LOW-ENERGY COOLING FOR IMPROVED THERMAL COMFORT IN OFFICES

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ABSTRACT

This study has explored the possibility and potential of using a thermal active mass system for reducing the temperature rise and increasing the thermal comfort in an office room. The Controlled Active Mass (CAM) will be used as a heat sink to absorb heat from the room in order to increase the thermal comfort. Physically, the CAM system was designed as a cubic-shaped tank filled with water, with the tank surfaces either polished or black. Full-scale laboratory measurements of the CAM system in an office room have been used to evaluate the temperature, air velocity and thermal comfort values, PMV, PPD and the equivalent temperature (t_{eq}). The measurements showed that, although the CAM size is relatively small compared to the office room, and the temperature difference between the room air and the temperature of the CAM is quite modest, the influence on the thermal comfort and indoor environment is quite apparent. This is particularly so when the surfaces of the CAM system are black, since the tank is able to absorb more heat from the room surfaces than can the polished CAM system. The CAM system does not cause any uncomfortable draughts and, since it is a low-exergy system, it has a considerable potential for future energy-efficient systems in buildings.

KEYWORDS

Thermal mass, measurements, PMV, PPD, thermal comfort

INTRODUCTION

Office buildings are often subject to substantial temperature variations during the day, with the building's structure acting as an active energy-storing mass. Appropriate selection of massive construction materials permits the building's energy storage behaviour to reduce the energy demand of the building. However, the need for cooling of office buildings is increasing, even in Nordic countries such as Sweden. This can be due to excessive influence from both internal and external heat loads. The increase in internal heat is partly due to the use of more electrical equipment that will raise the indoor air temperature. One of the reasons for the increase in outdoor influence is the trend for using more glazing in facades. This increases insolation, and thus also contributes to a rise in the interior temperature during the day.

For many years, there has been interest in using the thermal capacity of different building materials to reduce temperature fluctuations and thus improve the indoor climate and reduce energy use. IEA Annex 37 (Annex 37 2004) “Low-exergy Systems for Heating and Cooling of Buildings” has investigated increased use of low-temperature heating systems and high-temperature cooling systems in low-exergy systems. Today, a number of different thermally active construction elements are available. Examples include the “Thermodeck”, where ventilation air passes through holes in concrete slabs that act as heat stores (Falk and Isfält 2002), and embedded water pipes in a slab floor that works as a heat accumulating mass (Schmidt 2002). Similarly, there are systems for cooling buildings where water pipes have been cast into the concrete building elements in floors, ceilings or walls (Arnold 2000, Hauser et al. 2000, Olesen 2000, Simmonds et al. 2000).

IEA Annex 44 (Perino 2007) "Integrating Environmentally Responsive Elements in Buildings" is concerned with various building components known as Responsive Building Elements (RBE). An RBE is defined as "a building construction element that assists in maintaining an appropriate balance between optimum interior conditions and environmental performance by reacting in a controlled and holistic manner to changes in the external or internal conditions and to occupant intervention". Thermal mass is one of the RBEs that that has been found to have the most promising potential for improvement and good take-up in the building sector: Thermal mass can be utilized in both passive and active ways. In passive thermal mass systems, the thermal energy is stored directly in the building structure hence the mass cannot be altered. For good performance of passive systems, the mass should have a high thermal capacity, such as that of a typical massive concrete structure, or should use the inner walls inside the building's thermal insulation. Active thermal systems, on the other hand, known as Thermo-Active Building Systems (TABS), consist of thermally massive structures incorporating ducts or pipes for circulation of thermal-energy-transferring media. This permits the flow of the medium, and the temperature of the thermal mass, to be changed to suit demand, and allows the supply of energy to or from the building to be controlled. In this way the thermal mass becomes active instead of passive, and the effect of the thermal mass can be controlled.

The thermal mass of buildings is affected by ambient temperature variations as well as by temperature variations inside the building. It may also be affected by solar radiation if it is located in the building so that it is directly exposed by the sun. Temperature variations over the day can be used to supply heat to the mass for cooling the building, or abstract it from the mass for heating the building. These are the most important variations that the thermal mass has to cope with. Short and more fluctuating temperature variations during the day are also reduced by the thermal mass.

The objective of this study is to use experiments to evaluate the potential of the Controlled Active Mass (CAM) system. The purpose of such a system is to obtain a good indoor climate and facilitate the use of energy sources with low environmental impacts and low exergy values. This paper will investigate how different variables of the CAM system influence the indoor environment in an office room.

