Controlled active mass for increased thermal comfort

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SUMMARY

The objective of this study was to evaluate the underlying physics and controlling parameters for designing a Controlled Active Mass (CAM) system. The purpose of such a system is to obtain a good thermal indoor climate and facilitate the use of energy sources with low environmental impact. The CAM system will be designed to cover the cooling demands for controlling the internal heat gains in a typical-sized office room for one person. The CAM unit will be constructed as a tank filled with water in which the level and temperature can be controlled depending on demand. Compared to other cooling systems such as passive cooling beams, the system should only be used when there is a cooling demand in the office. We also expect that the CAM system will be possible to achieve more energy savings and better indoor climate compared to other active mass systems.

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.

For many years, there has been an interest in using the heat capacity of different building materials to reduce temperature fluctuations and thus improve the indoor climate and reduce energy use. IEA Annex 37 [1] “Low-exergy Systems for Heating and Cooling of Buildings” has investigated increased use of low-temperature heating systems and high temperature cooling systems in what are known as low-exergy systems. Today, there are a number of different thermally active construction elements available. Examples include the “Thermodeck”, where ventilation air passes through holes in concrete slabs that act as heat stores [2], and embedded water pipes in a flat-slab floor that works as a heat accumulating mass [3]. Similarly, there are systems for cooling buildings where water pipes have been cast into the concrete building elements in floors, ceilings or walls [4, 5, 6, 7].

IEA Annex 44 [8] “Integrating Environmentally Responsive Elements in Buildings” is concerned with various building components known as Responsive Building Elements (RBE). RBE is defined as “a building construction element that assists to maintain 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”. It concentrates on five specific RBEs that seem to have the most promising potential for improvement and good take-up in the building sector: Advanced Integrated Façades, Thermal Mass, Earth Coupling, Dynamic Insulation Walls and Phase-

Change Materials. This report concentrates on thermal mass, and so does not discuss the other types further here.

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. When the thermal mass, such as roofs and external walls, is directly exposed to the ambient air, it is classified as external thermal mass. If it is exposed to the indoor air, it is referred to as internal mass. For good performance of passive systems, the mass should have a high heat capacity, such as that of a typical massive concrete structure, or with inner walls inside the building's thermal insulation. Compared to a building with a low thermal capacity, such a design can show an annual energy saving of about 5-10 %.

Active thermal systems, on the other hand, and 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 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. Temperature variations over the day can be used to supply heat to (for cooling the building), or abstract it from (for heating the building), the thermal mass. 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 was to evaluate the underlying physics and controlling parameters for designing a Controlled Active Mass (CAM) system. The purpose of such a system is to obtain a good thermal indoor climate and facilitate the use of energy sources with low environmental impact and low exergy value. This paper will describe the definition of a CAM system and some of the underlying theory of the design process.

THEORY

The energy storage capacity of the thermal mass will work together with other energy transfer processes in the office building. Heat is gained or lost in the office through heat conduction through the building envelope, thermal radiation through windows, ventilation through openings and infiltration/exfiltration through leakage. The following subsystems are included in the office; outdoor air, building envelope, furniture, the CAM system itself, ventilation air, room air, person, computer, lights and other equipment.

Thermal mass

The building envelope, furniture and equipment in the building all contribute to thermal mass. The energy that is supplied or stored in the thermal mass will be transferred to the room air and affect the thermal climate in the building. Depending on the shape, volume, location, thermal load etc., the thermal mass will affect the indoor air differently. There are three parameters that mainly govern energy transfer from the thermal mass to the indoor air: the convective heat transfer coefficient on the surface of the thermal mass, the thermal diffusivity within the thermal mass and the specific energy storage capacity of the thermal mass.

By expression the time scales for these parameters, we can quantify how the different parameters will influence the energy transfer from the thermal mass to the room air.

The building envelope is affected by the outdoor air and contributes to the thermal mass. Temperature variations in the outdoor air will penetrate the building envelope, to a depth and at a rate that depends on the physical properties of the wall. The penetrating depth δ, of the temperature variations with frequency omega into the building envelope, is described as:

$$\delta = \sqrt{\frac{2\kappa}{\varpi}} \; ;$$

where κ is the thermal diffusivity (thermal conductivity /(density*specific heat)) of the building envelope. The effective thermal mass is either equal to the thickness of the wall d or the penetration depth δ. If the penetration depth is less than the wall thickness, then the effective thermal thickness is equal to the penetration depth.

Furniture inside the building contributes to passive thermal storage. Furniture with volume $V_{Furniture}$ and surface area $A_{Furniture}$ can be lumped into a sphere with radius d as:

$$d = 3V_{Furniture} / A_{Furniture}$$

Time scale for thermal diffusion within the thermal mass:

$$\frac{d^2}{\kappa}$$

Here d is a characteristic length of the thermal mass and κ is the thermal diffusivity of the building envelope. This is the characteristic time scale for thermal diffusion to affect mass temperature.

