper part of the occupied zone[240]. In this case the sensor can be installed in the main exhaust air duct. Nevertheless, according to Drangsholt[54], this location can give a good indication of occupancy, but will not cover any poorly ventilated zones.

When sensors are mounted in the room, the placement should be as near as possible to the occupied zone. Following installation positions should be avoided: in the corners of the room, close to doorways and open windows, areas that receive direct sun light or are influenced by the supply/exhaust air streams, areas that are directly affected by indoor pollutant sources, e.g. breathing zone[12, 80, 187, 188]. The recommended positioning height in the room with mixed ventilation is between 0.3 and 1.8 m above the floor[38]. With displacement ventilation the recommended location is in the occupied zone at about head height[202]. In addition, with displacement ventilation the concentration set point should be set lower than that normally recommended for mixing ventilation. Otherwise the sensor would seldom decide the control[202].

A.5 Conclusions

Demand controlled ventilation systems have the potential to provide a significant decrease in energy use when compared to reference systems with constant airflow rates, while achieving a comparable level of indoor climate. Therefore the application of DCV systems has increased during the last decades. A DCV system based on temperature control, commonly referred to as a VAV system, has been the most widespread DCV system strategy so far. However, DCV systems where the airflow rates are controlled based on the indoor air quality parameters have also become of interest.

The purpose of this review was to summarize the literature on the current technology and application of DCV systems for non-industrial buildings. The specific interest was the application of DCV systems for indoor air quality control, since control of thermal comfort with these systems have been studied already to a great extent. The literature review reveals that the technology of DCV systems has developed during the last decade, but further developments are expected. The information found in the literature review can be summarized as follows:

- Indicators, such as Carbon dioxide, occupancy, VOCs and relative humidity, can been used as control parameters for ventilation control in DCV systems in order to assure the required indoor air quality. Carbon dioxide is commonly used as an indicator for occupancy generated pollutants. Additionally, when the number of people occupying the room is known the presence of people can be used as an indicator. For controlling the pollutants from other sources than people, the direct measurement of VOCs and particles can be of interest. However, it can be difficult to identify the reference VOC gases that need to be controlled based on the health and comfort effects on humans. In spaces with elevated humidity levels, relative humidity can be used as a control parameter for a DCV system. However, humidity is not recommended as a single decision variable in DCV systems for indoor air quality control.

- The following sensor types can be applied for indoor air quality control with DCV systems: humidity sensors, Carbon dioxide sensors, mixed-gas sensors, occupancy sensors. Additionally, combined sensors, incorporating possibilities to measure more than one indoor climate parameter, have become available in the market, providing more flexibility to DCV systems. Development in sensor technology has made mass production of sensors possible, thus decreasing the price of sensors considerably. Moreover, the stability and accuracy of currently available sensors has improved, thus decreasing the costs for calibration and maintenance. Nevertheless, data on the performance of currently available sensor technologies of DCV systems is rather limited and more research is needed in this field.

- DCV systems have been used in a variety of applications including offices, schools, conference rooms/auditoria, dwellings, restaurants and entertainment clubs. DCV systems based on Carbon dioxide or occupancy control are applied commonly to auditoria, schools and to office areas with variable and unpredictable occupancy patterns. The control based on measurement of mixed-gases has been applied to restaurant areas, entertainment clubs and other premises where non-occupancy related pollutants are dominating. In dwellings, the application of DCV systems has to a great extent concentrated on humidity control. However, different studies have shown that controlling the ventilation based on relative humidity as a single parameter may not be sufficient to maintain the required indoor climate. Combined control based on occupancy, CO_2 and humidity levels is recommended in dwellings.

- The energy use of a DCV system depends on many parameters, such as variation of loads in time, hours of use, control strategy, system design, etc. Energy savings compared to the conventional CAV system are highest in rooms with fluctuating occupancy and high density occupancy. For estimating the energy use and potential energy savings of a DCV system it is essential to correctly evaluate the occupancy patterns in the building. The economic profitability of a DCV system is also affected by the initial investment costs, required maintenance of the system and the policy of an energy price. The cost-effectiveness of each application of DCV needs to be assessed separately.

- The most common control strategy applied to airflow control in a DCV system is automatic feedback control, where the calculation of the control signal is based on measurements of the controlled input, e.g. pollutant concentration. A complementary way of control is by feed-forward control. In a feed-forward control approach the airflow rates are corrected based on the evaluation of actual occupancy by measuring airflow rates and pollutant concentrations, such as CO_2, in the supply and room air.

- Different guidelines exist for the most suitable location of the controlling sensor, depending on the type of air distribution, type of premises and design of the system. The installation of a controlling sensor in the duct system is recommended in conditions where the airflow control system serves a single zone or when the zones served by the airflow control system have similar occupancy patterns. When sensors are mounted in the room, the placement should be as near as possible to the occupied zone. Additionally, with displacement ventilation the concentration set point should be set lower than that normally recommended for mixing ventilation.

APPENDIX B

B Detailed description of experimental methodology

This appendix describes the experimental methodology and the test equipment used in the different studies in detail.

B.1 Evaluation of the performance of the simplified DCV system solution – tests in the field

B.1.1 Case study 1

The first case study was carried out in an existing office building, which is built in early 1960-ies. The building locates in the campus of Chalmers University of Technology in Gotheburg. The building with the area of 3500 m^2 has 107 office rooms on 5 floors. Figure B.1 shows a photo of the building and a typical floor plan.

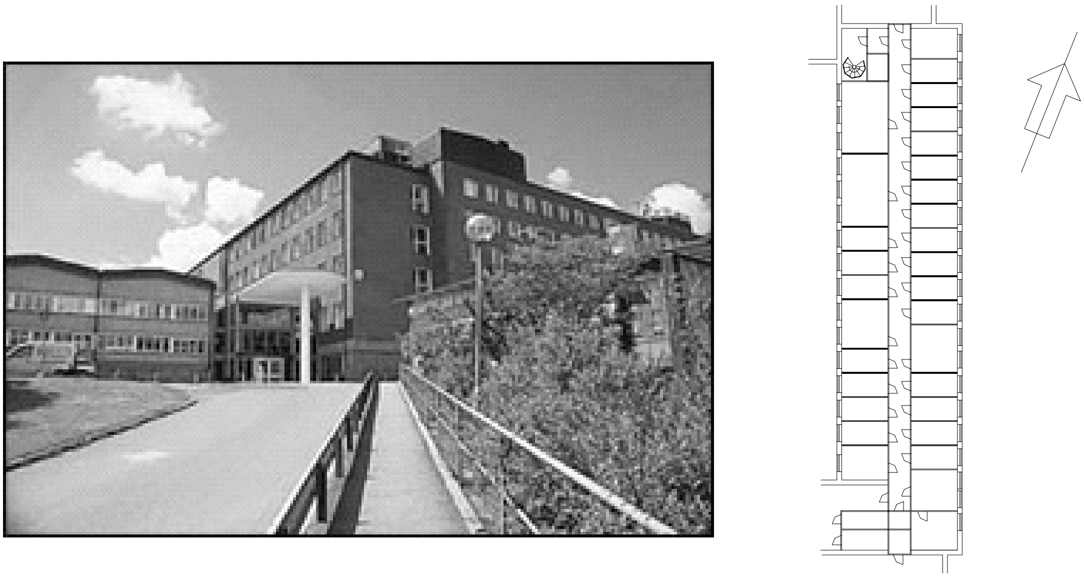


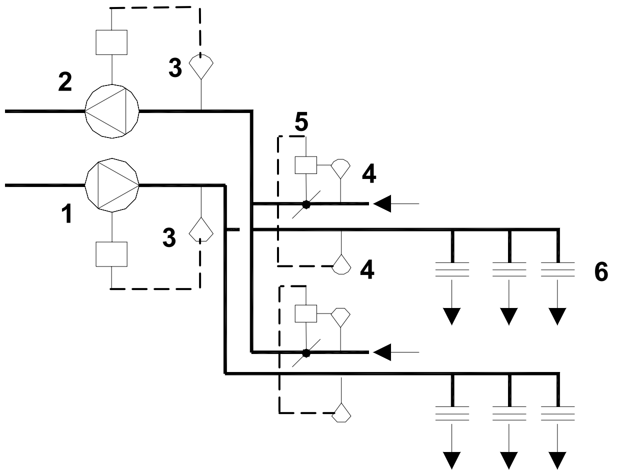
Figure B.1 A photo and a scheme of a typical floor plan in *Case study 1*

The air distribution in the rooms is with mixing ventilation from ceiling diffusers. The exhaust air from each room is transferred to the corridor through a transfer air grille above the doors. The rooms are heated by hydraulic radiators below the windows.

The air handling system in the building was reconstructed in 2003. The ventilation system was changed from a CAV system to a DCV system. The aim was to improve indoor climate in rooms, e.g. the previous system had no central cooling, and also achieve energy savings. The old supply air devices were changed to pressure independent variable air volume diffusers. Consequently no extra active control dampers were installed in the supply air system.

The existing approx 15 years old air-handling unit with regenerative air-to-air heat recovery and the original duct system were preserved during the renovation. However, a cooling coil was installed in the air-handling unit during the rebuilding. In addition, variable frequency inverters for fan speed control were installed for both supply and exhaust air fans in order to maintain a specific static pressure in the main ducts near the air-handling unit. The supply and exhaust airflow rates are balanced on each floor.

This is done by measuring the supply and exhaust airflow rates on the main ducts and controlling the exhaust airflow rate with a damper installed in the main exhaust air duct. A schematic picture of the installed DCV system in this building is presented in figure B.2.



In the figure:
1 Supply air fan with a variable frequency inverter
2 Exhaust air fan with a variable frequency inverter
3 Pressure sensor
4 Airflow measurement device
5 control damper for the exhaust air
6 Pressure independent variable supply air diffusers

Figure B.2 A scheme of the installed DCV system in *Case study 1*

After the renovation the supply air temperature from the central air handling unit is approx. +13 °C to +14 °C all year around. The duct system is not insulated. Therefore the supply air warms up to some extent in the ducts before reaching the outlets.

All the variable supply air diffusers, the DCV diffusers, are equipped with room temperature and occupancy sensors. Each supply air device is programmed for two low airflow rates and one maximum airflow rate. If the room is empty and the room temperature is below +23 °C, the supply air device is working with the minimum airflow rate 5 l/s. When someone enters the room the airflow rate increases to 10 l/s, which corresponds to approx 1.1 h^{-1} in a typical room with the size of 11 m^2. If the room temperature increases over +23 °C, the airflow rate from the diffuser increases up to the maximum 40 l/s in order to keep the room temperature on the desired level. The maximum airflow rate 40 l/s corresponds to 4.5 h^{-1} in a typical room with the size 11 m^2.

The air-handling system is in operation during working hours. Outside this period of time the ventilation system is switched off or running under minimum air flow rates. Night cooling is applied summertime. If the room temperature increases higher than +21 °C during non-working hours and the outdoor temperature at the same time is below +17 °C, all the supply air devices will be fully opened and the air handling unit starts. When the room temperature gets lower than +23 °C or if the outdoor temperature gets higher than +17 °C the air handling unit stops.

To avoid simultaneous cooling and heating in rooms, a dead band of 2 ºC in set between the set points of supply air devices and the radiators thermostat valves.

The data of the ventilation system before and after renovation are presented in Table B.1. Due to the lack of data about the energy consumption with the old HVAC system, the numbers given in Table B.1 are calculated with the simulation program BV^2[44].

The aim was to compare and predict the effect of rebuilding the system from CAV to DCV.

Table B.1 The calculated parameters of the air-handling system before and after the renovation in the *Case study 1* building. The temperature efficiency is given as an average over the year

System parameter	**Before rebuilding CAV system**	**After rebuilding DCV system**
Design airflow rate	5,6 m^3/s	5,6 m^3/s
Minimum sum airflow of supply diffusers	-	0,86 m^3/s
Operation time	~3500 h/year	~3500 h/year
Supply air temperature	18°C	15°C
Exhaust air temperature	23 °C	23°C
Heat recovery- temperature efficiency	average 75%	average 78%
Specific fan power- SFP at design airflow	2,5 $kW/m^3/s$	2,5 $kW/m^3/s$
Electrical energy needed for fans	14,8 kWh/year, m^2	7,7 kWh/year, m^2
Heat energy needed	6,6 kWh/year, m^2	0,05 kWh/year, m^2
Cooling energy needed for cooling the air	-	16,5 kWh/year, m^2
Heat energy needed for radiators	83,2 kWh/year, m^2	77,8 kWh/year, m^2

B.1.2 Case study 2

The second case study was carried out in a modern office building in Gothenburg. The new administration building for the Sahlgrenska Academy at Gothenburg University was taken in operation in spring 2004 and consists of two parts. The newly built part of the building, designated as *Case study 2A,* has 1820 m^2 of premises area (LOA) on three floors. It includes 14 cell office rooms, 7 meeting rooms, a lecture hall, the Faculty Club, a break room, a copy room, a storage room and a kitchen. Additionally, there is a big open space foyer and entrance area. The Faculty club is designed for conference and festive activities, e.g. official dinners. The total gross area of the building is 2500 m^2 (BTA).

The other, older part of the building, designated here as *Case study 2B,* consists of mainly cell office rooms with total premises area of 1967 m^2 (LOA) on five floors. The total gross area of the building is 2500 m^2 (BTA). The facility has 58 office rooms, 5 copy rooms, 5 meeting rooms, 5 break rooms, 3 rooms for archives and library and a few storage and equipment rooms. This building part was originally built in the 1960ies, but only the radiator system was kept during the renovation. All other building services systems have been fully changed, including the ventilation system. A photo of the building and a typical floor plan is shown on figure B.3.

Floor heating is used in the majority part of the *Case study 2A*, whereas office rooms have hydraulic radiators under the windows. Both cooling and heating systems are connected to a borehole heat pump/water chiller system.

Figure B.3. A photo and a scheme of the building in *Case study 2*. Building *A* marks the new building part - *Case study 2A*, building *B* is the fully renovated building part - *Case study 2B.*

Both building parts have demand controlled ventilation systems supported from separate air-handling units. The air-handling units consist of filters, regenerative air-to-air heat exchanger, a fan system with variable frequency inverters, heating and cooling coils. Heating coils are installed on the exhaust side of the system for dumping the heat coming from the water chiller condensers in summertime. They also can be used for heating the supply air through the regenerative heat exchanger. The heat exchanger is designed to raise the outside air through to the required supply air temperature +13 °C - +14 °C at the design outdoor conditions with -16 °C temperature. The supply air temperature is kept the same all year around. Due to the heat gains in the duct system the supply air temperature to the rooms is approx +15 °C. The duct system is insulated with 30 - 40 mm mineral wool insulation in main and branch ducts. The connection ducts are insulated in the *Case study 2A* building part with 30mm mineral wool. In *Case study 2B* building the connection ducts are not insulated.

The air distribution to the office rooms is with mixing ventilation from ceiling diffusers and the exhaust air is transferred from each room to the corridor through a transfer air grille above the door. The exhaust air is typically taken from the corridors.

The DCV system is built up similarly to the system in *Case study 1*, shown on figure B.2. A constant static pressure is maintained in the main ducts near the air-handling unit. The supply and exhaust airflow rates are balanced on each floor by measuring the supply and exhaust airflow rates on the main ducts and controlling the exhaust airflow rate with a damper installed in the main duct next to the exhaust air shaft.

Similar pressure independent DCV diffusers as in the *Case study 1* are installed to the rooms. The airflow rates are controlled by room temperature and occupancy sensors. Each DCV diffuser is programmed for two low airflow rates and one maximum airflow rate. If the room is empty and the room temperature is under +23 °C, the diffuser is working with the minimum airflow rate 7 l/s, which corresponds to approx 0.7 h^{-1} in a typical office room. When someone enters the room the airflow rate increases to 10 l/s, which corresponds to approx 1 h^{-1} in a typical room with the size of 13 m^2. If the room temperature increases over +23 °C, the airflow rate increases up to maximum 30 l/s, which corresponds to approx 3 h^{-1} in a typical office room. In a few conference rooms the maximum airflow rate per device is 50 l/s.

The lecture hall in the *Case study 2A* building part has a DCV system controlled by CO_2-sensors. The set point for the CO_2-sensors is 700 ppm. The supply air is delivered to the room from grilles located under the chairs with the supply air temperature of +19 °C. The supply air is warmed up to +15 °C, which is supplied from central air-handling unit, via a re-heating coil. The exhaust it managed via exhaust air grilles close to the ceiling.

The air handling system is in operation during working hours. Nighttimes the ventilation system is switched off or running with minimum airflow rates.

The design parameters of the ventilation systems in *Case study 2* building are presented in Table B.2.

Table B.2 The design parameters of air-handling systems in *Case study 2*

System parameter	***Case study 2A***	***Case study 2B***
Design airflow rate	5,0 m^3/s	3,6 m^3/s
Maximum total airflow of supply diffusers	4,2 m^3/s	3,0 m^3/s
Minimum total airflow of supply diffusers	0,71 m^3/s	0,66 m^3/s
Operation hours	3500 h/year	3500 h/year
Supply air temperature to the rooms	15°C	15°C
Exhaust air temperature	22°C	22°C
Heat recovery- temperature efficiency	min 82%	min 82%
Specific fan power- SFP at design airflow	2,1 $kW/m^3/s$	1,9 $kW/m^3/s$

B.1.3 Measurement techniques and instrumentation

Thermal comfort and noise measurements were carried out in a number of selected office rooms in both case studies. The rooms chosen for the measurements were typical cellular office rooms. The aim of the measurements was to evaluate indoor climate parameters in the rooms with pressure independent DCV supply air devices. Both measurements were made at the conditions of the maximum supply airflow rate to the room and with the supply air temperature about +15 °C. The airflow rates to the rooms were changed by logging into the device with the palm computer and changing the settings.

The thermal comfort measurements were mainly focused on the risk of local thermal discomfort in rooms. Room temperature, local mean air velocity and variations in air velocity were measured in order to evaluate the risk of draught. Two different measurement instruments were used in the case studies. A preliminary requirement for selecting an instrument for these measurements was to have an omni directional air velocity transducer that is able to measure air velocity down to 0,05 m/s and fluctuations up to 2 Hz[32]. This is important for evaluating draught rate in the room. A “Brüel & Kjaer Model 1213 – Thermal Climate Analyzer” was used for the Case study 1. A SWEMA 300 measurement instrument with SWA 01 comfort probe was used for the same kind of measurements in Case study 2. The characteristics of both instruments are given in Table B.3.

Table B.3 Information about the instruments used for thermal comfort measurements

Instrument	Measuring Range, [°C]	Measuring Range, [m/s]	Uncertainty [°C]	Uncertainty [m/s]
B&K 1213 Thermal climate analyser	-20°C…50°C	0,05…1 m/s	± 0,2 °C	± 0,02 m/s
SWA 01+ SWEMA 300logger	10°C…40°C	0…1,0 m/s	± 0,3 °C	± 0,02 m/s

The noise measurements included measuring the sound pressure levels in the rooms. The noise measurements were carried out with a "Brüel & Kjær" sound analyser, type 2260 Investigator including application BZ7206 version 2.1. The sound pressure levels were measured for different frequencies divided in thirds of the octave band. The measurement range was set to 9.7 - 89.7 dB. An "A" frequency weighting was used. Before starting up the measurements the instrument was externally calibrated in the field with the manufacture's sound level calibrator.