DEFINITION OF THE CAM SYSTEM

The purpose of a CAM system is to reduce the need for cooling in offices and, at the same time, to provide a good indoor climate. The system can be seen as a combination of active and passive thermal mass systems, with which both the thermal mass and the temperature can be varied. While the CAM installation absorbs heat from the office area, it can be seen as a passive system, since there is no medium flowing in the system and the exchange of energy between CAM and the office is not controlled. On the other hand, when there is an increased need for cooling in the office, the water in the system can be replaced by fresh cold water to increase the cooling capacity and increase the capacity of absorbing heat from the office air. CAM thus becomes an active system that can be controlled depending on demand from the occupants. The CAM system allows the user to change both the effective mass and the temperature during the day.

The CAM system will contribute to a better thermal comfort in essentially three ways: by reducing temperature rise during the working day, by reducing the effect of temperature fluctuations and also through permitting the cooling capacity to be changed to suit weather conditions and seasons, which will give a more adaptable thermal comfort. Many office buildings have a high cooling demand due to solar radiation through glazed facades and through transmission through walls during the summer. It may therefore be necessary to have a central cooling system connected to the ventilation unit for achieving a comfortable supply temperature. The purpose of the CAM system is not to replace the central cooling system but rather to meet the cooling need for internal heat loads such as computers, lighting, occupants etc. and to complement the central system. For a more thorough explanation of the CAM system and the underlying physics and driving parameters behind it, see Törnström et al., 2007.

THERMAL COMFORT

To ensure that the CAM system creates good thermal comfort in real conditions, it is essential to focus on the occupants in the system since it is their comfort requirements that finally decide what type of design that will succeed in the long run. It is consequently very important to use comfort evaluation methods originating from human reactions and not only surface and air temperatures.

It can be quite difficult to show the combined effects from different heat losses exchanged between individuals and their surroundings. It is therefore very useful to convert these values into something easier to understand, such as the PMV index (Fanger 1970, ISO 7730 2006) for whole-body evaluation, or the equivalent “experienced” temperature (t_{eq}) (Nilsson 2004, ISO 14505) for local evaluation. The intentions in this study are to look at how both whole body and local influences of the positioning of the CAM system affect the subjective experience of thermal comfort.

A person is thermally comfortable when he/she feels that the surrounding is neither cooler nor warmer than preferable, i.e. it is a condition when the person’s heat production can be emitted without physical discomfort. The following six factors are of significance for the human thermal balance; the activity level (metabolism), the thermal insulating capacity of the clothing (often measured in the special unit 1 clo = 0.155 m^2C/W), the air temperature, the air velocity, the mean radiant temperature and the water vapour partial pressure in the air. In order to quantify if humans are in thermal comfort, the two indices, PMV and PPD as well as equivalent “experienced” temperature (t_{eq}), have been used in this study.

The PMV index

The PMV (Predicted Mean Vote) index is based on the comfort equation and on the modified version of the generally applied ASHRAE scale, where -3 is defined as cold, 0 as neutral and +3 is hot. The comfort equation expresses the condition where a large group of persons rate the conditions as 0 on the scale. Since the degree of thermal discomfort is closely related to the thermal load that influences the person, the degree of thermal discomfort can be defined as a function of the thermal load.

The PPD index

In order to obtain a more distinct expression of the degree of thermal discomfort, the PPD (Predicted Percentage of Dissatisfied) has been defined. After comparing the calculated PMV value, it was assumed that the best measurements of the heat loss from a person will be obtained by measuring the heat loss from a sensor which has the same size, form, surface and surface temperature as the person concerned. This has led the use of thermal manikins when measuring thermal comfort. The following relationship between the PMV and PPD values has been used:

$$PPD = 100 - e^{(-0.03353 \times PMV^4 - 0.2179 \times PMV^2)} \qquad (1)$$

The equivalent temperature

The equivalent “experienced” temperature is a recognised measure of the effects of both whole-body and local non-evaporative heat loss from the human body. It is particularly useful whenever complex local interactions of various heat fluxes are present. The equivalent temperature is derived from the operative temperature by the inclusion of the important effect of air velocity on a heated body. The advantage of t_{eq} is that it expresses the effects of combined thermal influences in a single figure, easy to interpret and explain. It is particularly useful for differential assessment of climatic conditions. The proven underlying hypothesis is that the t_{eq} value always represents the same "subjective" response, irrespective of the kind of combinations of heat losses. Local t_{eq} values are evaluated in clothing-independent comfort zone diagrams (Nilsson 2006).