Time scale for convective heat transfer at the surface of the thermal mass:

$$\frac{\rho \; C \; V_{Active}}{S_{Active} \; h}$$

Here ρ is the density and C is the specific heat capacity of the air surrounding the thermal mass, V_{Active} is the volume of the thermal mass, and where S_{Active} is the surface area of the thermal mass. The heat transfer coefficient h can be found from different empirical expressions, such as the type of convection (forced, mixed or natural) at the surface of the thermal mass, and whether the surface is horizontal or vertical [9, 10]. This is the time scale for convection to affect mass temperature.

In this study the thermal mass is an active system, in which the thermal storage mass and its temperature may be varied by changing the water in the CAM tank.

Time constant for charging

$$\tau = \frac{V_{Active}}{q_W}$$

Here V_{Active} is the volume of the thermal active mass and q_w is the volume flow rate of the water filling of the CAM. This is the time it takes to charge the tank with new fresh tap water.

Temperature variations

The temperature of the outdoor and indoor air will affect the heat transfer to the thermal mass and the temperature of the incoming ventilation air will also influence the system and the thermal comfort in the office.

The outdoor air temperature T_a is described by a mean temperature T_0 with amplitude of variation of outdoor temperature ΔT_a, and frequency ϖ [Hz].

$$T_a(t) = T_0 + \Delta T_a \cos(2\pi\varpi t)$$

The characteristic time scale for variation of the outdoor temperature is the *forcing time scale* $1/\varpi$.

There are different parameters and physical phenomena that affect the indoor air temperature in the office.

Time scale for ventilation

The building must be ventilated with fresh supply air to achieve a good indoor air quality. For a room with volume V and ventilation flow rate q, the time scale for the ventilation can be expressed by the nominal time constant for the ventilation:

$$\tau_n = \frac{V}{q}$$

The time it takes to replace the air within the room is at least twice the nominal time constant.

Time scale for mixing within the room

$$\frac{V^{1/3}}{U}$$

Where U is a characteristic velocity which can be set equal to the velocity that is not experienced as a draught, say 15 cm/s, and V is the ventilation flow rate.

Time scale for convection to affect interior temperature

$$\frac{\rho\ C\ V}{S\ \ h}$$

where S is the room surface and ρ, C and V are properties of the thermal mass in the office building envelop. This corresponds to the energy transfer between the exterior and the indoor air.

Ratio between scales

By using the above defined time scales, we can find relationships between them and also how the different energy transfer processes are affected by each other. We can, for example, quantify how changes in outdoor air will affect the thermal energy transfer of the thermal mass.

The ratio $\frac{\varpi\rho Cd}{h}$ of the time scale for convection at the surface to the forcing time scale indicates whether there is time for significant energy to be transferred to the thermal mass before the outdoor temperature changes appreciably.

The ratio $\frac{d^2\varpi}{\kappa}$ of the time scale for diffusion to the forcing time scale indicates whether there is time for temperature variations to penetrate the thermal mass before the outdoor temperature changes appreciably.

Evaluation of the occupants' thermal comfort situation

To ensure that the CAM system creates good thermal comfort in real conditions, it is essential to focus on the occupants in the system, using thermal comfort evaluation methods originating from people. 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 that are based on human reactions, and not just temperatures of surfaces and air.

It can be quite difficult to communicate the combined effects from different heat losses to and from individuals. It is therefore very useful to convert these values into something easier to understand, such as the PMV index [11, 12] for whole-body evaluation and the equivalent "experienced" temperature (t_{eq}) [13, 14]. 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.

DEFINITION AND PLANNED EVALUATION OF CAM

Here follows the definition and application of the Controlled Active Mass (CAM) system. The methods that will be used to evaluate the CAM system in an office room are presented together with the CAM variables that will be evaluated.

Definition of the CAM system

The purpose of the Controlled Active Mass system is to reduce the need for cooling in offices and at the same time to provide a good indoor climate. CAM 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 transfers cooling energy to the office area it can be seen as a passive system, since there is no media flowing in the system. On the other hand, when there is an increased need for cooling in the office, the water in the system can be replaced by new cold water to increase the cooling capacity. CAM thus becomes an active system that can be controlled depending on demand from the occupants of the building. The CAM system allows us to change both the mass and the temperature during the day. The thermal mass is changed by varying the level of filling.

The CAM system will contribute to a better thermal comfort in two ways: by reducing temperature fluctuations, due to an even distribution of cooling in the office, and also through permitting the cooling load 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 system but rather to meet the cooling need for internal heat loads such as computers, lighting, occupants etc.

The thermal mass will be constructed as a tank filled with water, the level of which can be varied depending on demand. The temperature of the water in the tank can also be controlled and varied by changing the water in the tank with new fresh tap water. The temperature of the water in the tank can thus 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 type of water source. The temperature of the incoming water to CAM must however be higher than the dewpoint of the office air in order to avoid condensation.