All of the selected rooms were locating far from the air-handling unit in order to avoid possible noise interference from the air-handling system. Still, problems with background noise occurred during the measurement time. To evaluate the noise levels generated by the DCV diffuser itself, it was presumed that it cannot exceed the minimum measured sound pressure level in the room.

The measuring sensors/transducers in thermal comfort and noise measurements were placed at the level of a sitting person's head, 1.1 m above the floor, near to the working place. The measurement time was approx 10 minutes in *Case study 1* and approx 3 minutes in *Case study 2.* The results are presented as an average over this time period. However, in *Case study 1* the local average air velocity and standard deviation of air velocity was calculated over the 3 minutes before the last measured minute. This was done to exclude the disturbing effect to air movement from people.

The airflows from the DCV diffusers were measured with the measurement equipment installed into the device. The simultaneous airflow rate values were read with a palm computer. According to the data from the manufacturer, the measurement uncertainty of the airflow measurement with the sensors in supply air diffuser is ± 2 l/s.

The supply air temperature and pressure in the duct just before the supply air device was also measured in the selected rooms. The supply air temperature was measured with probe SWA 31 connected to SWEMA 300 logger, which measures the temperatures in the range of –20…+80°C with the uncertainty of ± 0.3 °C. The given uncertainty includes a probe together with any calibrated SWEMA Air 300 logger. The pressure in the duct was measured with the Prandtl-tube, which has the uncertainty of ± 0.5 Pa.

The energy use of the air-handling systems in both case studies was also monitored during one year period of time. In the first case study, *Case study 1,* the presented results cover the period of January 2004 to December 2004; in the second case study, *Case study 2,* the results are taken from the period May 2004 to April 2005. A small gap in the measurement period occurred during the second case study in *Case study 2B* and as a result there was no values recorded during the period of 5-19 of August.

The use of electrical energy for supply and exhaust air fans were measured. The supply and exhaust airflow rates were evaluated by measuring pressure difference with sensors inside the fan casing (*Case study 2*) or with static pressure difference measurements over the heat exchanger (*Case study 1*). The thermal energy needed for supply air heating and the cooling capacity needed for the supply air cooling was evaluated by measuring temperatures in different points in the air-handling system. The temperatures were measured after the supply fan, after the heat exchanger, after the cooling coil, before and after the heating coil, outdoors and after the air-handling unit on the exhaust air side. In *Case study 1,* the supply and return water temperatures of the heating coil were also measured. The sampling time was 60 seconds and the results are presented as one-hour average values.

The energy consumption and airflow rate measurements in both case studies were carried out by CIT Energy Management AB[104, 105], on commission by the building owner, Academiska Hus. Therefore the measurement techniques and instrumentation will be not discussed deeply in this thesis work. However, all of the values lower than the minimum airflow rate in the system were considered to be part of the measurement error and the corresponding values were not accounted in the analysis.

Besides physical measurements for thermal comfort evaluation in office rooms, questionnaires of the users' perceptions and their preferences were carried out in both case studies. The used questionnaire is based on ISO 10551[102] standard and consists of questions about indoor environmental parameters such as perceived room temperature, air movement, air humidity, noise, light and air quality. This kind of questionnaire has been commonly accepted and used also in many previous studies[194, 201]. The used questionnaire is presented in APPENDIX D.

The total number of questionnaires distributed in *Case study 1* was 104 for evaluating the winter period and 114 for evaluating the summer period. The percentage of questionnaires returned was approx 42% both times. This low percentage was due to the fact that many university workers in that building were lacking of time to fill it in and not all the distributed questionnaires were returned. However, the results were obtained from at least half of the office rooms per floor. In *Case study 2* 55 questionnaires were distributed for the summer period and 70 for the winter period. All together 53% of the summer questionnaires and 67% of the winter ones were answered.

As a result mean values of the occupants′ votes for different parameters were calculated for both case study buildings for summer and winter period. Additionally, the answers of the questionnaires were statistically analyzed in order to find possible significance differences between the summer and winter cases. Significance tests were done by using *Student's T-test* (statistical hypothesis test), which compares the actual difference between two means in relation to the variation in the whole data. The chosen significance level in the analysis accounted here is 95 % ($p = 0.05$).

B.2 Evaluation of the performance of the simplified DCV system solution – tests in the laboratory

B.2.1 The test room and the test set-up

Laboratory measurements were carried out in a simulated environment: in a full size office cube built inside the laboratory hall. The test set-up consisted of a test room, a supply air fan with frequency inverter and with a pressure control, a sound attenuator, a supply air heater with an air temperature control, an airflow measuring device, a pressure independent variable supply air diffuser and temperature sensors. The temperature sensors were used for monitoring temperatures in the duct and inside and outside the test room. All sensors were connected via a logger to a personal computer for monitoring purpose. A schematic picture of the test set-up is shown in figure B.4.

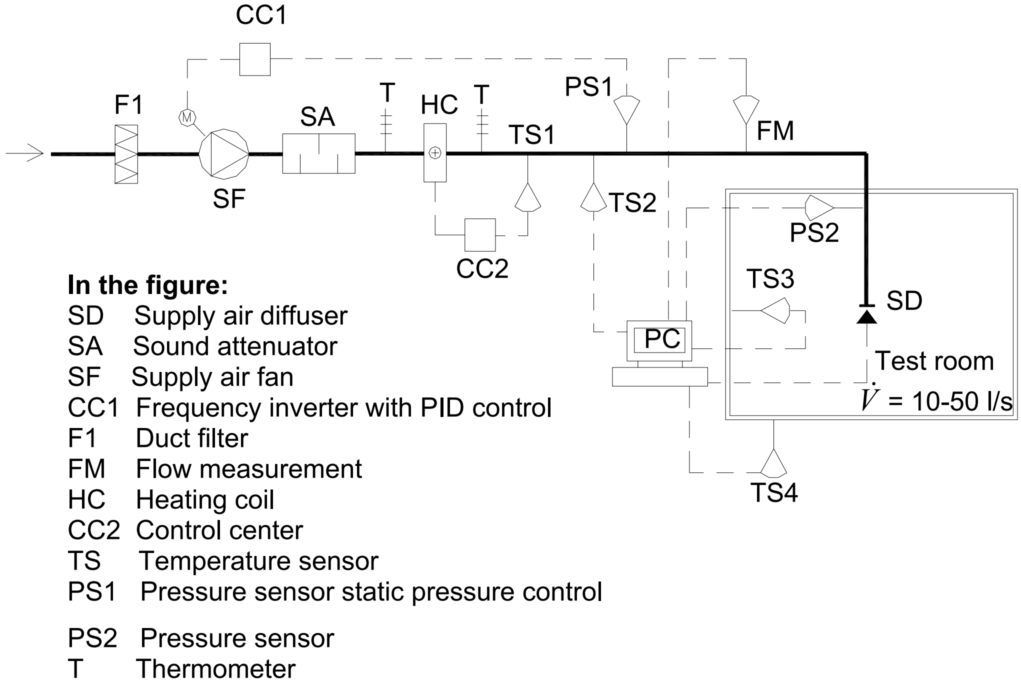


Figure B.4 A scheme of the test set-up for the laboratory experiments.

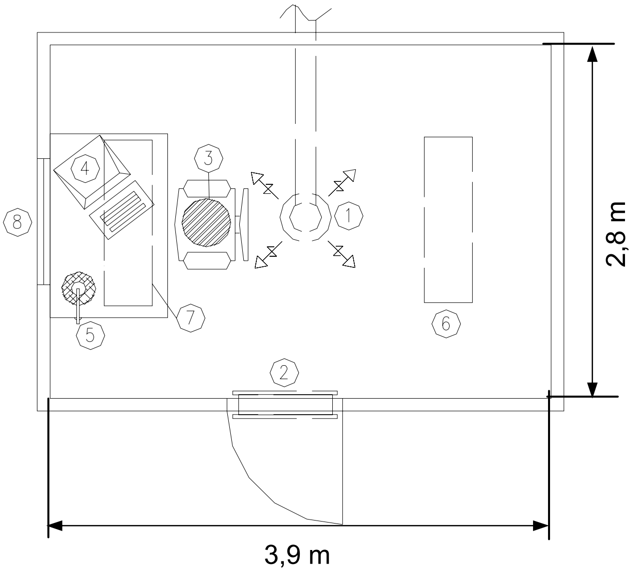
The test room was constructed with plaster boards on a wooden framework. The internal dimensions of the test room were: width 3.9 m, length 2.8 m and height 2.7 m. To imitate a common office environment the room was filled with usual office equipment: a table, a chair, a computer and lighting.

The internal heat loads were simulated with a computer (120W), a dummy (80W) and lighting (total 370W). The artificial light consisted of four fluorescent tube fittings (85 W with ballast) plus a table lamp (30W heat gains). Figure B.5 presents photos of the test room.

Figure B.5 The test room in the laboratory measurements. The room was constructed to simulate the conditions of a common cell office room. A placement of heat loads: computer, dummy and lighting can be seen on the right photo.

The air was supplied from a variable supply air diffuser mounted in the middle of the ceiling. Two different arrangements were tested: one with the diffuser free from the ceiling and one with the diffuser in the suspended ceiling. Without suspended ceiling the height from the ceiling to the discharge area of the device was 30 cm and from the device to the floor 2.4 m. With suspended ceiling the latter height was increased to 2.7 m (the device itself with the duct was installed above the test room box to simulate the suspended ceiling case).

For the exhaust air a transfer air device was installed above the door, under the ceiling. A schematic picture of the test room layout is given in Figure B.6



In the figure:

1	supply air diffuser D160
2	transfer air device D160
3	dummy
4	personal computer
5	table lamp,
6	ceiling lamp
7	ceiling lamp
8	window

Figure B.6 The layout of the test room. The size of the test room was ~11 m^2.

The airflow rate to the room varied between 10 - 50 l/s, which corresponds to 1.2 – 6.1 h^{-1}. The supply air temperature was kept constant +15 °C and for all the tests the operative temperature in the occupied zone and also outside the office cube was kept 22 ± 1 °C.

A variable frequency inverter for fan speed control was installed for the supply air fan in order to maintain a specific static pressure in the duct. The set value for constant static pressure in the duct was approx. 50 Pa.

Testing was made for different airflow rates. The heat loads were adapted to the airflow in order to obtain the correct room temperature. The testing was performed after steady-state conditions in the room were fully established.

A schematic picture of the variable DCV supply air diffuser tested in the laboratory is shown in figure B.7. The work principle of the diffuser is following. The distance between the lamella plates, shown in figure B.7, varies according to the required airflow rate and the set static pressure before the device and is controlled by a traversing motor, which gets impulses from the controlling sensor. The control and regulating equipment as well as the sensors are built into the supply air device and the simultaneous values can be read with the computer.

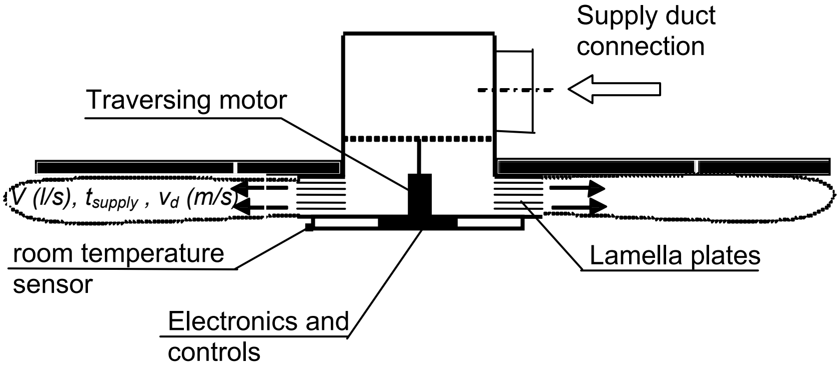


Figure B.7 Tested DCV supply air diffuser

B.2.2 Measurement techniques and instrumentation

Thermal comfort measurements were carried out under different test conditions with constant supply air temperature +15°C conditions and variable airflow rates. Every measurement case was done in three replicates and the results are presented as an average over these three measurements. The measurement period for each measurement was 3 minutes.

Air temperature and air velocities were measured in a number of room points as shown in figure B.8. At each room position the measurements were taken at 3 heights, 0.1m, 0.6 m, 1.1m, which is based on the position of a sitting person[13]. Three SWEMA 300 measurement instruments with SWA 01 and SWA 03 comfort probes were used for these measurements. The characteristics of the sensors are given in table B.3 above. The draught probe SWA 01 is an older type of this type of a sensor, but the measurement characteristics are the same as SWA 03. The time constant of the sensors is 0.25 seconds. The expanded uncertainty for temperature measurement in different room points in the test room is evaluated to be ± 0.4 °C, with coverage factor $k = 2$. The evaluation measurement uncertainties for temperature measurements in the test room and laboratory hall are presented in chapter C.3 in APPENDIX C.

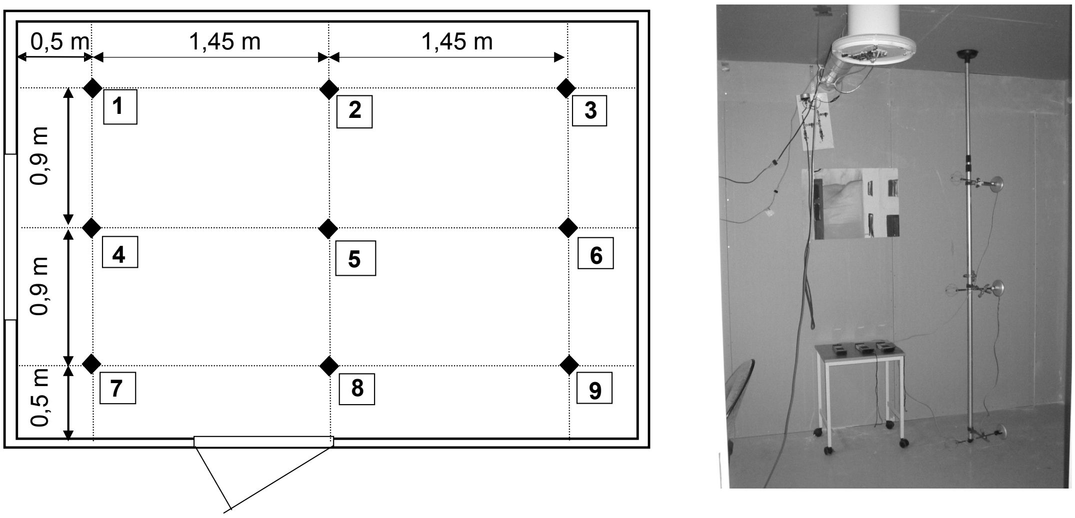


Figure B.8 The measurement points in the room and a photo of the measurement set up.

The steady-state conditions were monitored using temperature data from sensors installed inside and outside the room. The operative temperature in the room was estimated in the position of a sitting person next to the work place, on the level of 1.1 m from the floor. For estimating the operative temperature a plane radiant temperature for six different directions was measured and the operative temperature was calculated according to equations B.1 and B.2 [32, 101].

$$t_{op} = a \cdot t_a + (1-a) \cdot \bar{t}_r \qquad [°C] \qquad \text{(eq. B.1)}$$

$$\bar{t}_r = \frac{0{,}18 \cdot \left(t_{pr}[up] + t_{pr}[down]\right) + 0{,}22 \cdot \left(t_{pr}[right] + t_{pr}[left]\right) + 0{,}30 \cdot \left(t_{pr}[front] + t_{pr}[back]\right)}{2 \cdot \left(0{,}18 + 0{,}22 + 0{,}30\right)}$$

(eq. B.2)

Where,

t_{op} operative temperature, °C;

a constant. For the values of relative air velocity $v_{ar} < 0.2$ m/s the value $a = 0.5$

$\bar{t}_r$ mean radiant temperature, °C. The equation 4.2 is used for calculating mean radiant temperature for a sitting person.

t_{pr} plane radiant temperature, °C. The direction given in the brackets in equation B.2 is the direction where the temperature is measured.

The supply air temperature was kept constant +15 ˚C during the measurement time and monitored with the temperature sensor installed in the duct.

The test room temperature and the laboratory hall temperature were measured with Pt-100 sensors. The same type of sensors was used for measuring plane radiant temperatures in the test room and the supply air temperature in the duct. All these temperature sensors were calibrated using Mercury thermometer, which has the uncertainty of ± 0.05 °C. The expanded uncertainty for the temperature measurement with Pt-100 sensors is ± 0.06 °C, with coverage factor $k = 2$. The expanded uncertainty for operative temperature measurement with six Pt-100 temperature sensors is ±

0.15°C, with coverage factor $k = 2$. The evaluation measurement uncertainties for temperature measurements in the test room and laboratory hall are presented in chapter C.3 in APPENDIX C.

The airflow rates in the system were measured with flow measuring devices installed in the ducts. The lower airflow rates 10 and 25 l/s were measured with "Fläkt Woods" IRIS damper. The higher airflow rates up to 50 l/s were measured with an adjustable circular measuring damper from "Swegon" type CRMc. According to the manufacturers data the method error for the IRIS type of a damper is ± 7% and for the other damper it is ± 5%.

The differential pressures for both measuring devices were measured with electronic pressure sensors. The uncertainty of the electronic pressure transmitter is ± 1%. The corresponding airflow rates were calculated according to the equation B.3:

$$\dot{V} = K\sqrt{\Delta p_m} \qquad \text{(eq. B.3)}$$

Where,

$\dot{V}$	air flow rate, l/s
K	factor which depends on the airflow rate and on the device setting
Δp_m	measured pressure difference in the measuring device, Pa

The *K* factors for different device obstructions that were used for measuring different airflow rates are given in table B.4.

Table B.4 The *K*-factors for flow measurement dampers

Damper	Airflow rate, l/s	K-factor
IRIS	10	1,6
	24	4,8
CRMc	50	15,8

The expanded uncertainty for airflow measurement with the IRIS damper is ± 8.2%. This expanded uncertainty is based on a combined uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approx. 95%. For the airflow measurement device CRM160 the expanded uncertainty is ± 6.2%. The evaluation measurement uncertainties for airflow measurements in the test room are presented in APPENDIX C.

The electronic pressure sensor was also used for the measuring of the pressure before the supply air device in the room. All the sensors (temperature and pressure sensors) were connected to a PC-logger 3100 and monitored from the computer with EasyView software version 5.5 Pro.