Table 1. Description of the connection between the measured quantities and equivalent temperature.

Action	Influence
Increased air speed ↑	↓ Lower t_{eq}
Decreased air temperature ↓	↓ Lower t_{eq}
Decreased mean radiant temperature ↓	↓ Lower t_{eq}
Decreased air speed ↓	↑ Higher t_{eq}
Increased air temperature ↑	↑ Higher t_{eq}
Increased mean radiant temperature ↑	↑ Higher t_{eq}

MEASUREMENTS

Test facility

The test facility that was used for all the experiments was a well-insulated room of 3.7 m x 2.6 m x 3.3 m (L×W×H), with a false ceiling 0.5 m below the true ceiling, as shown in Figure 1. The test room, which was designed as an office room, was situated inside a large indoor facility, with steady-state conditions, at the Laboratory of Ventilation and Air Quality at the Centre for Built Environment at the University of Gävle. In the test cases, the heat loads to the office was from the façade wall (200 W), the manikin (100 W), the computer (100 W) and the lighting (84 W).

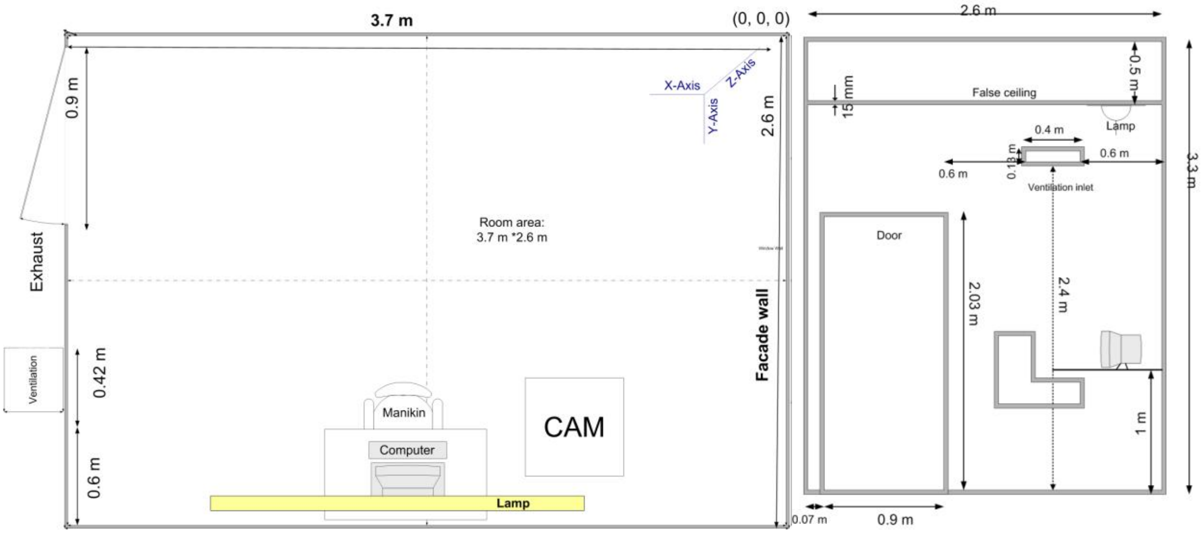

Figure 1. Top and side view of the test room.

The thermal mass was constructed as a cubic-shaped tank of size 0.6 x 0.6 x 0.6 m, made from aluminium and filled with water. The CAM temperature can be controlled and varied by changing the water in the tank with new fresh tap water. The temperature of the water can be altered between room air temperature and the temperature of the incoming tap water which, for Swedish conditions, varies between 4 °C and 12 °C, depending on the season and the type of water source. However, the temperature of the incoming water to the CAM system must be higher than the dewpoint of the office air in order to avoid condensation.

Measuring equipment

The temperatures of the room air, the supply and exhaust air, the surface temperatures of the test room and the temperature of the CAM surface and the water inside the CAM were measured using thermocouples. The thermocouples that were used were Type T thermocouples with an accuracy of ±0.1 °C for temperatures 10 to 30 °C. Thermistor anemometers were used for measuring the air velocities inside the test room for evaluation of the air flows in the room. Type CTA (Constant Temperature Anemometer) thermistors were used. These thermistors have an error of ±1 cm/s due to direction, calibration and the accuracy of the calibration equipment. The set-up of the temperature and velocity equipment is shown below in Figure 2.