Application of CAM

During the evaluation the CAM system will be placed in a test room with dimensions 2.6*3.7*2.8 m (*W***L***H*), as shown in Figure 1 below. The test room corresponds to a typical-sized office room for one person. The room is well insulated, and is located inside a large test hall with a normal indoor climate, so that the climate inside the test room is not influenced by its surroundings. There are therefore no transmission losses through the test room envelope.

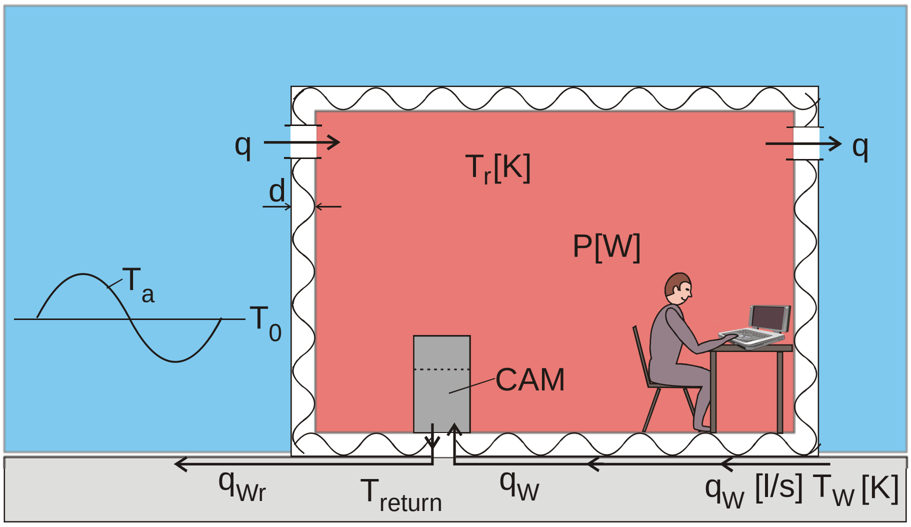

Figure 1. Test room for evaluation of CAM

In this study the CAM system will be designed to cover the cooling demands for controlling the internal heat gains from occupants, computers and lighting. For this specific case, this gives a total cooling requirement of 284 W in order to control the internal heat loads in the room. The occupant for the measurements will be simulated using a mannequin. The internal heat loads affecting the room during daytime in normal working hours, which means that cooling is needed only during these hours. The room is ventilated with a low-velocity inlet device located 2.4 m above the floor, with the exhaust opening located in the opposite wall.

Methods to be used for evaluation of CAM

Experiments and simulations will investigate how CAM will affect the thermal comfort in the room and energy-saving potential. Temperature and air velocity distributions in the office will be measured. Temperature measurements will be made using thermocouples and infrared thermograph. The velocity and turbulence levels in the room will be measured using sensors located around the mannequin and CAM. The air flows in the room will also be visualized using smoke. Measurements will also be used to determine boundary conditions that should be used as input for the simulations. The measured results will also be used for validation of the calculated values.

Simulations will be made to achieve a detailed description of the temperature and velocity distribution in the whole office room. Computational Fluid Dynamics (CFD) will be used for the numerical predictions. The same cases that have been evaluated will be simulated and a detailed comparison between the calculations and the measurements will be made. Some extra additional cases will be performed using CFD to evaluate the potential with CAM and its influence on the indoor climate.

CAM variables to be evaluated

How the CAM system influences the air movements in the office and thermal climate has to be examined. This will be made from various approaches, including the position of the CAM unit, its temperature, the amount of water in it, and when the water should be changed. When performing the CFD calculations the size, shape and the total cooling load will also be evaluated.

For the experimental evaluation, one geometrical configuration of CAM system will be examined, i.e. the volume, size and shape will be constant. In order to change the cooling capacity of CAM, both the temperature and the amount of water will be changed. Performance might also be affected by the position of the CAM unit, and so the experiments will also investigate the effect of different locations on the thermal climate in the office. It is important that the cooling need of the office should be fulfilled, but the unit should also improve occupants' thermal comfort.

DISCUSSION

CAM can be viewed as a cooling sink that should balance the thermal loads of occupants and equipment in the office. Compared to other cooling systems such as passive cooling beams, the system should be used only when there is a cooling demand. However, passive beams provide cooling all day, even though the demand may have decreased. Another advantage is that with CAM one can predict where the chilled air is released to the room and draught problems might be avoided. With beams, the airflow is more unstable and harder to predict, and draught problems might arise.

An evaluation of the CAM system is interesting, as we expect that it should be possible to achieve energy savings and better indoor climate than from other active mass systems. Compared with traditional active systems, such as systems with embedded pipes or ducts, the thermal mass is placed directly in the room, thus giving a more direct energy transfer. There is also no continuous drive energy requirement needed to transfer the energy into the building, since the cooling in the tank is exchanged only when there is a demand.

In real use of CAM systems the best solution must also take into account possible different prices for cooling and heat energy during the day or year. It is also important to know the working time schedule and the heat load from lighting, equipment, occupants etc.

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