B.3 Adapting the duct system to DCV with low inlet temperature - measurements in the field

B.3.1 Measurement techniques and instrumentation

The scheme of the tested DCV air distribution system is shown in Figure B.9. The duct system supplies air to 11 different office rooms (devices 1-11) and to one conference room (devices 12-13). The maximum designed airflow rate for offices is

30 l/s and for conference rooms 50 l/s per diffuser. The minimum airflow rate is 7 l/s for all devices. All the connection ducts from the main duct have the same length 2.5 m and in conference room 3.0 m. The distance between connection ducts is 2.8 m. All ducts are insulated with the insulation thickness of l_i = 30 mm and the thermal conductivity of the duct layer is $\lambda_i = 0.035$ W/(m·K).

The air temperatures in the duct were measured in 7 different points in the system, marked with numbers in the Figure B.9. The measurement points 1, 4, 5 and 7 were inside the main duct. The points 2, 3, 6 and 8 correspond to the supply air temperatures from the DCV diffusers. The air temperatures in different points in the ducts were measured with Pt-100 temperature sensors. The sensors were connected to the logging and monitoring system. The expanded uncertainty for the temperature measurement with the Pt-100 sensors is ± 0.06 °C, with coverage factor $k = 2$.

The airflow rates to the rooms were changed by logging into the device with the palm computer and changing the settings. The airflows from the DCV diffusers were measured with the measurement equipment installed into the device. The simultaneous airflow rate values were read with a palm computer. According to the data from the manufacturer, the measurement uncertainty of the airflow measurement with the sensors in supply air diffuser is ± 2 l/s.

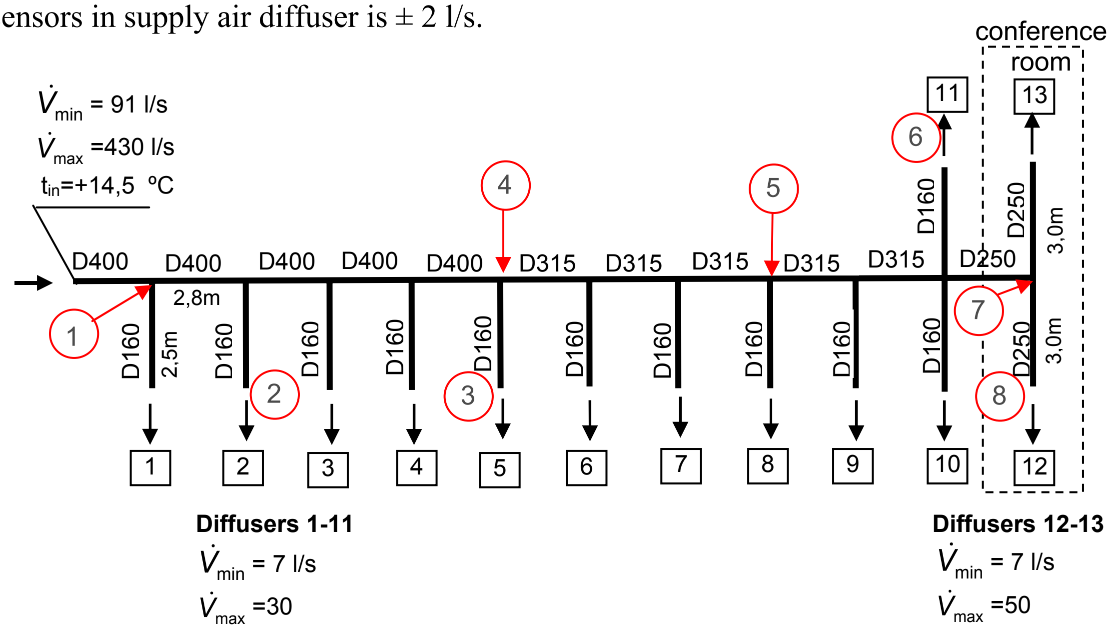


Figure B.9 The scheme of the air distribution system used for evaluating the variable flow effects on temperature change in the duct system. The numbers in the circles mark the measurement points. The measured supply air temperature at the beginning of the main duct was t_{in} = +16.3 °C, the temperature in the rooms about t_o = +22 °C. The duct diameters are marked as e.g. D400, which correspond to D = 400 mm.

B.4 Performance tests of DCV sensors - specification of the tested sensors

Table B.5 Compilation of the manufacturer’s data for the sensors *S1* to *S5*.

Property/ specification	**Sensor model**				
	S1	**S2**	**S3**	**S4**	**S5**
Sensing method	NDIR	NDIR	NDIR	NDIR	NDIR
Sensitive gases	CO_2	CO_2	CO_2	CO_2	CO_2
Measurement range	0-2000 ppm	0-2000 ppm	0-2000 ppm	0-2000 ppm	0-2000 ppm
Output signal	0 – 10 V	0 – 10 V	0 – 10 V	0 – 10 V	0 – 10 V
Power supply	24 V AC	24 V AC	24 V AC	24 V AC	24 V AC
Signal processing intelligence and self-adjustment	digital filtering; ABC logic 1)	digital filtering ABC logic 1)	digital filtering ABC logic 1)	digital filtering ABC logic 1)	CPU; special filter technology
Uncertainty	20ppm ± 5% m/v 2)	20ppm ± 5% m/v 2)	30ppm ± 3% m/v 2)	30ppm ± 3% m/v 2)	50ppm ± 3% m/v 2)
Annual zero drift	± 10 ppm (nominal)	± 10 ppm (nominal)	± 0.3 % of range	± 0.3 % of range	± 100 ppm/ 5 years
Response time	< 3 min (τ_{63})	< 3 min (τ_{63})	2 min (τ_{63})	< 3 min (τ_{63})	1 min (τ_{63})
Pressure influence	1.6 % per 1 kPa	1.6 % per 1 kPa	1.6 % per 1 kPa	1.6 % per 1 kPa	+0.15 % per hPa
Temperature influence	wsp 3)	wsp 3)	wsp 3)	wsp 3)	-0.35 % /°C
Humidity influence	wsp 3)	wsp 3)	wsp 3)	wsp 3)	n/a 5)
Expected lifetime	> 15 years	> 15 years	> 15 years	> 15 years	> 10 years
Calibration intervals	no 4)	no 4)	no 4)	no 4)	5 years

Table B.6 Compilation of the manufacturer’s data for the sensors *S6* to *S10*.

Property/ specification	**Sensor model**				
	S6	**S7**	**S8**	**S9**	**S10**
Gas sensing method	NDIR	NDIR	NDIR/MOS	NDIR	NDIR
Sensitive gases	CO_2	CO_2	CO_2 /VOCs	CO_2	CO_2
Measurement range	0-2000 ppm	0-2000 ppm	0-2000 ppm n/a 5) - VOC	0-2000 ppm	0-2000 ppm
Output signal	0 – 10 V	0 – 10 V	0 – 10 V→ ppm or % $_{IAQ}$	0 – 10 V	0 – 10 V
Power supply	24 V AC	24 V AC	24 V AC	24 V AC	24 V AC
Signal processing intelligence and self-adjustment	CPU; special filter technology	reference light source	reference light source	reference light source	reference light source
Uncertainty	40ppm ± 2% m/v 2)	50ppm ± 2% m/v 2)	50ppm ± 2% m/v 2); n/a 5) - VOC	50ppm ± 2% m/v 2)	50ppm ± 2% m/v 2)
Annual zero drift	± 5 % of range / 5 yr.	< ± 20 ppm	< ± 20 ppm	< ± 20 ppm	< ± 20 ppm
Response time	1 min (τ_{63})	< 5 min (τ_{63})	< 5 min (τ_{63})	< 5 min (τ_{63})	< 5 min (τ_{63})
Pressure influence	+0.15 %/ hPa	n/a 5)	n/a	n/a 5)	n/a 5)
Temperature influence	<0.15 % FS of reading/°C	< ± 2 ppm/°C	<± 4 % of reading	< ± 2 ppm/°C	< ± 2 ppm/°C
Humidity influence	n/a 5)	n/a 5)	n/a 5)	n/a 5)	n/a 5)
Expected lifetime	> 10 years	n/a 5)	n/a 5)	n/a 5)	n/a 5)
Calibration intervals	5 years	8 years	8 years	8 years	8 years

Note 1: ABC logic – automatic baseline correction for drift compensation

Table B.7 Compilation of the manufacturer's data for the sensors *S11* to *S15*.

Property/ specification	**Sensor model**				
	S11	**S12**	**S13**	**S14**	**S15**
Gas sensing method	NDIR/MOS	solid state electrolyte	solid state electrolyte	MOS	MOS
Sensitive gases	CO_2 /VOCs	CO_2	CO_2	CO_2	VOCs
Measurement range	0-2000 ppm n/a 5) - VOC	400-4000 ppm	400-4000 ppm	400-3000 ppm	0-30 ppm
Output signal	0 – 10 V→ ppm or % $_{IAQ}$	0 – 4 V	0 – 4 V	0 – 5 V	0 – 5 V→ kΩ
Power supply	24 V AC	5 V DC	5 V DC	5 V DC	5 V DC
Signal processing intelligence and self-adjustment	reference light source	self-adjustment with signal processing	self-adjustment with signal processing	ABC logic1)	no
Uncertainty	50ppm ± 2% m/v 2); n/a 5) - VOC	± 20 % m/v	± 20 % m/v	n/a 5)	n/a 5)
Annual zero drift	< ± 20 ppm	n/a 5)	n/a 5)	n/a 5)	n/a 5)
Response time	< 5 min (τ_{63})	< 1.5 min (τ_{90}))	< 1.5 min (τ_{90})	1 min (τ_{80})	n/a 5)
Pressure influence	n/a	n/a 5)	n/a	no	n/a 5)
Temperature influence	<± 4 % of reading	negligible	negligible	yes	n/a 5)
Humidity influence	n/a 5)	negligible	negligible	yes	n/a 5)
Expected lifetime	n/a 5)	> 10 years	> 10 years	10 years	n/a 5)
Calibration intervals	8 years	n/a	n/a	1 years	n/a 5)

Table B.8 Compilation of the manufacturer's data for the sensors *S16* to *S18*.

Property/ specification	**Sensor model**		
	S16	**S17**	**S18**
Gas sensing method	MOS	MOS	MOS
Sensitive gases	VOCs	VOCs	VOCs
Measurement range	0-10 ppm	1-10 000 ppm	350 - 2000 CO_2 prediction
Output signal	0 – 5 V→ kΩ	ppm	kΩ or ppm in CO_2 equivalents
Power supply	5 V DC	5 V DC	12 V DC
Signal processing intelligence and self-adjustment	no	output signal is processed to ppm	yes, the output signal is processed to CO_2 eq
Uncertainty	n/a 5)	n/a 5)	n/a 5)
Annual zero drift	n/a 5)	n/a 5)	n/a 5)
Response time	n/a 5)	n/a 5)	n/a 5)
Pressure influence	n/a 5)	n/a 5)	negligible
Temperature influence	n/a 5)	n/a 5)	negligible
Humidity influence	n/a 5)	n/a 5)	yes
Expected lifetime	n/a 5)	n/a 5)	10 years
Calibration intervals	n/a 5)	n/a 5)	no 4)

Note 2: the sensor is uncertainty given at specified test conditions, see chapter 3.6.3. m/v – measured value; Note 3: wsp- within specified uncertainty ; Note 4: no calibration is required for this sensor; Note 5: n/a- no information available

B.5 Characteristic performance of CO_2-sensors - tests in the laboratory

B.5.1 The test set-up

The performance tests of the selected sensors were carried out in small-scale test chamber called CLIMPAQ (The Chamber for Laboratory Investigations of Materials, Pollution and Air Quality). This chamber is traditionally used for emission testing of building materials. However, due to its specific design it was found to be suitable also for the current test program. The CLIMPAQ is made of glass and stainless steel and has an internal volume of the empty chamber of 50.9 litres. The dimensions are 1005 x 250 x 220 (h) mm. The design and construction details of the CLIMPAQ box can be found in the Nordtest report NT Build 482 [161]. Figure B.10 provides a schematic picture of the test set-up used for the CO_2-sensor performance tests.

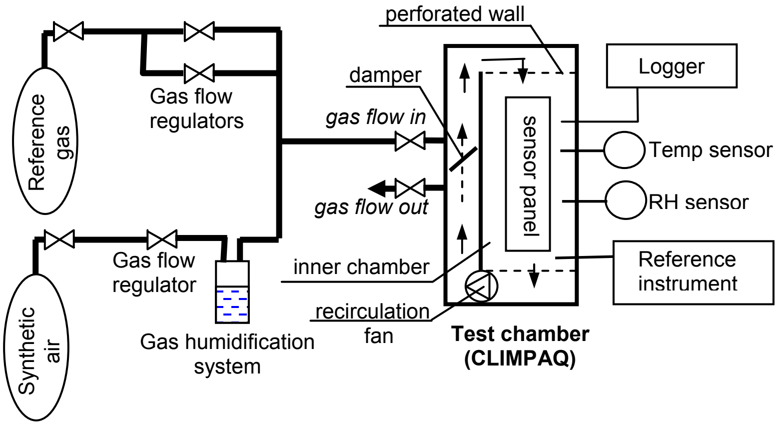


Figure B.10 Schematic picture of the test set-up for CO_2-sensor testing.

The test chamber has a smaller inner chamber, with the size of 810 x 215 x 220 (h) mm, where the panel of the test sensors was placed, see Figure B.10. This chamber is built in a way that parallel gas inflow and outflow is assured through the perforated inner walls. Additionally, air recirculation is enabled by a small fan installed into the box. The recirculation rate can be controlled with a recirculation damper between the gas flow inlet and outlet connections.

A high concentration CO_2 gas was used for mixing with the synthetic air in order to achieve the required concentration level. The amount of reference gas needed for the specified concentration was controlled by three different gas flow regulators. Two of them where installed on the reference gas flow pipes and one was installed on the synthetic air flow pipe. Before the final mixing of the gases, the synthetic air was humidified to the required level specified by the conditions needed in the test chamber.

B.5.2 Instrumentation and measurement techniques

The reference CO_2-gases were ordered in the gas bottle from the manufacturer with the specified concentration levels of 4999 ± 100 ppm and 1600 ± 32 ppm. The majority of tests were carried out with using the higher concentration, 4999 ppm CO_2 gas for mixing. In stability and repeatability tests the 1600 ppm CO_2 gas was used and supplied directly from the bottle. The synthetic air used for mixing had purity class N40, which corresponds to 99.99 % of purity. The maximum levels of pollutants were specified by the manufacturer as follows: $H_2O < 5$ ppm, $CO < 1$ ppm, $CO_2 < 1$ ppm, $HC < 0.5$ ppm.

The supply flow rates of the reference gas and synthetic air were measured with a soap bubble meter before and after each test in order to evaluate the concentration of the mixture supplied to the chamber. The estimated expanded uncertainty of measurement associated with determining the reference CO_2-concentration in the test is between ± 3.4 % and ± 4.7 % of the calculated value, with coverage factor $k = 2$. The higher values correspond to the lower concentration levels. The evaluation of measurement uncertainty is presented in APPENDIX C. Additionally, a reference instrument was connected the test chamber for comparison and evaluation of the stability of the reference conditions. The reference instrument used was an Innova Photoacoustic Multi-gas Monitor 1302.

The temperature and relative humidity were continuously monitored in the test chamber. The reference ambient test conditions were kept constant in a range of 22 ± 2 °C for temperature and 40 ± 5 % for relative humidity. A combined temperature and humidity sensor was used for measuring the ambient conditions in the test chamber. The measurement uncertainty of the combined temperature and humidity sensor connected to the logger is ± 0.1 °C and ± 2.8 % r.h. respectively, with coverage factor $k = 2$. The pressure in the test chamber was based on atmospheric conditions, with a small overpressure in the inner test chamber. Due to the special design of the test chamber with a recirculation fan, the pressure pattern is not equal over the all chamber area. There is a small under pressure close at the suction side of the fan and slight over pressure in the rest of the areas. However, the test chamber is designed to be airtight. Air leakage with 100 % recirculation and without external supply air is about 0.0003 1/s. The uncertaint of atmospheric pressure measurement is ± 1 hPa. The air velocities in the inner test chamber were within the limits specified for normal indoor conditions.

All of the tested sensors were selected and tested by the respective manufacturer prior the delivery to the testing laboratory. Special care was undertaken in packaging and handling the sensors prior testing. The sensors were installed according to the manufacturer’s instructions. Each sensor was subjected to the manufacturer-stated voltage input and kept in a specified stability range, i.e. 24 ± 4.8 V or 5 ± 0.2 V, depending on the sensor. The requirements for pre-heating time, specified by the manufacturers, were followed for all of the sensors. The sensors were continuously connected for weeks before carrying out the planned performance tests. All of the sensors were connected to a logging and data monitoring system. The analogue output signals 0-10 V or 0-5 V from the CO_2 transmitters were transformed to concentration readings in ppm, designating parts per million. The test room in the laboratory was kept free of strong electric and magnetic fields. Shielded wires were used for making connections to the power supply and test sensors.

Some preliminary tests were carried out prior to the performance tests in order to evaluate the test set-up and inspect if any malfunctioning occurs with the sensors. These tests included observing the sensor reading at normal indoor conditions and at zero gas concentration in the test chamber. The manufacturers were informed and consulted when problems were identified. Considerable baseline offset was observed on some of the non-dispersive infrared CO_2-sensors during the set-up tests. This can be caused by possible transportation/installation damages. Since these tested sensors include self-adjustment systems, the occurring drift was considerably decreased during the pre-heating time.

Testing of the sensors was generally performed at steady-state conditions. In specific, the values were obtained after the output signal of the test sensors and reference instrument was stable for more than 10 minute period of time. Typically, the conditions in the test chamber satisfied the steady- state conditions within 30 minutes after a step change in CO_2 concentration. The air exchange rate in the test chamber was about 8-9 h^{-1}. The sampling time of the logging system was set to 10 seconds. The results are commonly presented as 5 minute average values, taken from the last 5 minute period of the steady state conditions before the next concentration change.

B.6 Performance tests of mixed-gas sensors in the laboratory

B.6.1 The test set-up

The performance tests of the selected mixed-gas sensors were carried out in a small-scale test chamber made of glass. The chamber has the shape of a big bottle and has a cover with several openings for gas pipe inflow and outflow and cable connections. The internal volume of the empty chamber is 5.3 litres; dimensions are 150 (D) x 350 (H) mm. Figure B.11 provides a schematic picture of the test set-up used for the mixed-gas sensor performance tests.

The test chamber is constructed in a way that good mixing of the supply gas inflow is assured. This was maintained by placing a perforated floor in the bottom of the chamber or installing a “sugar lump” gas diffuser to the end of the inflow pipe. The gas supply was in both cases from the bottom of the chamber.