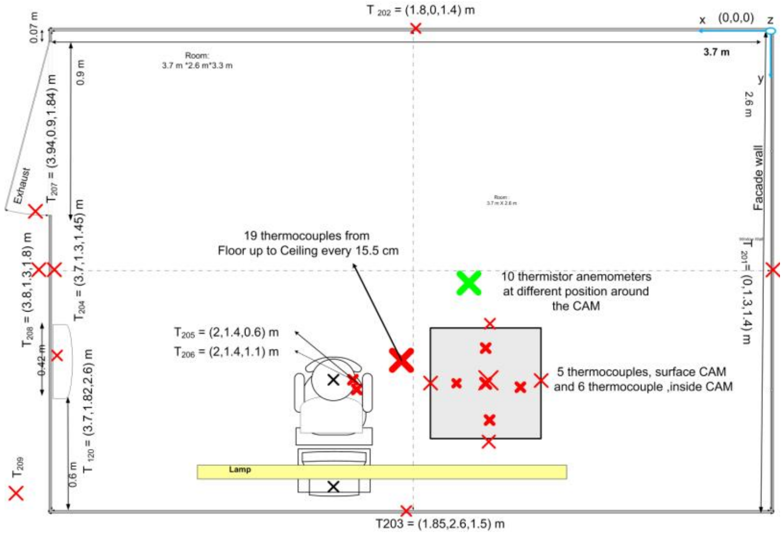

Figure 2. Measurement set-up and placement of the temperature and velocity sensors.

Measurement procedure

The first measurements were made before the CAM system was installed in the office room. Measurements were then made in order to compare a polished CAM system and a black CAM system, and finally the black CAM system was investigated with different supply air temperatures. The water volume of the CAM system was chosen as 2.5 times a human body volume (216 litres), and the temperature a little less than half that of the human body temperature (17 ºC). For all measurements, the starting temperature of the water in the CAM system has been kept at the same level. For a more thorough explanation of the measuring procedure see Ghahremanian and Janbakhsh 2007.

The thermal comfort was examined and the PMV, PPD and t_{eq} values were calculated on the basis of the measured dry heat loss, the activity level, the clothing, and water vapour partial pressure in the air. The thermal comfort measurements were made in the test room using the COMFY Test EQ-21 equipment. This gives an objective assessment of the thermal climate when the activity level and the clothing of the person under investigation are set on the apparatus. The sensing body of the COMFY test is chosen so that the relationship between the heat emitted by convection and radiation is same as that of a person. The shape of the sensor results from efforts to obtain the same projected radiation area factors for the sensor in six directions as for a person. The sensor can also be adjusted to represent the person located in different positions, standing, sitting or recumbent. The surface temperature of the sensor is the same as that of the person to be simulated, having clothing with the same clo and with heat loss corresponding to the thermal comfort in the actual surrounding.

RESULTS AND DISCUSSION

The following are the results from the measurements, with a comparison between the polished and the black CAM system. Since the available cooling effect of the CAM (which is about 50 Watt) is quite moderate compared to the internal heat loads, the CAM will have only modest effect on the room air temperature, see Figure 3. For these cases all of the heat loads were activated in the office room. One can see that in the first half hour the temperature in the office increases with about one degree while it during the remaining 8.5 hours stays relatively constant and fluctuates around this mean value. This is valid for all the three cases thus showing no real effect from the CAM-system on the overall room air temperature.

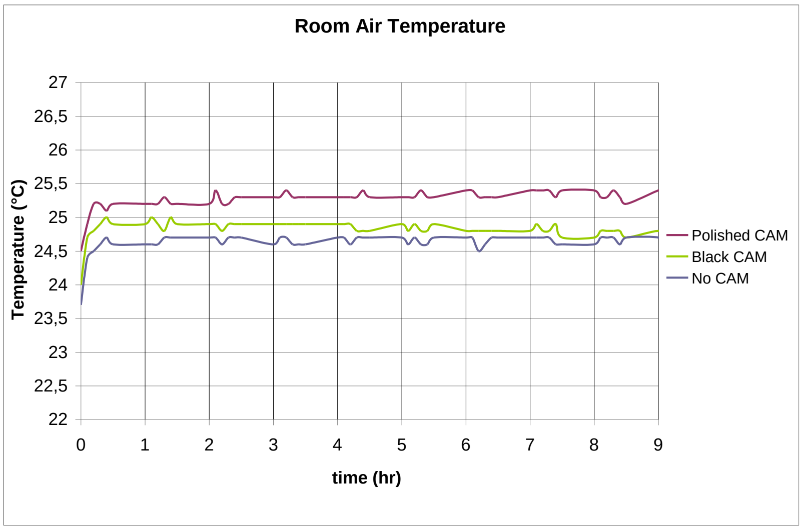

Figure 3. Room air temperature in the middle of the office.