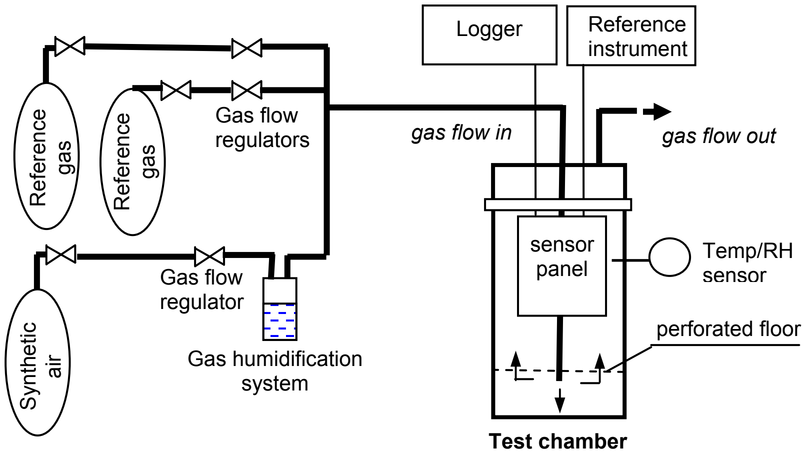


Figure B.11 Schematic picture of the test set-up for mixed-gas sensor testing.

High concentration VOC gases were used for mixing with the synthetic air in order to achieve the required concentration levels. The amount of reference gas needed for the specified concentration was controlled by three different gas flow regulators. Two of them where installed on the reference gas flow pipes and one was installed on the synthetic air flow pipe. Before the final mixing of the gases, the synthetic air was humidified to the required level specified by the conditions needed in the test chamber.

B.6.2 Instrumentation and measurement techniques

The reference VOC gases were ordered in gas bottles from the manufacturer with the specified concentration levels of 102.8 ± 2.1 ppm for toluene and 98.9 ± 4.9 ppm for acetone. The concentrations were based on pure VOC gas and synthetic air mixture. Synthetic air was additionally used for achieving the required different concentration levels in the laboratory tests. The synthetic air used had purity class N52, which corresponds to 99.9992 % of purity. The maximum levels of pollutants specified by the manufacturer are as follows: $H_2O < 3$ ppm, $CO < 1$ ppm, $CO_2 < 1$ ppm, $HC < 0.1$ ppm, $NO_X < 0.1$ ppm.

The supply flow rates of the reference VOC gases and synthetic air were measured with a soap bubble meter before each test in order to estimate the concentration of the mixture supplied to the chamber. The evaluated expanded uncertainty of measurement associated with determining the reference VOC-concentration in the test chamber with this method is in a range of ± 10 - 15 % of the calculated value at concentrations higher than 1 ppm.

However, it was preliminary suspected that the plastic casings etc., which are part of the sensor assemblies, emit VOC-substances to some extent, influencing the VOC concentrations in the test chamber. Therefore, in the majority of tests the reference VOC gas concentrations in the test chamber were determined by means of Tenax adsorption tubes. This method makes it possible to determine a large number of organic compounds and their concentrations. The expanded uncertainty for this method is about ±16 % of the calculated value for VOC mixture concentration. The Tenax tubes were analysed by Flame Ionization Detector, FID, in gas chromatography. The details of measurement uncertainties for evaluating the reference concentration in the test chamber are described in APPENDIX C.

Additionally, a reference instrument was connected to the test chamber for monitoring the stability of the reference gas concentration. The reference instrument used was an Innova Photoacoustic Multi-gas Monitor 1302. This instrument measures a total content of volatile organic compounds, $TVOC_{PAS}$.

The reference ambient test conditions were kept constant in the test chamber and were in a range of 24 ± 2°C for temperature and 40 ± 5 % for relative humidity. The temperature and relative humidity were continuously monitored in the test chamber. The combined temperature/humidity sensor was placed at the level of sensor panel in the glass chamber. The same sensor was used as in CO_2-sensor testing. The measurement uncertainty of the temperature and humidity sensor connected to the logger is ± 0.1°C and ± 2.8 % respectively, with coverage factor $k = 2$. The pressure in the test chamber was based on atmospheric conditions, with a small overpressure in the inner test chamber. The uncertaint of atmospheric pressure measurement is ± 1 hPa. The air velocities in the test chamber were within the limits specified for normal indoor conditions.

All of the tested sensors were selected and tested by the respective manufacturer prior the delivery to the testing laboratory. Special care was undertaken in packaging and handling the sensors prior to testing. Each sensor was subjected to the manufacturer-stated voltage input and kept in a specified stability range, i.e. 24 ± 4.8 V or 5 ± 0.2 V, depending on the sensor. The two specimens of sensor *S18* had their own power supply adaptor provided by the manufacturer. All of the sensors were connected to a data acquisition system. The output of the sensors *S15*, *S16* and *S8* was logged with a common data logger. The sensors *S17*, *S18* and *18A* used a different logging system provided/recommended by the manufacturer. The sampling time of the common logging system was set to 10 seconds. The logging system for sensors *S17*, *S18* and *18A* registered the values every 1 second. The test room in the laboratory was kept free of strong electric and magnetic fields. Shielded wires were used for making connections to the power supply and test sensors.

Sensors *S15* and *S16* represent the type of sensing elements that are incorporated to the commercially available sensor transmitters. An external electrical circuit was built in accordance with the recommendations of the manufacturer was connected to these sensors. From sensor modules *S15* and *S16* an analogue output signal 1-5 V is measured and correlated to the sensing elements resistance R_s as follows:

$$R_S = \frac{V_C - V_{out}}{V_{out}} \cdot R_L \quad [\mathrm{k\Omega}] \qquad \text{(eq. B.4)}$$

Where R_S is electrical resistance of the sensor in kΩ; V_C is circuit voltage 5 V; V_{out} is output signal 1-5 V; R_L is the load resistance, which is determined to be 50 kΩ.

Sensor *S8* has an analogue output signal 0-10 V, which according to the manufacturer corresponds to 0-100 % of indoor air quality levels. From the sensor *S17* a digital output signal was received, expressed as ppm. The sensors *S18* and *S18A* have also digital output. With the manufacturer logging and monitoring system provided for these sensors, resistance R_S in Ω and as a prediction of CO_2 equivalent units is presented. In these sensors the VOCs present in the room, especially from human respiration and metabolism, are correlated to CO_2 equivalent units.

The requirements for pre-heating time, specified by the manufacturers, were followed for all of the sensors. Some preliminary tests were carried out prior to the performance tests in order to evaluate the test set-up and inspect if any malfunctioning occurs with the sensors. The manufacturers were informed and consulted when some problems were identified. A test with only synthetic air was conducted at the beginning of the experiments. The aim was to estimate the background gases emitted from the plastic casings of the sensors assemblies and from connecting wires inside the test chamber. The background concentration levels were analysed by means of Tenax adsorption tubes. The individual compounds with the highest concentrations identified in the test chamber in these tests were: siloxane, phenol, nonanal, toluene and decanal. The last two compounds were also detected in the synthetic air in very small concentration. Nevertheless, only air from one bottle was used for testing the background concentrations. There can be some differences between individual synthetic air bottles. It can be assumed that the origin of the other detected VOCs, such as siloxane, phenol and toluene is the sensor assemblies.

Testing of the sensors was performed at generally steady-state conditions. In specific, the values were obtained after the output signal of the test sensors and reference instrument were stable for more than 10 minutes. The supply airflow rate to the test chamber was in a range of 6.6 l/min to 6.9 l/min and the corresponding air exchange rate was about 92 - 98 h^{-1}. The time to reach steady state conditions depends on the concentration levels. With higher VOC levels the time to reach steady- state conditions is shorter than with lower VOC concentrations. Reaching a steady- state conditions at close to 0 ppm concentration, with synthetic air only, was almost impossible. After 3 hours of experiment the sensor output values were still slowly changing. Due to economic reasons it was not possible run the test for an unlimited time and therefore the results at the close to 0 ppm VOC concentration levels should not be considered as absolute values. They are also not used in the calculation of different characteristics. The results are presented as 5-minute average values, taken from the last 5-minute period of the steady state conditions before the next concentration change.

B.7 Performance tests of mixed-gas sensors in a full scale test room

B.7.1 The test set-up

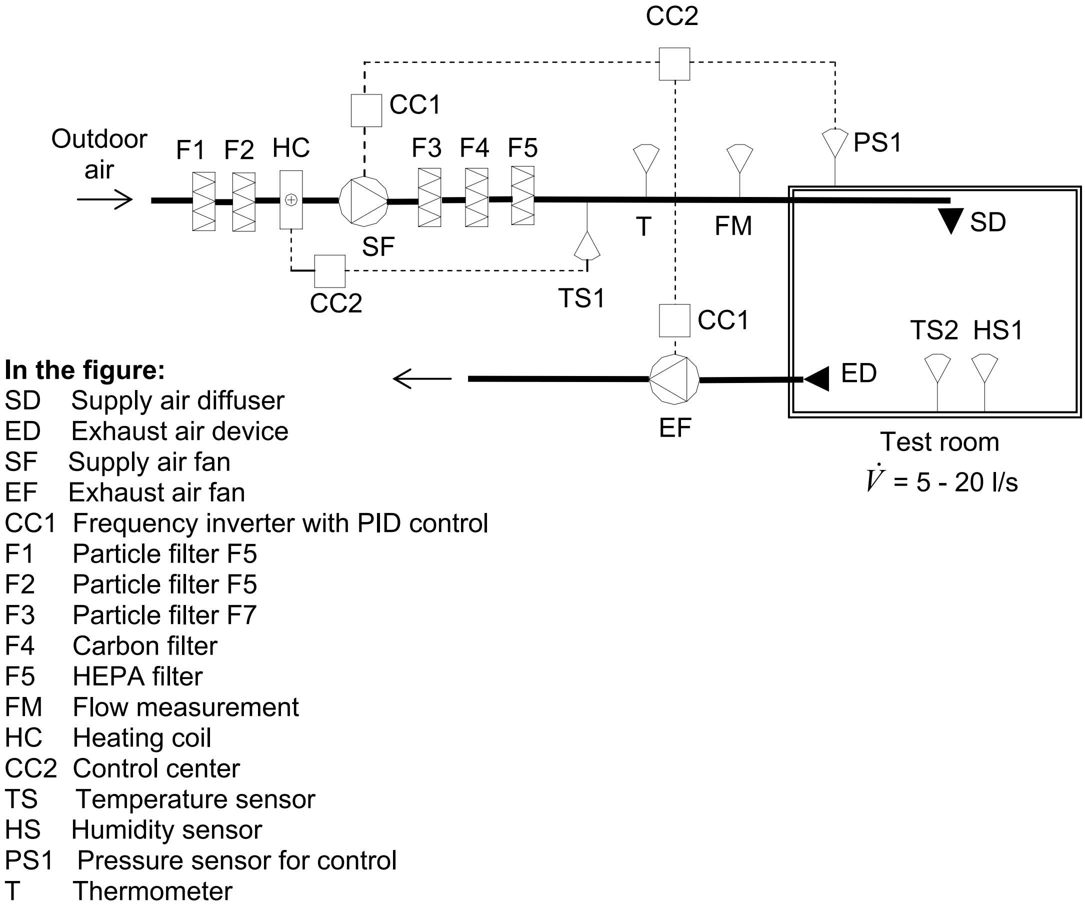
The tests were carried out in a full scale environmental chamber, which has low background emissions of pollutants. A climate chamber locating in the laboratory of Building Services Engineering at Chalmers University of Technology was used for this study. The test room has been built for testing gaseous and particulate emissions from construction materials and office equipment and it has been used in earlier studies [2]. In this test chamber it is possible to simulate real life situations under controlled environmental and supply air conditions and small chamber surface influence.

The dimensions of test room are: length 3.5 m, width 2.4 m and height 2.3 m, which gives a floor area of 8.4 m^2 and volume of 19.3 m^3. The test room is made of brushed stainless steel walls, floor and ceiling. The connections are sealed with hidden rubber gasket to make it airtight. Due to the specific construction and materials the emissions from the surfaces of the room and the adsorption on these surfaces are kept to minimum.

The supply air to the test room is filtered through a five stage filter system: two filters of class F5, filter of class F7, gas adsorption filter made from active carbon and finally HEPA filter. In order to maintain the required temperature and humidity condition in the room the system is fitted with an air heater and a humidifier. The supply air temperature was 1-2 ˚C lower than the room temperature. However, due to the very low airflow rates supplied to the room in the test conditions it was not possible to use the pre-installed air humidifier. A local air humidifier was placed in the room. This humidifier ultrasonically vaporizes the water and has an electronic humidistat incorporated to the device. The volume of the water tank of the humidifier is 4 litres which with continuous operation must be filled on a daily basis.

The supply and exhaust airflow rates are controlled by fans with variable control of speed. The air is supplied to the test room through the supply air diffuser, which enables the supply air jet with sufficient speed and throw in order to achieve proper mixing with room air. The room air is removed through an exhaust air device located close to the opposite wall next to the ceiling.

A schematic picture of the test room and the applied components in the ventilation system supporting the room is shown in Figure B.12.



In the figure:

SD	Supply air diffuser
ED	Exhaust air device
SF	Supply air fan
EF	Exhaust air fan
CC1	Frequency inverter with PID control
F1	Particle filter F5
F2	Particle filter F5
F3	Particle filter F7
F4	Carbon filter
F5	HEPA filter
FM	Flow measurement
HC	Heating coil
CC2	Control center
TS	Temperature sensor
HS	Humidity sensor
PS1	Pressure sensor for control
T	Thermometer

Figure B.12 The scheme of the air-conditioning system for the full scale test room.

B.7.2 Instrumentation and measurement techniques

Different pollutant sources, i.e. office furniture, PC with screen, linoleum floor, were placed in the room according to the test program. Following sensor models were tested in the current study: *S8, S15, S16, S17* and *S18.* Additionally sensors *S3* and *S5* were used for monitoring the ambient carbon dioxide concentration in the test room.

The test sensors were all installed side by side on a small board and hanged on a metal rodd. The metal rodd was placed to the middle of the test room. The board with the sensors was at the height of 1.1 m above the floor. All sensors were connected to a logging system placed outside the test room. The same logging and monitoring system was used as in the sensor characteristic tests.

The requirements for pre-heating time, specified by the manufacturers, were followed for all of the sensors. The output of the sensor was continuously monitored at the different pollutant source cases and unless specified otherwise the results represent 1-hour average values at steady-state conditions before and after the emission sources were placed to the room.

The environmental test conditions in the environmental chamber were kept at the level of +22 ± 1.5°C for temperature and 45 ± 5 % for relative humidity. The temperature and relative humidity were continuously monitored at the location of the test sensors. The sensor was placed next to the sensor panel. The measurement uncertainty for the temperature and humidity sensor connected to the logger is ± 0.1 °C and ± 2.8 %

respectively, with 95% confidence interval. The pressure in the test room was based on atmospheric conditions, with a slight overpressure in the test room. Over-pressure about 10 Pa in relation to the laboratory hall was kept in the test room. The air velocities in the test chamber were within the limits specified for normal indoor conditions.

The supply air flow rate to the test room was set between 6.8 -7.1 l/s, corresponding to 1.2 – 1.3 h^{-1} and was kept constant at all test conditions. The supply airflow rates were measured with a flow measuring flange installed on the supply air duct to the test room. The supply airflow rate was measured by a throttle flange VEAB C-092, with a diameter 25 mm. The pressure difference over the airflow measurement device was measured with the manometer. The measurement uncertainty including the throttle flange calibration and manometer uncertainty is given to ± 0.5 l/s [2].

The total VOC gas concentration in the supply air was continuously monitored with a photoacoustic spectroscopy instrument, PAS, from Innova, type 1314. The aim of this measurement is to monitor the stability of the supply air concentrations and evaluate its impact on the conditions in the room. The instrument measures a total content of volatile organic compounds, TVOC. The instrument is calibrated against toluene for measurement of hydrocarbons and the concentration is stated as toluene equivalents.

Gas concentrations in the room and in the supply air were in several test determined by adsorbent sampling tubes filled with Tenax-TA and the VOCs identified and quantified by Flame Ionization Detector, FID, in gas chromatography. This method enables to determine a large number of hydrocarbons simultaneously from very low to very high concentrations. A total TVOC concentration can also be determined. However the two TVOC levels measured with photoacoustic spectroscopy and gas chromatography are not comparable. Therefore, the designations $TVOC_{PAS}$ and $TVOC_{GC}$ will be used in this study.

The location of the Tenax sampling point was next to the sensor stand. The sampling was done through a Teflon tube, connected to the room through specially made wholes in the test room wall. The Tenax adsorption tubes and sampling pump were locating outside the test room. The VOCs were sampled as 6 l and 12 l samples in duplicate on Tenax TA at a nominal flow of 100 ml/min and 200 ml/min for 30/60 minutes, depending on the tests, using flow-controlled pumps. The sampling airflow rates were checked with a rotameter before and after each sampling. The sampling procedure recommendations and consultancy was received from the SP Technical Research Institute of Sweden.

B.7.3 Set-up testing

Some preliminary tests were carried out prior the performance tests. These tests included determination of the air tightness of the test room and evaluating the mixing of air in the test room.

B.7.3.1 Determination of air tightness of the clean room

The air tightness of the room was determined by means of a pressure testing. The exhaust air diffuser was sealed and excess pressure was created in the test room. Fan speed was increased until the required testing pressure was reached. The excess pressure in the room is measured with U-tube manometer. The results of the tests can be seen in table B.9. The measurement uncertainty of the leakage measurement is given as ± 3 % [2].

Table B.9 Leakage measured in the test room during pressure testing

Pressure difference over airflow device Δp_{flow}, Pa	Supply airflow rate V, l/s	Overpressure in the room Δp_{dif}, Pa	Leakage l/s
5	3.5	50	3.5
20	6.5	120	6.5
40	9.5	180	9.5

B.7.3.2 Evaluation of air mixing in the room

The mixing of air in the room was evaluated by conducting tracer gas measurements. Laughing gas, N_2O was used as tracer gas which was supplied to the room via plastic tube connected to the supply air duct. The concentration decay was monitored with a photoacoustic spectroscopy instrument from Innova, type 1302. The gas concentrations were measured in 3 different points in the room at 110 cm above the floor and in the exhaust air device. The location of the measurement points is given in figure B.13. The distance from the wall at measurement point 3 was about 20 cm. Since simultaneous measurement of these points was not possible, the several tracer gas tests were carried out. The supply airflow rate was between 6.9 l/s to 7.0 l/s and the pressure difference in the test room relative to its surroundings was 8 Pa. The results are shown in figure B.14. The figure shows the comparison between the measured tracer gas concentrations in the different measurement points.

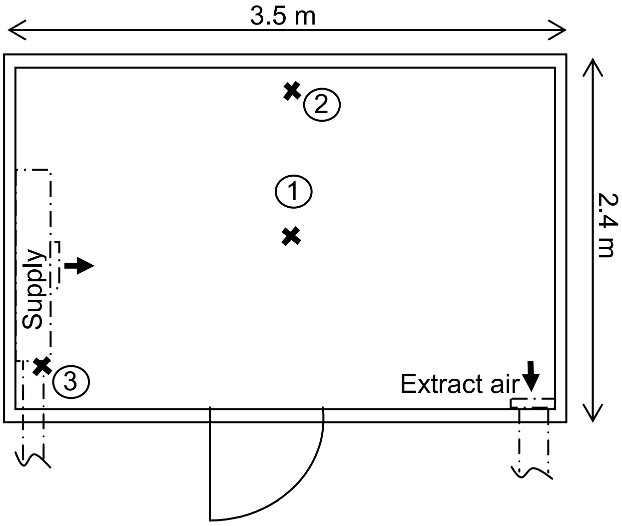


Figure B.13 The location of the measurement points in tracer gas tests. The cross x marks the different measurement points. The tracer gas concentrtions were measured in 3 different points in the room at 110 cm above the floor and in the exhaust air device.

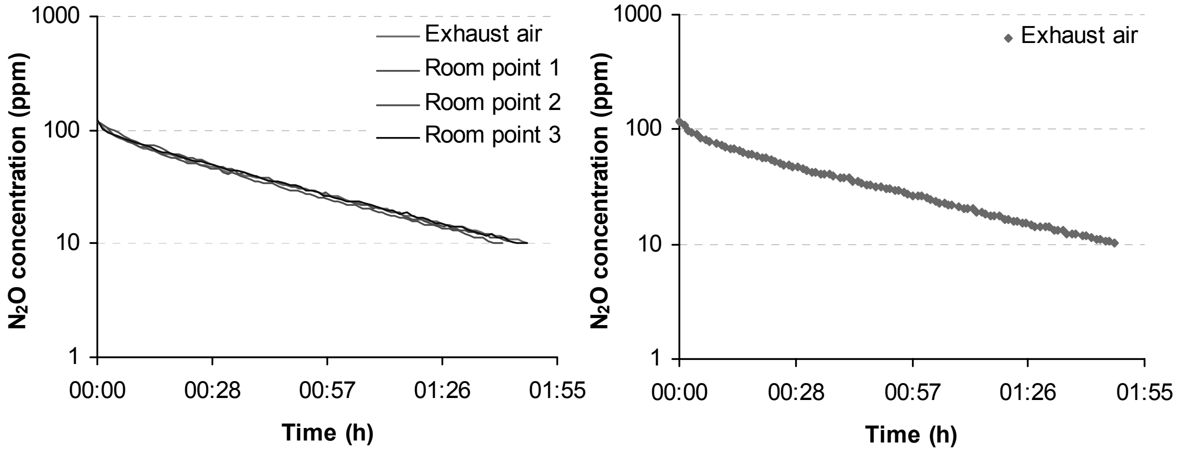


Figure B.14 Tracer gas concentration in different measurement points in the room at 110 cm above the floor. For the complete mixing the concentration decay lines measured at the different points in the room and at the exhaust air device should coincide.

With the complete mixing the concentration decay curves, corresponding to the measurements at the different points in the room and at the exhaust air, should coincide[2]. As can be seen from left diagram in the Figure B.14 the decay curves coincide quite well. The measured values in the exhaust air side, presented on the right diagram in Figure B.14, show a virtually linear relation between gas concentration and time on the logarithmic scale, which indicates an almost complete mixing in the test room[2]. The respective test point chosen for the location of the sensor panel for all of the conducted tests was measurement point 1.

The nominal time constant of the ventilation system of the clean room is 1.24 h^{-1}, based on the measurement in the exhaust air duct. The nominal time constant is obtained from curve adaption through linear regression of the measured gas concentrations.

B.7.3.3 Specification of the pollutant emission sources used in different tests

<u>Furniture</u>

New office furniture was bought for this test, including an office table, chair and bookshelf. The table is made from Medium Density Fibre Board, birch veneer with clear acrylic lacquer and has legs made from aluminium steel. The seat and back of the office chair is made of polypropylene plastic with galvanized steel for holders and has a cotton cover. The book shelf is made of particleboard, printed and embossed acrylic paint and covered with clear acrylic lacquer. The furniture was delivered from the shop to the laboratory hall packed and disassembled. The un-packaging and assembling was done directly prior to the testing.

A table lamp was placed in the test room during testing, since the test room has no artificial lighting. The aim was to visually monitor the test conditions and the sensors during the tests. The table lamp was made from steel.

Additionally, a local room humidifier was placed in the room in order to achieve the required humidity conditions. The cover of the device is made from plastic. The humidifier was always placed on the floor and with the vapour nozzle direction upwards.

An old personal computer (PC) and a CTR monitor
A five-year old personal computer was used for emission testing together with older type of CTR monitor, with the size of 17´´. The computer had been running constantly prior delivery to the laboratory and for 24-hours in the laboratory before placing to the test room. A self-scan was scheduled for the computer during the test.

A new personal computer and a LCD monitor
A new personal computer was used for emission testing together with a new type of LCD monitor, with the size of 17´´. The computer had been running for a short time prior delivery to the laboratory and for 1-hour in the laboratory before placing to the test room. A self-scan was scheduled for the computer during the test.

Linoleum floor
A floor cover made from linoleum was used for the testing. The whole test room floor was covered with linoleum in the test. Before testing the linoleum was polished with a traditional polishing agent for linoleum floors.

Linoleum cleaning agent
A universal cleaning agent was used in the testing, which is commonly used by the office cleaners. The concentrate of the cleaning agent was mixed with water according to the specifications by the manufacturer. The towel used for cleaning was wetted to the water-cleaning agent concentration and weighted before washing the floor. After the washing was finished the towel was weighted again in order to evaluate how much water-cleaning concentration was put to the floor. The total amount of cleaning-agent/water mixture used for washing was 55 g.

1 person
The person participating in the test was a female adult with the age of 27 years and weight of 70 kg. The person was not wearing any perfumes at the time of the test procedure.

B.8 Performance tests of the CO_2-sensors and mixed-gas sensors in the field

B.8.1 The test set-up

The tests were carried out in a meeting room in an existing office building in Denmark. The building has two floors. On the first floor situates four meeting rooms, a kitchen and storage rooms and on the second floor five office rooms and two big open office areas. The building operates with three separate DCV systems, using 100 % of outdoor air.

The room chosen for the sensor performance tests is a meeting room designed for maximum 8 persons. The dimensions of the meeting room are: length 4.5 m, width 3.5 m and height 2.6 m, which give a volume of 40.95 m^3 and 15.75 m^2 floor area. The test room has big windows on one side of the test room, facing north/west side.

The air is supplied to the test room with a pressure dependent VAV diffuser. The room air is removed via exhaust air device in the ceiling. The pressure on the supply air side is kept constant by fan speed control. The exhaust airflow rates are controlled by the exhaust air fan according to the supply airflow rate and with the preset under pressure conditions in the room. The ventilation system connected to the meeting room supports also four other rooms. Cooling of supply air is applied in the central ventilation unit.

The designed airflow rate to the meeting room is in a range of 20 - 70 l/s. The airflow rates are controlled by means of a combined CO_2/temperature sensor. The existing sensor has also a built-in P-controller. The sensor measures the CO_2 concentration and temperature. The values of the two parameters are compared with the preset set-points and a common ventilation demand signal is sent to the regulating damper in the VAV supply air diffuser. The set points set to the sensor are: minimum opening for the damper 400 ppm CO_2 or +20˚C and maximum opening for the damper 1000 ppm CO_2 or +24˚C. The current CO_2/temperature sensor/controller is a new sensor and is similar to the sensors *S1* and *S3* tested in this sensor study, except that the test sensors have no controller functions. The old sensor/controller was replaced two weeks prior testing. The other CO_2/temperature sensors in the building have been in operation for about five years.

A schematic picture of the ventilation system and test room is given in figure B.15. The location of measurement points in the room and in the system is market with numbers.

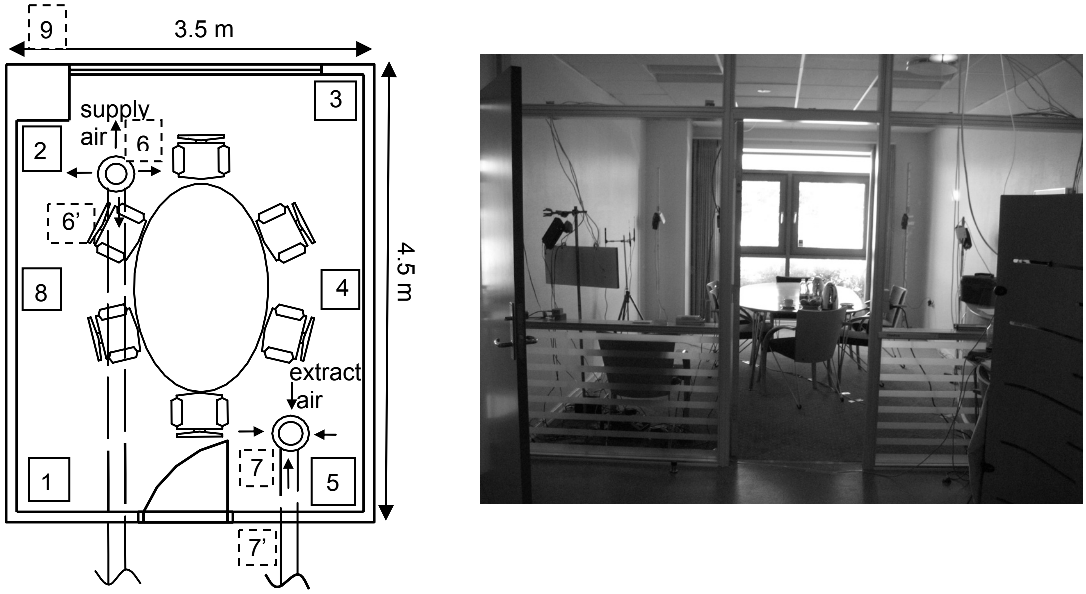


Figure B.15 Schematic picture and photo of the meeting room. The location of the measurement points in the room and in the duct system are marked with numbers. Points 1 to 5 and 8 were locating in the room, points 6 and 7 in the duct or in the supply/exhaust air device. Measurement point 9 locates outside.

B.8.2 Instrumentation and measurement techniques

The test sensors were placed to the different points in the room and ducts, shown in figure B.15. The test sensors were locating in the room points 1 to 5, in the supply air duct point 6' and in the exhaust air duct point 7'. The logging system was locating outside the test room. Temperature, relative humidity and carbon dioxide concentrations were measured at the same room locations as the test sensors. Temperature and humidity sensors were also placed to supply and exhaust air side and outdoors, in points 6, 7 and 9 in figure A.6. Tinytag Ultra loggers, type TGU -1500, were used for this measurement. The uncertainty of the temperature and relative humidity sensor is ±0.5 ˚C at +20 ˚C and ± 3 % r.h. at +25˚C respectively. The reference carbon dioxide instruments used were CO_2-Tinytag loggers G-79. The uncertainty of the CO_2-sensor is ±(20 ppm + 3 % of measured value).

The content of ultrafine particles in the room air and outdoors was measured at the different test conditions. For room measurement a particle counter TSI model CPC 3007 was used. This enables particle number concentration measurements and data recording in the particle size range from 0.01 to larger than 1 μm. According to the manufacturer the concentration accuracy up to 100 000 particles cm^{-3} is ± 20 % of reading. For measuring ultrafine particles concentration outdoors a particle counter P-Trak 8025 was used and the concentration accuracy can be roughly estimated to be about ± 30 % of reading [144].

Close to the seating area, at room point 8, thermal comfort parameters, such as air velocity and temperature, were also monitored. A "Brüel & Kjaer Model 1213 – Thermal Climate Analyzer" was used for these measurements. The uncertainty of the instrument is ± 0.2 ˚C for temperature measurement and ± 0.02 m/s for measurement of air velocity.

The supply and exhaust airflow rates were measured and logged continuously. Flow measuring devices were installed on supply and extract air ducts, type FMDU/FMDTR100 from "Lindab". According to the manufacturers data the method error for this type of a device is ± 5%. The pressure drop over the flow measurement device was measured with SWEMA 3000 including SWA 07 pressure probe and with SWEMA 3000md measurement instrument. According to the manufacturer the uncertainty of these instruments is ± 1 Pa ± 2 % of measured value, after zeroing: ± 0.3 Pa ± 2 % of measured value. The expanded uncertainty for airflow measurement is estimated to be ± 7 %, with coverage factor $k = 2$.

B.8.3 Set-up testing

B.8.3.1 Evaluation of air mixing in the room

Tracer gas measurements were carried out in the test room in order to determine the air mixing and air change rate in the room. Laughing gas, N_2O was used as tracer gas which was supplied to the room directly. The concentration decay was monitored with a photoacoustic spectroscopy instrument from Innova, type 1302. The gas concentrations were measured in different room points in the room at 110 cm above the floor and in the exhaust air device. The chosen room points were the same as the location of the test sensors. It was not possible with one instrument to carry out a simultanoues measurement at different locations. Instead, different sampling tubes were placed to the the different sampling locations. The connection to the measurement instrument was changed between the different tubes systematically to cover all the points.

The results are shown in figure B.16. The figure shows the comparison between the measured tracer gas concentrations in the different measurement points. For almost complete mixing in the room the concentration decay curves, corresponding to the measurements at the different points in the room and at the exhaust air, should have linear relation between gas concentration and time in logarithmic scale [2]. The nominal time constant of the ventilation system of the meeting room was 2.5 h^{-1}, based on the measurement in the exhaust air duct.

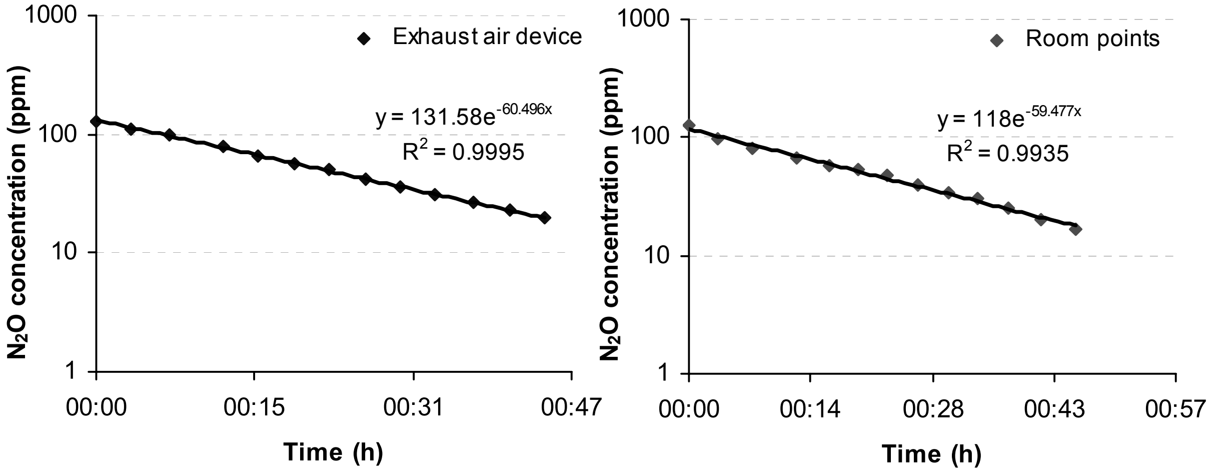


Figure B.16 Tracer gas concentration in different room points and in the exhaust air device in the meeting room. For the perfect mixing the concentration decay lines measured at the different points in the room and at the exhaust air device should be linear in the logarithmic scale.

B.9 Monitoring occupancy in office buildings- a case study

B.9.1 The case study building and measurements techniques

The monitoring of occupancy patterns was carried out in a university administration building locating in Gothenburg. The same building was used for this case study as in the DCV system study, *Case study 2B,* described in APPENDIX B.1. The facility has 58 office rooms, 5 copy rooms, 5 meeting rooms, 5 break rooms, 3 rooms for archives and library and a few storage and equipment rooms. Some of the rooms in this building have been rented out to other organizations than the university administration. However, their activities are related to administration in the research field.

The airflow rates supplied to the majority of room are controlled by the temperature and occupancy sensors, which are built into the variable supply air diffuser. The DCV diffuser also includes the control and regulating equipment. All together there are 95 DCV diffusers in this building. A few of the rooms have more than one DCV diffuser.

The occupancy status in different rooms has been determined by occupancy sensors. Therefore, monitoring of occupancy was possible only in the rooms where the DCV diffusers are installed. All together there are 76 such rooms out of 83 rooms, excluding all corridor areas and toilets. The rooms without the DCV diffusers are the storage and equipment rooms, e.g. server rooms.

Due to the limitations in the technology of occupancy sensors used, it is possible to only determine whether a room is occupied or not. The sensors do not give any information about the number of people in the room. However, according to the room layouts and design, the office rooms are intended to have only one occupant. A few office rooms are bigger and have two occupants. The meeting rooms are designed for up to 10 people, depending on the room. The copy rooms and break rooms are used by the employees in the building.

The occupancy sensors applied to the DCV supply air diffusers are passive infrared type. This type of sensor detects changes in infrared radiation which occur, when there is movement by a person or object which is different in temperature from the surroundings. According to the specifications of these sensors even slight motions made by people will be detected easily.

The detection from the occupancy sensor is registered as a point in time, given with uncertainty in seconds. However, the logging system registers the present occupancy data polled from the DCV diffusers, after a specified time period in minutes. This time period is about 4.5 minutes. The sampling interval is dependent on the specifications of the logging system used for collecting the data. The building has a central server for logging and online visualisation of the network of DCV supply air diffuser. This server is installed and programmed by the company who produces the DCV diffuser. For saving the data from the occupancy sensors the server connects to the DCV supply air devices and registers the instantaneous reading.

Due to the load of the network and technical properties of the server it is not possible to connect to all of the devices in the building at the same time. The logging is set in a way that in about every 2 seconds the server connects to one device. Each DCV diffuser has a specific number for communication between the diffuser and the server. The logging starts from diffuser nr 1, which is situated on the first floor and goes in a series till the DCV diffuser with the highest number. After the data from all the devices is registered the logging starts again from the first device. All together there are 95 DCV diffusers in the case study building. However, the number of devices programmed to the server and for logging is 127. This is done in order to add flexibility to the system and in case more DCV diffuser will be installed to the building in the future. The non-existing devices show all values as 0 in the log file and are not considered in the current data processing. Nevertheless, the sampling period for one diffuser is depending on all the programmed diffusers in the system. The sampling interval is about 4 minutes and 20 seconds in the case study building.

The registered data from the DCV diffusers contains each room’s status as either “occupied” marked as “1” in the data or “unoccupied” corresponding to “0”. Additionally, an associated time and date stamp of data registration is marked. An occupied event occurs when someone enters the empty room and the sensor detects motion. There is no switch-on delay time for the sensor to register from unoccupied to occupied event. If the sensor does not detect movement in the room anymore an unoccupied event is registered. Commonly a switch–off delay time is applied for sensors in order to avoid false detections of room occupancy, e.g. when the person does not move in the room. The switch-off delay time is the time duration from the latest detected movement until the occupancy sensor registers that the room is unoccupied. Two different switch-off delay times are set in the devices in the study building: 5 min and 10 minutes. However, for the majority of the measurement period the devices operated with 10 minutes of switch-off time.