The temperature rise of the water inside the black and the polished CAMs over eight hours was also measured, representing a normal working day. This was done to investigate how the surface colour, and thus the emissivity, of the CAM influences its heat absorption performance. The results are presented in the table below.

Table 2. Initial conditions, supply air temperature and temperature of the water inside CAM

Initial conditions	**Black CAM (°C)**	**Polished CAM (°C)**	**($T_{black\ CAM}$–$T_{polished\ CAM}$)**
T_{room} (initially)	23.3	23.6	
T_{water} (initially inside CAM)	17.9	17.6	
T_{in} (supply air temperature)	16.1	16.3	
Position of thermocouples			
Top near manikin	19.6	18.0	1.6
Near façade wall	18.7	17.7	1
Near manikin	18.8	17.8	1
Bottom centre	18.4	17.6	0.8
Centre of CAM	18.7	17.7	1
Top centre	19.3	17.9	1.4

This shows that the temperature of the black CAM increases more rapidly than that of the polished CAM, and consequently absorbs more heat from the office room. The major reason is that the black CAM (with an emissivity of about 0.9) interacts in the radiation process and absorbs heat from the surrounding surfaces due to radiation. Since the emissivity of the polished CAM is so low (around 0.08) there will be very little heat transfer due to radiation.

When the polished CAM was placed in the office room induces some additional air flows induces into the room. Due to the higher surface temperature of the black CAM, the velocities around it are lower than for the polished CAM. However, the average velocity and turbulence close to the polished CAM and the black CAM against the manikin and façade wall are the same.

PMV, PPD and the equivalent temperature were evaluated for three different cases: one case without CAM, and two cases with the black CAM but different supply air temperatures. For these cases the activity was assumed to be 70 W/m^2, the clothing was 1 clo, and the water vapour pressure 6 mbar (according to ISO 7730). The sensor was placed at the manikin position at the two different recommended heights, 0.6 and 1.1 m. These heights are valid for a person sitting near the CAM.

Table 3. Thermal comfort indices results for the office room

	Height (m)	**PMV**	**PPD**	t_{eq} **(ºC)**
Without CAM (T_{in}=16ºC)	0.6	0.20	5.8	23.5
	1.1	0.40	8.3	24.5
Black CAM (T_{in}=16ºC)	0.6	0.15	5.5	23.0
	1.1	0.25	6.3	23.5
Black CAM (T_{in}=17.2ºC)	0.6	0.25	6.3	24.6
	1.1	0.40	8.3	24.5

CONCLUSIONS

From the measurements, we have seen that although the CAM size is relatively small compared to the volume of the office, and the temperature difference between the room air and the water temperature of the CAM is quite moderate, the influence on the thermal comfort and indoor environment is quite apparent, thus showing a considerable potential for the CAM. The black CAM system, in particular, has potential to improve the thermal comfort indexes (PMV, PPD and t_{eq}) since it absorbs more heat from the room surfaces than does the polished CAM system. The results show that introducing a black CAM system in an office will not only give a higher comfort with improved PMV, PPD and t_{eq}, but may also allow the supply air temperature to be increased, which means that energy use for the central cooling system can be decreased. The CAM does not cause any uncomfortable draughts and, since it is a low-exergy system, it has a considerable potential for the future. However, there are still some parameters of the CAM that needs to be further investigated, such as the size and shape of the CAM for maximum effect in terms of improvement of the thermal comfort for persons working in the office. In addition, the temperature of the water inside the CAM, and thus its surface temperature, needs to be more thoroughly evaluated. We need to consider both the influence on the experienced microenvironment at the workstation, due to excessive draughts and radiation asymmetry, and also limitations on the temperature levels in order to avoid condensation on the surface of the CAM. The location and position of the CAM must also be tested in order to find the most favourable position. Other work includes that of controlling of the temperature and mass of the CAM system.

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