B.9.2 Data processing and measurement uncertainties

The occupancy in the rooms was monitored during the period of 10th of September 2007 to 11th of September 2008. The data logged from the DCV diffusers is saved on a small memory card connected to the server. The memory card is emptied every couple of months by stopping the logging in the server, removing the card and saving the data from it. Therefore, some gaps in the measurement period can be seen in the data which are up to 15 minutes. Additionally, it happened that due to some errors in the server and due to some broken devices no data was saved for a short period of time for all or some of the devices. These periods have not been considered when analysing the data.

The clock in the server system does not follow the hourly summer and winter time changes, but is adjusted according to time when the system was started or adjusted. All of the recorded data follows the summer time. Therefore before processing the occupancy data the registered times were adjusted with 1 hour between the last Sunday in October till last Sunday in March in respective years of measurement.

The measured data has been analysed by using MySQL database programming. First the data registered from each device was divided on room basis. This means that the data collected from the rooms with multiple devices have been presented as a common output for the given rooms. It can occur that the different occupancy sensors in the same room indicate different occupancy status. This can happen for example when the person is out of the coverage area of one of the sensors but is still in the room. The output from all of the occupancy sensors in the same room was compared. If one of the sensors showed “occupied” event then the status of the room at that time moment was considered as occupied. In addition, situations occurred when the data was not saved for one of the devices in the room due to errors with the device or with the data saving system. These time intervals have not been considered in the analysis.

Since all of the devices have 5 or 10 minutes shut-off delay times in the occupancy sensors, these times have been subtracted in the processing of the data each time it has been registered from occupied to unoccupied event. This would help to evaluate the actual occupancy period in the rooms. The results will be presented for both cases: with and without the switch-off delay times of the occupancy sensors. The switch-off delay time of 5 minutes was applied only during two weeks of time at the beginning of the measurement period. During other times the switch-off delay time was 10 minutes.

Occupancy factors were calculated from the sorted data on room basis. The occupancy factor is defined here as the number of occupied rooms in a given time divided by the total number of rooms in the building. The total number of rooms in the building is considered to be the number of rooms which have DCV diffusers installed. Nevertheless, some errors occurred with some DCV diffusers in the building during the measurement period. The actual maximum number of rooms where connection with the device was established varied between 69 till 75. This number does not follow any regular pattern and the rooms, where the devices showed errors for a period of time, are random. Therefore the occupancy factor has been calculated based on the total number of measured rooms.

As described before, due to the technical properties of the server, it is not possible to connect to all of the devices in the rooms at once. There is about 2 seconds difference between the two consecutive devices in a series. The maximum time difference in logging between the first and last room in a series is about 3.5 minutes. Therefore, the evaluated occupancy factor in this study represents the occupancy factor within 3.5 minutes time intervals. The uncertainty introduced to the results due to non-simultaneous sampling is difficult to evaluate.

In addition to the occupancy factors, the occupancy periods have been evaluated. In the data analysis the time periods from the first “occupied” event till the first “unoccupied” event is considered as occupied period. The time period from the first “unoccupied” event till the first “occupied” event is considered as unoccupied period. Some uncertainty will be introduced to the evaluated occupancy periods since the exact time when the room will go from unoccupied to occupied and from occupied to unoccupied is not registered. These events take place within the sampling interval. Therefore the maximum uncertainty for one occupied time period in the room is less than 4.5 minutes.

The periods of occupancy have been evaluated for the normal period of occupancy for different rooms: offices, copy rooms, meeting rooms, rest rooms, etc. The normal period of occupancy is considered to be between 7:00 and 18:00 from Monday to Friday, except holidays. Additionally, the last week in December and the month of July have not been included in the calculations, since many people are on holidays during this time.

APPENDIX C

C Evaluation of uncertainty of measurement

This chapter presents the detailed procedures for calculation of uncertainty of measurement in different studies. The uncertainty of measurement has been particularly evaluated for measurements, where determining the value of a particular quantity required measurements with a number of instruments and methods. In addition the uncertainty of measurement has been evaluated for the reference instruments that needed calibration on the site.

The main components of uncertainty of measurement are defined in chapter C.1. This chapter is based on International Organization of Legal Metrology guide OIML G 1-100 "*Evaluation of measurement data – Guide to the expression of uncertainty in measurement*" [109]. The calculations of measurement uncertainties at different studies are presented in chapters C.2 to C.4. The presented measurement uncertainty budgets are based on the recommendations and examples made in the OIML G 1-100 guide and in the European co-operation for Accreditation document EA 4/02 "Expression of the Uncertainty of Measurement in Calibration"[56] Additionally, recommendations given in the measurement uncertainty evaluation guideline within Building Services Engineering, Chalmers [98] have been used.

C.1 Introduction

The objective of a measurement is to determine the value of the measurand, which is the value of the particular quantity to be measured [109]. The output quantity Y can depend on a number of input quantities X_i (i = 1,2,…,N) according to the functional relationship:

$$Y = f(X_1, X_2, ..., X_N) \qquad \text{(eq. C.1)}$$

However, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate. An estimate of the measurand, denoted by y, is given by:

$$y = f(x_1, x_2, ..., x_N) \qquad \text{(eq. C.2)}$$

Where $x_1, x_2, ..., x_N$ are input estimates.

Uncertainty of measurement is defined as a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand [109]. Uncertainty of measurement comprises many components. These components can be categorized, based on the method used to evaluate them, in two groups:

- Type A: those that are evaluated by statistical methods
- Type B: those that are evaluated by other means

All of the uncertainty components are modelled by probability distributions quantified by variances or standard deviations. The estimated standard deviation associated with each input estimate x_i is defined as a standard uncertainty and denoted by $u(x_i)$. Each input estimate x_i and its associated standard uncertainty $u(x_i)$ are obtained from a distribution of possible values of the input quantity X_i.

A type *A* evaluation is used to obtain a value for the repeatability or randomness of a measurement process. It is represented by a statistically estimated standard deviation of a sample mean of *n* independent repeated values for an input quantity X_i. For such a component the *Type A standard uncertainty* is $u(x_i) = s(\overline{X}_i)$ and can be expressed as [109]:

$$u(x_i) = s(\overline{X}_i) = \left[\frac{1}{n(n-1)} \sum_{j=1}^{n} (X_j - \overline{X}_i)^2 \right]^{\frac{1}{2}} \qquad \text{(eq. C.3)}$$

Where ,

$u(x_i)$	standard uncertainty associated with the estimated value of each input quantity x_i. The input quantities contribute to the estimated value of the output quantity y in function form as follows: $y = f(x_1, x_2, \ldots, x_N)$
$s(\overline{X}_i)$	standard deviation of a sample mean of *n* independent repeated values for an input quantity X_i
X_j	*j*th repeated observation of randomly varying input quantity X_i
n	number of observations in a sample
$\overline{X}_i$	arithmetic mean of *n* repeated observations of randomly varying input quantity X_i

The uncertainty components obtained by a type *B* evaluation cannot be estimated by repeated measurements. They account for errors that usually remain constant while the measurements are made. These are for example uncertainties associated with measurement instruments, measuring methods, etc.

In contrast to Type *A* standard uncertainty, estimated from an experimentally determined frequency components, the expected standard uncertainty $u(x_i)$ of a Type *B* evaluation is obtained from an assumed probability distribution. This assumed probability distribution is based on all the available information, which may include previous measurement data, manufacturer's specifications, data provided in calibration reports, etc. For example, when only upper and lower limits for an input quantity X_i are possible to estimate a uniform or rectangular distribution is assumed. Then x_i is the midpoint of the interval, $x_i = (a_- + a_+)/2$, with the associated variance

$$u^2(x_i) = \frac{(a_+ - a_-)^2}{12} \qquad \text{(eq. C.4)}$$

If the difference between the bounds $a_- - a_+$ is denoted by $2a$, the equation C.4. becomes:

$$u^2(x_i) = \frac{a^2}{3} \qquad \text{(eq. C.5)}$$

When the standard uncertainties $u(x_i)$ of the input estimates x_i have been derived from both Type *A* and Type *B* evaluations, the combined standard uncertainty of the output estimate *y* can be evaluated. The combined standard uncertainty $u_c(x_i)$ is the estimated standard deviation associated with the output estimate or measurement result *y* and can be calculated as follows :

$$u_c(y) = \left[\sum_{i=1}^{N} c_i^2 \cdot u^2(x_i) \right]^{\frac{1}{2}} \qquad \text{(eq. C.6)}$$

Where,

$u_c(y)$	combined standard uncertainty of output estimate y.
c_i	sensitivity coefficient. It is equal to a partial derivate with respect to input estimate x_i of the functional relationship f between the measurement result y and the input estimates.
N	number of input estimates x_i on which the measurement output depends

In order to provide a confidence interval for the output estimate y, an expanded uncertainty U should be calculated. Expanded uncertainty is a quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand [109]. It is obtained by multiplying the combined standard uncertainty $u_c(y)$ by a *coverage factor k*:

$$U = k \cdot u_c(y) \qquad \text{(eq. C.7)}$$

Where,

U	expanded uncertainty of output estimate y that provides a confidence interval $Y = y \pm U$
k	coverage factor. A value $k = 2$ gives a level of confidence of approx. 95%
$u_c(y)$	combined standard uncertainty of output estimate y.

The coverage factor is a numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

C.2 Laboratory measurements with a DCV supply air diffuser

C.2.1 Air temperature measurements in the test chamber and in the laboratory hall

The test room temperature and the laboratory hall temperature were measured with Pt-100 type of sensors. The same type of sensors were also used for measuring plane radiant temperatures in the test room and the supply air temperature in the duct. All these temperature sensors were calibrated using a mercury thermometer. The measured temperatures with Pt-100 sensors were corrected taking into account the observed difference between the sensor reading and the reference thermometer. The uncertainties associated with the results of the temperature measurements in the tests include:

- $u(t_{cal})$- the uncertainty assigned to the calibration of the reference thermometers. According to the certificate of calibration, the uncertainty of the mercury thermometer is: ± 0.05 °C
- $u(t_{read})$- the uncertainty assigned to the reading from the mercury thermometer. The resolution of the reading is half of the value between the two ticks in the scale, which is ± 0.05 °C

- $u(t_{method})$- the uncertainty assigned to the calibration method. The uncertainty is be estimated to be ± 0.1 °C
- $u(t_{dif})$- the uncertainty associated with the comparison of Pt-100 sensors and the Mercury thermometer. The experimental standard deviation characterizing the comparison of the reference thermometer and Pt-100 sensors was determined from the variability of six repeated observations of the difference in temperature. The standard uncertainty associated with the arithmetic mean is ±0.01 °C
- $u(t_{log})$- the uncertainty assigned to the measurement with the logging system, where the Pt-100 sensors were connected. The uncertainty is considered to be ± 0.01 °C

The uncertainty budget for the temperature measurement with Pt-100 sensors is presented in table C.1.

Table C.1 Uncertainty budget for the temperature measurement using Pt-100 temperature sensors

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$ [ºC]	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$ [ºC]
$u(t_{cal})$	Calibration of the reference thermometer	0.03	rectangular	1.0	0.03
$u(t_{read})$	Temperature reading	0.03	rectangular	1.0	0.03
$u(t_{method})$	Calibration method	0.06	rectangular	1.0	0.06
$u(t_{dif})$	Repeated observations of the measured difference	0.01	normal	1.0	0.01
$u(t_{log})$	Uncertainty from the logger	0.006	rectangular	1.0	0.006
$u_c(t)$	Combined standard uncertainty		normal		0.07
U	Expanded uncertainty		normal (k=2)		0.14

The calculated expanded uncertainty for operative temperature measurement with six Pt-100 temperature sensors is ± 0.4 °C, with a coverage factor of $k = 2$.

C.2.2 Air temperature measurements in the test chamber using SWEMA 300 with SWA comfort probes

Air temperature and air velocities in the test room were also measured with SWEMA 300 measurement instruments with SWA 01 and SWA 03 comfort probes. The characteristics of the sensors were given in table B.3, chapter B.1, APPENDIX B. The draught probe SWA 01 is an older type of this type of a sensor, but the measurement characteristics are the same as SWA 03. The uncertainties associated with the results of the temperature measurements with these instruments include:

- $u(t_{cal})$- the uncertainty assigned to the calibration of the SWEMA 300 with SWA 01 or SWA 03 probes. According to the certificate of calibration the sensor uncertainty is ± 0.3 °C
- $u(t_{inst})$- the uncertainty assigned to the positioning of the sensors, which is assumed to be about ± 0.05 °C

Table C.2 gives the uncertainty budget for the temperature measurement with SWEMA 300 with SWA 01 or SWA 03 probes in different room points in the test room.

Table C.2 Uncertainty budget for the temperature measurement using SWEMA 300 with SWA comfort probes

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$ [ºC]	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$ [ºC]
$u(t_{cal})$	Calibration of SWEMA instrument	0.2	rectangular	1.0	0.2
$u(t_{inst})$	Method uncertainty	0.03	rectangular	1.0	0.03
$u_c(t)$	Combined standard uncertainty		normal		0.2
U	Expanded uncertainty		normal (k=2)		0.4

C.2.3 Determining the airflow rates supplied to the test room using airflow measurement devices in the duct

The airflow rates supplied to the test room were measured with air flow measuring and control devices installed into the supply air duct. The lower supply airflow rates 10 l/s and 25 l/s were measured with “Fläkt Woods” IRIS damper. The Iris Damper is based on the orifice plate principle. The higher airflow rates up to 50 l/s were measured with a flow control damper from “Swegon” type CRMc. Both of the dampers have manometer connections for measuring the differential pressure. The differential pressures were measured with electronic pressure sensors. The corresponding airflow rates can be calculated according to the following equation:

$$\dot{V} = K\sqrt{\Delta p_m} \qquad \text{(eq.C.8)}$$

Where,

$\dot{V}$ airflow rate, l/s;

K flow coefficient of the unit, which depends on the airflow rate and the device settings;

Δp_m measured pressure difference in the measuring device, Pa

The *K* factors for different device obstructions that were used for measuring different airflow rates were given in Table B.4, chapter B.2, APPENDIX B. Each damper is calibrated individually. The method error provided by the manufacturers is about ± 5% to ± 7%, depending on the mounting position within the ventilation system. However, the measuring devices were also calibrated with a reference airflow measuring instrument prior to the testing.

The uncertainties associated with the results of the airflow rate measurements with these instruments include:

- $u(\dot{V}_{cal})$- the uncertainty assigned to the calibration of the airflow measuring devices. According to the manufacturers data the uncertainty of the reference instrument is ± 5% from the measured airflow rate

- $u(\dot{V}_{inst})$- the uncertainty associated with the installation of the airflow measurement devices into the supply air duct. The uncertainty is considered to be ± 2% from the measured airflow rate
- $u(\Delta p_m)$- the uncertainty associated with measuring differential pressures with the electronic pressure transmitter connected to the logging system. The expanded uncertainty of pressure measurement with the electronic pressure sensor connected to the logger is estimated to be ± 2.1 % from the measured value, with a coverage factor of $k = 2$

Table C.2 gives the uncertainty budget for the temperature measurement with SWEMA 300 with SWA 01 or SWA 03 probes in different room points in the test room.

Table C.3 presents the uncertainty budget for determining the airflow rate supplied to the test room.

Table C.3 Uncertainty budget for determining the airflow rate supplied to the test room with the two types of airflow measuring devices in the duct.

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$ **[%]**	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$ **[%]**
$u(\dot{V}_{cal})$	Calibration of the airflow measuring device	2.9	rectangular	1.0	2.9
$u(\dot{V}_{inst})$	Installation of the device	1.2	rectangular	1.0	1.2
$u(\Delta p_m)$	Measurement with the electronic pressure sensor	1.05	normal	0.5	0.5
$u_c(\dot{V})$	Combined standard uncertainty		normal		3.2
U	Expanded uncertainty		normal (k=2)		6.4

C.3 Laboratory measurements with CO$_2$-sensors

C.3.1 Determining the reference temperature and relative humidity in the test chamber

The temperature and relative humidity in the test chamber were measured with a combined temperature/humidity sensor. This sensor was calibrated in the laboratory of SP Technical Research Institute of Sweden. The results of the temperature and humidity measurements in the test chamber in the current study have been corrected based on the observed difference between the sensor reading and the reference instrument used in the calibration.

The uncertainties associated with estimating the temperature and relative humidity values in the test chamber in the current study include:

- $u(t_{cal})$; $u(\varphi_{cal})$- the uncertainty assigned to the calibration measurement. According to the laboratory of SP Technical Research Institute of Sweden the uncertainty of calibration measurement is ± 0.1 °C and ± 2.5 % r.h. This uncertainty includes the uncertainties associated with the random and systematic effects of the reference measurement.

- $u(t_{log})$; $u(\varphi_{log})$ - the uncertainty assigned to the measurement with the logging system, where the temperature/humidity sensor was connected. The uncertainty is evaluated to be ± 0.002 °C and ± 0.003 % r.h.
- $u(t_{res})$; $u(\varphi_{res})$ - the uncertainty assigned to the truncation due to the resolution of the logger, where the temperature/humidity sensor was connected. The least significant digit of interest for the temperature and relative humidity readings is 0.01 °C and ± 0.01% r.h. The uncertainty associated to the truncation is ±0.005 °C and ± 0.005 % r.h.

The uncertainty budget for the temperature and relative humidity measurement in the test chamber is presented in Tables C.4 and C.5.

Table C.4 Uncertainty budget for the temperature measurements in the test chamber with the combined temperature/humidity sensor

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$ [ºC]	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$ [ºC]
$u(t_{cal})$	Calibration of the sensor	0.06	rectangular	1.0	0.06
$u(t_{log})$	Uncertainty from the logger	0.001	rectangular	1.0	0.001
$u(t_{res})$	Rounding due to the logger resolution	0.003	rectangular	1.0	0.003
$u_c(t)$	Combined standard uncertainty		normal		0.06
U	Expanded uncertainty		normal (k=2)		0.12

Table C.5 Uncertainty budget for the humidity measurements in the test chamber with the combined temperature/humidity sensor

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$ [%]	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$ [%]
$u(\varphi_{cal})$	Calibration measurement	1.4	rectangular	1.0	1.4
$u(\varphi_{log})$	Uncertainty from the logger	0.002	rectangular	1.0	0.002
$u(\varphi_{res})$	Rounding due to the logger resolution	0.003	rectangular	1.0	0.003
$u_c(t)$	Combined standard uncertainty		normal		1.4
U	Expanded uncertainty		normal (k=2)		2.8

In the calculations also the random effects associated with the series observations ambient temperature and relative humidity in the test chamber is considered. This is done by evaluating the standard deviation of the temperature/relative humidity sensor readings and including it to the combined standard uncertainty evaluations.

C.3.2 Determining the reference CO_2-concentration in the test chamber

Reference gas concentration in the test chamber is derived from the measurement of the flow rates of high concentration carbon dioxide and synthetic air. The carbon dioxide concentration in the test chamber can be obtained from the following equation:

$$C_{ref} = \left[\left(C_{CO_2} \cdot \frac{\dot{V}_{CO_2}}{\dot{V}_{CO_2} + \dot{V}_{SA}} \right) + \left(C_{SA} \cdot \frac{\dot{V}_{SA}}{\dot{V}_{CO_2} + \dot{V}_{SA}} \right) \right] \cdot f_{mixing} \qquad \text{(eq.C.9)}$$

Where,

C_{ref}	concentration of carbon dioxide in the test chamber, ppm;
C_{CO2}	concentration of carbon dioxide in the gas bottle, ppm. Gas bottle with factory specified gas concentration of 4999 ppm was used for mixing in the experiments;
C_{SA}	concentration of reference gas (carbon dioxide) in the synthetic air gas bottle, ppm. According to the supplier of reference gases, the concentration of carbon dioxide in the synthetic air is < 0.1 ppm;
$\dot{V}_{CO_2}$	flow rate of high concentration carbon dioxide from the gas bottle, l/min;
$\dot{V}_{SA}$	flow rate of the synthetic air from the gas bottle, l/min;
f_{mixing}	coefficient of the mixing. With perfect mixing the coefficient is equal to 1.

The uncertainties associated with estimating the carbon dioxide concentration in the test chamber in sensor tests include:

- $u(C_{CO2})$ - uncertainty due to variable composition of the carbon dioxide in the gas bottle. According to the supplier of the reference gas, the uncertainty of the analyzed value of the gas concentration in the gas bottle is ± 2 %. A gas bottle with gas concentration of 4999 ppm was used for mixing in the experiments.
- $u(C_{SA})$ - uncertainty due to variable composition of the synthetic air in the gas bottle. According to the supplier of the synthetic air bottles, the concentration of carbon dioxide in the synthetic air is < 0.1 ppm.
- $u(V_{CO2})$ – uncertainty of measurement of high concentration CO_2-gas with the gas flow measuring and control equipment. Since the supply flow rate of reference gas was not constantly measured it is difficult to evaluate random variations in the flow rate. The measurements were done at the beginning and at the end of each CO_2-concentration step change. However, based on the experience of the calibration laboratory of SP Technical Research Institute of Sweden[171], the expanded uncertainty of measurement with the gas flow control and measuring devices is within ± 1.5 % of measured flow rate.
- $u(V_{SA})$ - uncertainty of measurement of synthetic air with the gas flow measuring and control equipment. Based on the experience of the calibration laboratory of SP Technical Research Institute of Sweden[171], the expanded uncertainty of measurement with the gas flow control and measuring devices is within ± 4.0 % of measured flow rate.
- $u(f)$ – uncertainty associated with mixing the reference gas with synthetic air and possible concentration gradients inside the test chamber. Based on the experience of the calibration laboratory of SP Technical Research Institute of Sweden[171], the uncertainty is within +0/-1 % of estimated reference gas concentration in the test chamber.

The uncertainty budget for estimating the reference concentration of CO_2 in the test chamber is given in table C.6. The uncertainty budget consists of an example of estimating the reference CO_2 concentration based on estimates of different input quantities and their standard uncertainties.

Table C.6 Uncertainty budget for estimating the concentration of CO_2 (C_{ref}) in the test chamber in sensor tests chamber. An example of estimating the reference CO_2 concentration based on estimates of different input quantities and their standard uncertainties is given.

Quantity X_i	**Estimate** x_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	c_i 1)	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$
C_{CO_2}	4999.0 ppm	57.7 ppm	rectangular	0.33	-18.8 ppm
C_{SA}	0.10 ppm	0.06 ppm	rectangular	0.67	-0.04 ppm
$\dot{V}_{CO_2}$	2.399 l/min	0.048 l/min	normal	460	-22.1 ppm
$\dot{V}_{SA}$	4.976 l/min	0.037 l/min	normal	222	8.2 ppm
f_{mixing}	1.00000	$5.77 \cdot 10^{-3}$	rectangular	1626	-9.4 ppm
Concentration estimate with combined standard uncertainty $u_c(C_{ref})$					
C_{ref}	1626 ppm		normal		31.6 ppm
Concentration estimate with expanded uncertainty U ($k=2$)					
C_{ref}	1626 ppm		normal		63.1 ppm (3.9 % relative)

Note 1: the sensitivity coefficients associated with different input estimates are evaluated by calculating the change in output estimate y (CO_2 concentration) due to a change in the input estimate within the described uncertainty limits.

C.3.3 Measuring the carbon dioxide concentration with the CO_2-sensors in the test chamber

The performance of CO_2-senors was evaluated by placing the sensors in the test chamber, with controlled value of carbon dioxide concentration. The uncertainties associated with the CO_2-sensor readings include:

- $u(C_{log})$ - the uncertainty assigned to the measurement with the logging system, where the test sensors were connected. According to the logger technical specifications the uncertainty is 0.0035 % of reading + 0.0005 % of range under normal operating temperature conditions (18 ºC – 28 ºC). The selected range for the measurements was 10 V, whereas 0 to 10 V corresponds to 0 to 2000 ppm of CO_2 for the majority of sensors. The uncertainty is evaluated to be between ± 0.014 ppm to ± 0.07 ppm when the reading is between 2 V to 10 V. Some sensors had a 0 to 5 V output corresponding to 400 to 4000 ppm. The uncertainty is evaluated to be ± 0.05 ppm.
- $u(C_{res})$ - the uncertainty assigned to the truncation due to the resolution of the logger, to which the CO_2-sensors were connected. The least significant digit of interest is 0.001 V. The uncertainty associated to the truncation is ± 0.0005 V corresponding to 0.1 ppm.

The uncertainty budget for the CO_2-sensor reading is presented in table C.7.

Table C.7 Uncertainty budget for the for the CO_2-sensor readings. An example of estimating the uncertainty of sensor reading based on the uncertainties from the logger.

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$ **[ppm]**	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$ **[ppm]**
$u(C_{log})$	Uncertainty from the logger	0.04	rectangular	1.0	0.04
$u(C_{res})$	Rounding due to the logger resolution	0.06	rectangular	1.0	0.06
$u_c(C_{iS})$	Combined standard uncertainty		normal		0.07
U	Expanded uncertainty		normal (k=2)		0.14

In order to make the best comparison with the available uncertainty data of the tested CO_2-sensors, the output values of all non-dispersive infrared sensors have been corrected to the standard test conditions of the factory calibration. The measured values of the test sensors have been corrected according to the following equation:

$$C_S = C_{iS} \cdot \frac{p_0 \cdot T_a}{T_0 \cdot p_a} \qquad \text{[ppm]} \qquad \text{(eq. C.10)}$$

Where,

C_S	corrected sensor reading of volume concentration, ppm;
C_{iS}	gas concentration indicated by the test sensor, ppm;
T_a	ambient temperature in the test chamber, K;
p_a	atmospheric pressure during the test, hPa;
p_0	pressure at the standard test conditions of the factory calibration, typically 1013 hPa;
T_0	temperature at the standard test conditions of the factory calibration. For some tested specimens the temperature at calibration is 298 K, for some sensors 293 K.

The uncertainties associated with the corrected non-dispersive infrared CO_2-sensor readings include:

- $u(C_{iS})$ – the uncertainty associated with the CO_2-sensor readings. According to the evaluation above the combined standard uncertainty of the CO_2-sensor reading is ± 0.07 ppm (see table C.7)
- $u(T_a)$ – the uncertainty associated with estimating the temperature value in the test chamber. Based on the evaluation above the combined standard uncertainty of the temperature measurement is ± 0.06 K (see table C.4)
- $u(p_a)$ - the uncertainty associated with estimating the ambient pressure. The uncertainty of ambient pressure measurement is ± 1 hPa.

The uncertainty budget for a corrected CO_2-sensor reading is presented in table C.8.

Table C.8 Uncertainty budget for the corrected CO_2-sensor readings. An example of estimating the uncertainty of sensor reading based on the uncertainties from the logger and temperature and pressure measurement.

Standard uncertainty component $u(x_i)$	**Source of uncertainty**	**Value of standard uncertainty** $u(x_i)$	**Probability distribution**	c_i	**Uncertainty contribution** $u_i(y) \equiv c_i \cdot u(x_i)$
$u(C_{iS})$	Uncertainty from the logger	0.07 ppm	normal	1.0	0.07 ppm
$u(T_a)$	Uncertainty from the temperature measurement	0.06 K	normal	5.4	0.30 ppm
$u(p_a)$	Uncertainty from the pressure measurement	0.6 hPa	rectangular	-1.6	-0.9 ppm
$u_c(C_S)$	Combined standard uncertainty		normal		1.0 ppm
U	Expanded uncertainty		normal (k=2)		2.0 ppm

Note 1: the sensitivity coefficients associated with different input estimates are evaluated by calculating the change in output estimate y (CO_2-sensor reading) due to a change in the input estimate within the described uncertainty limits.

The results from the certain performance tests are presented as a deviation of the sensor reading from the estimated reference concentration in the test chamber, i.e. $C_{dif} = C_S - C_{ref}$,. The combined uncertainty associated with this deviation can be obtained from the following equation:

$$u_c(C_{dif}) = \sqrt{u_c^2(C_S) + u_c^2(C_{ref})} \qquad \text{[ppm]} \qquad \text{(eq.C.11)}$$

Where,

$u_c(C_{dif})$ the combined uncertainty associated with the deviation of the sensor reading from the estimated reference concentration in the test chamber, i.e. $C_{dif} = C_S - C_{ref}$;

$u_c(C_S)$ the combined standard uncertainty of the CO_2-sensor reading in the test chamber, ppm. In the calculations also the random effects associated with the series observations of the CO_2-sensor readings and ambient temperature in the test chamber is considered. This is done by evaluating the standard deviation of the CO_2-sensor output and temperature sensor readings and including it to the combined standard uncertainty evaluations.

$u_c(C_{ref})$ the combined standard uncertainty of the estimated reference concentration in the test chamber, ppm.

C.4 Laboratory measurements with mixed-gas sensors

C.4.1 Determining the concentration of reference gas mixture VOC1 in the test chamber by Tenax sampling

In the majority of the mixed-gas sensor tests the reference concentration of VOCs in the test chamber was determined by means of Tenax adsorption tubes. In this method the sample air is pumped through the cartridges filled with Tenax TA and analysed with Flame Ionization Detector, FID, in gas chromatography in the laboratory of SP Technical Research Institute of Sweden. For tests with VOC1 gas mixture duplicate sampling was applied.

The reference concentration of gas mixture VOC1 (toluene) in the test chamber can be obtained from the following relationship:

$$C_{ref} = \frac{M_{VOC1}}{\tau_{tenax} \cdot \dot{V}_{tenax}} \cdot k_{VOC1} \qquad \text{(eq. C.12)}$$

Where,

C_{ref}	volume concentration of the reference VOC gas (toluene) in the test chamber, ppm;
M_{VOC1}	estimated mass of toluene present in the sampling tube that was used in the test, ng;
τ_{tenax}	sampling time for the tenax test, min;
$\dot{V}_{tenax}$	airflow rate through the tenax adsorption tube by active pumping, l/min;
k_{VOC1}	coefficient for calculating from mass concentration of toluene to volume concentration of toluene in. The coefficient is determined from the following equation:

$$k_{VOC1} = \frac{\widetilde{V}}{\widetilde{M}} = \frac{\widetilde{R} \cdot T_a}{p_a \cdot \widetilde{M}} \qquad \text{(eq. C.13)}$$

Where,

$\widetilde{V}$	molar volume, dm^3/mol;
$\widetilde{M}$	molar mass, g/mol. For toluene the molar mass is $\widetilde{M}$ = 92.14 g/mol;
$\widetilde{R}$	gas constant, $\widetilde{R}$ =8314.34 J/(kmol/K);
T_a	ambient temperature in the test chamber, K;
p_a	atmospheric pressure during the test, kPa.

The uncertainties associated with estimating the reference gas mixture VOC1 (toluene) concentration in the test chamber by Tenax sampling includes:

- $u(M_{VOC1})$ - the uncertainty associated with determining the mass of toluene present in the Tenax sampling tube with the test analysis method used in the calibration laboratory of SP Technical Research Institute of Sweden. The expanded uncertainty of the analysis method is estimated to be within ± 15 % of the analysed value, with the coverage factor k = 2 [178]. This uncertainty includes both the random and systematic effects associated with the analysis method.
- $u(\tau_{tenax})$ - the expanded uncertainty associated with estimating the sampling time, which is ± 1 minute.
- $u(\dot{V}_{tenax})$- the uncertainty associated with measuring the airflow rate through the Tenax adsorption tube with the airflow measuring and controlling equipment. The airflow rate passing the Tenax tube was controlled by a sampling pump and measured with a ball flow meter (rotameter). The expanded uncertainty of gas flow control with flow controllers and airflow measuring devices is estimated to be within ± 5 % of measured airflow rate [178].
- $u(T_a)$ – the uncertainty associated with estimating the temperature value in the test chamber in order to evaluate the coefficient for calculating from mass concentration

of toluene to volume concentration of toluene. Based on the evaluation above the combined standard uncertainty of the temperature measurement is ± 0.06 K (see Table C.4). In the calculations also the random effects associated with the series observations of ambient temperature in the test chamber must be considered.

- $u(p_a)$ - the uncertainty associated with estimating the ambient pressure in order to evaluate the coefficient for calculating from mass concentration of toluene to volume concentration of toluene. The uncertainty of ambient pressure measurement is ± 1 hPa. In the calculations also the random effects associated with the series observations of ambient pressure in the test chamber must be considered.

The uncertainty budget for estimating the reference concentration of gas mixture VOC1 (toluene) in the test chamber by means of Tenax sampling tubes is given in table C.9. The uncertainty budget consists of an example of estimating the reference toluene concentration based on estimates of different input quantities and their standard uncertainties (see equation C.12).

Table C.9 Uncertainty budget for estimating the reference concentration of gas mixture VOC1 (C_{ref}) in the test chamber by Tenax sampling. An example of estimating the reference VOC concentration based on estimates of different input quantities and their standard uncertainties is given.

Quantity X_i	**Estimate** x_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	c_i **1)**	**Uncertainty contribution** $u_i(y)$
M_{VOC1}	12012 ng	901 ng	normal	$7.8 \cdot 10^{-5}$	0.07 ppm
$\dot{V}_{tenax}$	0.1 l/min	0.0025 l/min	normal	-9.2	-0.02 ppm
τ_{tenax}	36 min	0.5 min	normal	-0.03	-0.01 ppm
T_a	299 K	0.7 K	normal	0.003	0.002 ppm
p_a	98.0 kPa	0.3 kPa	normal	$-8.5 \cdot 10^{-3}$	-0.003 ppm
Concentration estimate with combined standard uncertainty $u_c(C_{ref})$					
C_{ref}	0.94 ppm		normal		0.07 ppm
Concentration estimate with expanded uncertainty ***U (k=2)***					
C_{ref}	0.94 ppm		normal		0.15 ppm (16.0 % rel.)

Note 1: the sensitivity coefficients associated with different input estimates are evaluated by calculating the change in output estimate y (VOC concentration) due to a change in the input estimate within the described uncertainty limits.

C.4.2 Determining the concentration of reference gas mixture VOC2 in the test chamber by Tenax sampling

In the sensor test with VOC2 reference gas mixture (toluene and acetone) the reference concentration of VOCs in the test chamber was determined only by means of Tenax adsorption tubes. In this test the Tenax sampling was done by having two adsorption tubes in a series. The reference concentration of gas mixture VOC2 (toluene and acetone) in the test chamber can be obtained from the following relationship:

$$C_{ref} = \frac{M_{VOC1}}{\tau_{tenax} \cdot \dot{V}_{tenax}} \cdot k_{VOC1} + \frac{M_{VOC2}}{f_{rec} \cdot \tau_{tenax} \cdot \dot{V}_{tenax}} \cdot k_{VOC2} \qquad \text{(eq. C.14)}$$

Where,

C_{ref}	total volume concentration of the reference VOC gases (toluene and acetone) in the test chamber, ppm;
M_{VOC1}	estimated mass of toluene present in the sampling tube that was used in the test, in nanograms. The mass has been estimated as a sum from the two adsorption tubes measured in a series.
M_{VOC2}	estimated mass of acetone present in the sampling tube that was used in the test, in nanograms. The mass has been estimated as a sum from the two adsorption tubes measured in a series.
τ_{tenax}	sampling time for the tenax test, min.
$\dot{V}_{tenax}$	airflow rate of through the tenax adsorption tubes by active pumping, l/min.
f_{rec}	recovery factor due to possible breakthrough of acetone from the Tenax tubes sampled in a series. The factor is depending on the chosen sampling method. Possible breakthrough of acetone from the tenax tubes in series sampling can occur. The uncertainty has been estimated by comparing the estimated masses present in the two sampling tubes. It is assumed that the third tube put to the series of adsorption tubes should contain 50 % of the toluene from the second tube[178]. The recovery factor is calculated based on the average of the estimated mass that the third sampling tube may include. The factor is varying from 0.8 to 1.0.
k_{VOC1}	coefficient for calculating from mass concentration of toluene to volume concentration of toluene. The coefficient is determined according to the equation C.13, presented in chapter C.4.1 in this APPENDIX C.
k_{VOC2}	coefficient for calculating from mass concentration of acetone to volume concentration of acetone. The coefficient is determined according to the equation C.13. The coefficient is determined according to the equation C.13, presented in chapter C.4.1 in this APPENDIX C. The molar mass for acetone is $\widetilde{M} = 58.08$ g/mol

The uncertainties associated with estimating the reference gas mixture VOC2 concentration in the test chamber by Tenax sampling includes:

- $u(M_{VOC1})$ - the uncertainty associated with determining the mass of toluene present in the Tenax sampling tube with the test analysis method used in the calibration laboratory of SP Technical Research Institute of Sweden. The expanded uncertainty of the analysis method is estimated to be within ± 15 % of the analysed value, with the coverage factor $k = 2$ [178]. This uncertainty includes both the random and systematic effects associated with the analysis method.
- $u(M_{VOC2})$ - the uncertainty associated with determining the mass of acetone present in the Tenax sampling tube with the test analysis method used in the calibration laboratory of SP Technical Research Institute of Sweden. The expanded uncertainty of the analysis method is estimated to be within ± 15 % of the analysed value, with the coverage factor $k = 2$ [178]. This uncertainty includes both the random and systematic effects associated with the analysis method.
- f_{rec} – the uncertainty associated with the recovery factor. The uncertainty of recovery factor is equal to the bandwidth between the maximum evaluated breakthrough and measured total mass of acetone in the sampling tubes.
- $u(\tau_{tenax})$ - the uncertainty associated with estimating the sampling time, which is ± 1 minute.

- $u(\dot{V}_{tenax})$ - the uncertainty associated with measuring the airflow rate through the Tenax adsorption tube with the airflow measuring and controlling equipment. The airflow rate passing the Tenax tube was controlled by a sampling pump and measured with a ball flow meter (rotameter). The expanded uncertainty of gas flow control with flow controllers and airflow measuring devices is estimated to be within ± 5 % of measured airflow rate [178].
- $u(T_a)$ – the uncertainty associated with estimating the temperature value in the test chamber in order to evaluate the coefficient for calculating from mass concentration of reference gas to volume concentration. Based on the evaluation above the combined standard uncertainty of the temperature measurement is ± 0.06 K (see table C.4). In the calculations also the random effects associated with the series observations of ambient temperature in the test chamber must be considered.
- $u(p_a)$ - the uncertainty associated with estimating the ambient pressure in order to evaluate the coefficient for calculating from mass concentration of reference gas to volume concentration. The uncertainty of ambient pressure measurement is ± 1 hPa[171]. In the calculations also the random effects associated with the series observations of ambient pressure in the test chamber must be considered.

The uncertainty budget for estimating the total reference concentration of gas mixture VOC2 (toluene and acetone) in the test chamber by means of Tenax sampling tubes is given in Table C.10. The uncertainty budget consists of an example of estimating the reference VOC mixture concentration based on estimates of different input quantities and their standard uncertainties (see equation C.14).

Table C.10 Uncertainty budget for estimating the reference concentration of gas mixture VOC2 (C_{ref}) in the test chamber by Tenax sampling. An example of estimating the reference VOC concentration based on estimates of different input quantities and their standard uncertainties is given.

Quantity X_i	**Estimate** x_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	c_i **1)**	**Uncertainty contribution** $u_i(y)$
V_{VOC1}	3409 ng	256	normal	$2.5 \cdot 10^{-4}$	0.06 ppm
V_{VOC2}	1853 ng	147	normal	$4.0 \cdot 10^{-4}$	0.06 ppm
f_{rec}	0.94	0.06	normal	0.7	0.04 ppm
$\dot{V}_{tenax}$	0.1 l/min	0.0027 l/min	normal	-14.9	-0.04 ppm
τ_{tenax}	10 min	0.5 min	normal	0.15	-0.08 ppm
T_a	296 K	0.7 K	normal	$-5.7 \cdot 10^{-3}$	0.004 ppm
p_a	97.1 kPa	0.5 kPa	normal	$-1.8 \cdot 10^{-2}$	-0.009 ppm
Concentration estimate with combined standard uncertainty $u_c(C_{ref})$					
C_{ref}	1.65 ppm		normal		0.13 ppm
Concentration estimate with expanded uncertainty ***U (k=2)***					
C_{ref}	1.65 ppm		normal		0.26 ppm (16 % rel.)

Note 1: the sensitivity coefficients associated with different input estimates are evaluated by calculating the change in output estimate y (VOC concentration) due to a change in the input estimate within the described uncertainty limits.

C.4.3 Determining the reference VOC concentration with flow rate measurement

In some of the mixed-gas sensor tests the reference concentration of VOCs in the test chamber was determined by measuring the flow rates of the reference gas and synthetic air. The concentration of the reference gas mixture VOC-1 (toluene) in the test chamber is derived from the measurement of the flow rates of high concentration toluene gas and synthetic air. The toluene concentration in the test chamber can be obtained from the following equation:

$$C_{ref} = \left[\left(C_{VOC1} \cdot \frac{\dot{V}_{VOC1}}{\dot{V}_{VOC1} + \dot{V}_{SA}} \right) + \left(C_{SA} \cdot \frac{\dot{V}_{VOC1}}{\dot{V}_{VOC1} + \dot{V}_{SA}} \right) \right] \cdot f_{mixing} \qquad \text{(eq. C.15)}$$

Where,

C_{ref}	concentration of the reference VOC gas (toluene) in the test chamber, ppm;
C_{VOC1}	concentration of the reference VOC gas (toluene) in the gas bottle, ppm. A gas bottle with the specified concentration of 102.8 ppm was used in the experiments;
C_{SA}	concentration of the reference VOC gas (toluene) in the synthetic air gas bottle, ppm. According to the supplier of reference gas, the concentration of VOCs in the synthetic air is < 0.1 ppm;
$\dot{V}_{VOC1}$	flow rate of the high concentration VOC gas (toluene) from the gas bottle, l/min;
$\dot{V}_{SA}$	flow rate of the synthetic air from the gas bottle, l/min;
f_{mixing}	coefficient of the mixing. With perfect mixing the coefficient is equal to 1.

The uncertainties associated with estimating the reference gas mixture VOC1 concentration in the test chamber by measuring the flow rates of the reference gas and synthetic air include:

- $u(C_{VOC1})$ - the uncertainty associated with the variable composition of VOC gas (toluene) in the gas bottle. According to the gas supplier the specified concentration of toluene in the bottle is: 102.8 ± 2.1 ppm. The uncertainty of the analyzed value ± 2 % is given with a 95 % interval of confidence (k =2).
- $u(C_{SA})$ - the uncertainty associated with the variable composition of the synthetic air in the gas bottle. According to the supplier of the synthetic air bottles, the concentration of VOCs in the synthetic air is < 0.1 ppm.
- $u(V_{VOC1})$ – the uncertainty associated with the measurement of reference VOC-gas with the gas flow measuring and control equipment. The reference gas flow rates were controlled by two different gas flow regulators. The flow rates supplied to the test chamber were measured with the soap bubble meter. The expanded uncertainty of estimating the gas flow rate with the gas flow control and measuring devices is evaluated to be within ± 10 % of measured flow rate [171]. The higher uncertainty values compared to the measurements with the CO_2-gas is due to the very low gas volume flow rates needed for achieving the required concentrations.
- $u(V_{SA})$ - the uncertainty associated with the measurement of synthetic air with the gas flow measuring and control equipment. The synthetic air flow rate was controlled by one gas flow regulator. The flow rate supplied to the test chamber

was measured with the soap bubble meter. The expanded uncertainty of estimating the synthetic air flow rate with the gas flow control and measuring devices is evaluated to be within ± 1.5 % of measured flow rate [171].

- *u(f)* – the uncertainty associated with the mixing the high concentration VOC gas with synthetic air and possible concentration gradients inside the calibration chamber. The uncertainty is evaluated to be within +0 /- 1 % of estimated reference gas concentration in the test chamber [171].

The uncertainty budget for estimating the reference concentration of gas mixture VOC1 (toluene) in the test chamber is given in table C.11. The uncertainty budget consists of an example of estimating the reference toluene concentration based on estimates of different input quantities and their standard uncertainties (see equation C.15).

Table C.11 Uncertainty budget for estimating the reference concentration of gas mixture VOC1 (C_{ref}) in the test chamber in sensor tests. An example of estimating the reference VOC concentration is given.

Quantity X_i	**Estimate** x_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	c_i **1)**	**Uncertainty contribution** $u_i(y)$
C_{VOC1}	102.8 ppm	1.05 ppm	normal	0.01	0.01 ppm
C_{SA}	0.1000 ppm	0.0577 ppm	rectangular	0.99	0.06 ppm
$\dot{V}_{VOC1}$	0.06 l/min	0.0032 l/min	normal	15.5	0.05 ppm
$\dot{V}_{SA}$	6.50 l/min	0.0488 l/min	normal	0.35	-0.01 ppm
f_{mixing}	1.0	$5.77 \cdot 10^{-3}$	rectangular	1.1	0.01 ppm
Concentration estimate with combined standard uncertainty $u_c(C_{ref})$					
C_{ref}	1.08 ppm		normal		0.08 ppm
Concentration estimate with expanded uncertainty *U (k=2)*					
C_{ref}	1.08 ppm		normal		0.15 ppm (14.1 % rel.)

Note 1: the sensitivity coefficients associated with different input estimates are evaluated by calculating the change in output estimate y (VOC concentration) due to a change in the input estimate within the described uncertainty limits.

APPENDIX D

D Questionnaires

This appendix presents the questionnaires used in different field studies.

D.1 Questionnaire used for DCV system case studies in the field

Questionnaire nr:_______________

Data:_________________

Indoor climate evaluation – EDIT- building at Chalmers

The aim of this questionnaire is to evaluate the work of the renovated air conditioning system in EDIT-building at Chalmers. CIT Energy Management AB with co-operation with Building Services Engineering- dep. of Energy & Environment at Chalmers is carrying out a questionnaire which is commissioned by Akademiska Hus AB. ***The purpose of this questionnaire is to study the building users' perceptions towards their indoor environment in general.*** This questionnaire was first carried out in spring 2004 and is repeated now after the summer 2005.

The air conditioning system in EDIT-building at Chalmers was fully renovated in 2003 and taken in operation in September 2003. After the renovation of the air-conditioning system, new supply air diffusers were installed to the ceiling of each office room. During the winter time 2003/2004 some small problems with the system work appeared, which fortunately have been solved by now. After the summer 2004, the system has worked in a way it was planned.

A place for personal comments is given under the question 11 at the last page.

This questionnaire refers to the indoor environment during the previous summer period. Think about the situation you have had in your room when the outdoor conditions were warm, which has been the period from May till September.

The questionnaire is given out in the morning and collected during the end of the day or before the afternoon next day

We would like to stress that answering to this questionnaire is voluntary and the information gather will be handled confidentially.

Sincerely yours,

Lennart Jagemar	*Mari-Liis Maripuu*
Associate professor	*PhD Student*

Air temperature

1a. How do you feel about the room temperature during this period of the year?

Cold	cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐1	☐2	☐3	☐4	☐5	☐6	☐7

1b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

1c. Please mark, how would you like to have the temperature during this period of the year?

Much colder	Colder	Slightly colder	It is good as it is	Slightly warmer	warmer	much warmer
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Air movement (Draught)

2a. How do you perceive the air movement (draught) during this period of the year?

Very low	Low	Slightly low	Neither high nor low	Slightly High	High	Very high
☐1	☐2	☐3	☐4	☐5	☐6	☐7

2b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

2c. Please mark, how would you like to have the air movement this period of the year?

Much Lower	Lower	Slightly Lower	It is good As it is	Slightly Higher	Higher	Much higher
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Air humidity

3a. How do you perceive the air humidity during this period of the year?

Very low	Low	Slightly low	Neither high nor low	Slightly High	High	Very high
☐1	☐2	☐3	☐4	☐5	☐6	☐7

3b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

3c. Please mark, how would you like to have the air humidity during this period of the year?

Much dryer	Dryer	Slightly dryer	It is good As it is	Slightly more humid	More humid	Much more humid
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Noise level

4a. How do you perceive the noise level in your room during this period of the year?

Very low	Low	Slightly low	Neither high nor low	Slightly High	High	Very high
☐1	☐2	☐3	☐4	☐5	☐6	☐7

4b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

4c. Please mark, how would you like to have the noise level during this period of the year?

Much Lower	Lower	Slightly Lower	It is good As it is	Slightly Higher	Higher	Much higher
☐1	☐2	☐3	☐4	☐5	☐6	☐7

4d. If you feel that the noise level is in some extent uncomfortable- what does it depend on?

Ventilation	☐1	
Lightning	☐2	
Office equipment e.g. computer	☐3	
Conversation, talking	☐4	
Noise outside	☐5	
Other	☐6	Other sources:________________________________

Lights- Office lightning

5a. How do you feel about the room lightning during this period of the year?

Very weak	Weak	Slightly Weak	Neither weak nor strong	Slightly strong	Strong	Very strong
☐1	☐2	☐3	☐4	☐5	☐6	☐7

5b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

5c. Please mark, how would you like to have the office lightning during this period of the year?

Much Weaker	Weaker	Slightly Weaker	It is good As it is	Slightly Stronger	Stronger	Much stronger
☐1	☐2	☐3	☐4	☐5	☐6	☐7

5d. If you feel that the office lightning is in some extent uncomfortable- what does it depend on?

Dazzling ☐1

Unequal lightning ☐2

Other ☐3 **Name other:**____

Lights – Day light

6a. How do you feel about the day light at your workplace during this period of the year?

Very weak	Weak	Slightly Weak	Neither weak nor strong	Slightly strong	Strong	Very strong
☐1	☐2	☐3	☐4	☐5	☐6	☐7

6b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

6c. Please mark, how would you like to have the day light during this period of the year?

Much Weaker	Weaker	Slightly Weaker	It is good As it is	Slightly Stronger	Stronger	Much stronger
☐1	☐2	☐3	☐4	☐5	☐6	☐7

6d. If you feel that the day light is in some extent uncomfortable- what does it depend on?

Dazzling ☐1
Reflection on the computer screen ☐2
Shadow effects ☐3
Other ☐4 Name other: ____________________________________

Indoor air quality

7a. How do you feel about the indoor air quality (air quality refers to dust/odours/stuffy) in the air) in the room during this period of the year?

Very bad	Bad	Slightly bad	Neither bad nor good	Slightly good	Good	Very good
☐1	☐2	☐3	☐4	☐5	☐6	☐7

7b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

7c. If you feel that the air quality is in some extent uncomfortable- what does it depend on?

Dust	☐1	
Odours	☐2	
Stuffy	☐3	
Other	☐4	**Name other:**____

7d. If you feel that the air quality is in some extent uncomfortable – does it appear during some particular time?

In the mornings	At lunchtime	In the afternoon	In the evening	Saturday/Sunday - holidays
☐1	☐2	☐3	☐4	☐5

Self influence to the indoor climate

8a. In what extent do you think you could influence following things?

	Not at all	A little	Certain amount	A lot	entirely
Temperature	☐1	☐2	☐3	☐4	☐5
Noise	☐1	☐2	☐3	☐4	☐5
Lightning	☐1	☐2	☐3	☐4	☐5
Day light	☐1	☐2	☐3	☐4	☐5
Indoor air quality	☐1	☐2	☐3	☐4	☐5

8b. Which needs do you think you have to change from the following?

	Not at all	A little	moderate	Big	Very big
Temperature	☐1	☐2	☐3	☐4	☐5
Noise	☐1	☐2	☐3	☐4	☐5
Lightning	☐1	☐2	☐3	☐4	☐5
Day light	☐1	☐2	☐3	☐4	☐5
Indoor air quality	☐1	☐2	☐3	☐4	☐5

Indoor environment

9a. How do you evaluate your indoor environment in generally during this period of the year?

Very bad	Bad	Slightly Bad	Neither bad Nor good	Slightly Good	Good	Very good
☐1	☐2	☐3	☐4	☐5	☐6	☐7

9b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

Working environment [According to WHO: *All factors – biological,* ***medical, physiological, social*** *and technical- which in the work situations an in the working place and its surroundings influence the individual*]

10a. In what extent do you feel your work assignments to be interesting and stimulating?

Not at all	A Little	Certain amount	Quite a lot	Entirely
☐1	☐2	☐3	☐4	☐5

10b. In what extent can you influence your working conditions?

Not at all	A Little	Certain amount	Quite a lot	Entirely
☐1	☐2	☐3	☐4	☐5

Other

11. Other comments regarding indoor environment in your work space

____

____

____

Background information

12. Are you a man or a woman?

Man	Woman
☐1	☐2

13. Which year are you born in?__________

14. How long have you worked in your present working space? __________months

15. How many work places, including your own, are there in your office room?

☐1	☐2	☐3	☐4	☐5

Have you answered to this type of questionnaire before (carried out in winter)

Yes ☐1
No ☐2

D.2 Questionnaire used for DCV sensors case study in the field

Questionnaire nr:________________

Data:_________________

Energy and Environment
Alireza Afshari and Mari-Liis Maripuu

04 Jun 2008
Reference:

Indoor climate evaluation – Meeting room at EXHAUSTO building

The aim of this questionnaire is to evaluate the work of the sensor based demand controlled ventilation (DCV) system in a meeting room at EXHAUSTO building, which is controlled with new type of air quality sensors. This questionnaire is carried out by SBi and dep. of Energy & Environment at Chalmers University of Technology under the project of "Demand controlled ventilation systems for energy efficiency and good indoor climate - Equipment and system requirements", which is supported by Nordic Innovation Centre (NIC). One important part of this project is field testing in real buildings and aims to get practical experience from DCV control with two types of DCV sensors, CO2 and VOC sensors.

The purpose of this questionnaire is to study the room users' perceptions towards their indoor environment <u>during the time</u> when they are in the meeting room. Think about the situation you had in the room when you were having a meeting.

The questionnaire is given out at the end of every meeting in this room.

We would like to stress that answering to this questionnaire is voluntary and the information gather will be handled confidentially.

Sincerely yours,

Alireza Afshari Docent	Mari-Liis Maripuu PhD-candidate

Background information

	Man	Woman
A. Are you a man or a woman?	? 1	? 2

B. Which year are you born in? ____________________

Air temperature

1a. How did you feel about the room temperature during the time of the meeting?

Cold	cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐1	☐2	☐3	☐4	☐5	☐6	☐7

1b. Did you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

1c. Please mark, how would you like to have had the temperature during the time of the meeting?

Much colder	Colder	Slightly colder	It is good as it is	Slightly warmer	warmer	much warmer
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Air movement (Draught)

2a. How did you perceive the air movement (draught) during the time of the meeting?

Very low	Low	Slightly low	Neither high nor low	Slightly High	High	Very high
☐1	☐2	☐3	☐4	☐5	☐6	☐7

2b. Did you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

2c. Please mark, how would you like to have had the air movement during the time of the meeting?

Much Lower	Lower	Slightly Lower	It is good As it is	Slightly Higher	Higher	Much higher
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Air humidity

3a. How do you perceive the air humidity during the time of the meeting?

Very low	Low	Slightly low	Neither high nor low	Slightly High	High	Very high
☐1	☐2	☐3	☐4	☐5	☐6	☐7

3b. Did you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

3c. Please mark, how would you like to have had the air humidity during the time of the meeting?

Much dryer	Dryer	Slightly dryer	It is good As it is	Slightly more humid	More humid	Much more humid
☐1	☐2	☐3	☐4	☐5	☐6	☐7

Indoor air quality

4a. How did you feel about the indoor air quality (air quality refers to dust/odours/stuffy) in the air) in the room during the time of the meeting?

Very bad	Bad	Slightly bad	Neither bad nor good	Slightly good	Good	Very good
☐1	☐2	☐3	☐4	☐5	☐6	☐7

4b. Did you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable
☐1	☐2	☐3	☐4	☐5

4c. If you feel that the air quality was in some extent uncomfortable- what did it depend on?

Dust	☐1	
Odours	☐2	
Stuffy	☐3	
Other	☐4	Name other:________________________________

Indoor climate

5a. How do you evaluate your indoor environment in generally during the time of the meeting?

Very bad	Bad	Slightly Bad	Neither bad Nor good	Slightly Good	Good	Very good
☐1	☐2	☐3	☐4	☐5	☐6	☐7

5b. Do you find it …?

Extremely uncomfortable	Very uncomfortable	uncomfortable	Slightly uncomfortable	Comfortable

☐1 ☐2 ☐3 ☐4 ☐5

Self influence to the indoor climate

6a. In what extent do you think you could influence following things?

	Not at all	A little	Certain amount	A lot	entirely
Temperature	☐1	☐2	☐3	☐4	☐5
Indoor air quality	☐1	☐2	☐3	☐4	☐5

6b. Which needs do you think you have to change from the following?

	Not at all	A little	moderate	Big	Very big
Temperature	☐1	☐2	☐3	☐4	☐5
Indoor air quality	☐1	☐2	☐3	☐4	☐5

Other

7. Other comments regarding indoor environment in your work space (e.g. noise level, lighting, day light, working environment)

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