Night-time ventilation cooling with latent heat storage

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ABSTRACT

Passive cooling of buildings is one of the energy-saving measures that can be employed in climates with predominantly sensible cooling loads. There are several passive cooling techniques that can be used in buildings; among them night-time ventilation. Night-time ventilation cooling utilizes diurnal swing of outdoor temperature and it has been used in many buildings. However, this passive cooling technique only works well when a building has a sufficient thermal mass. In case of heavy-weight building structures (brick, stone, concrete etc.) building structures themselves form a thermal storage mass. On the other hand, a purpose-provided thermal storage capacity may need to be added to light-weight building structures in order to make night-time ventilation cooling work effectively.

Phase change materials seem to be a very promising medium for thermal storage in many applications including passive cooling of buildings. The advantage of phase change materials (PCMs) in comparison with sensible heat storage materials is the ability of PCMs to store huge amount of heat in a narrow band of temperature around the melting point due to absorption and release of latent heat. A set of experiments both laboratory and full scale have been carried out in order to investigate the performance of latent heat storage in passive cooling of buildings.

KEYWORDS

Passive cooling, latent heat storage, phase change materials

INTRODUCTION

The shift from the heavy-weight to light-weight building structures, which occurs in many European countries, together with the improvement of thermal insulation properties of the building envelopes, brings about problems with thermal comfort of building occupants in summer. The growing use of air-conditioning in Europe and throughout the world increases amount of electricity consumed in operation of buildings. There are no doubts that air-conditioning is unavoidable in certain buildings. Nevertheless, many buildings can be cooled in a natural (passive) way at least during certain periods of the year. Passive cooling is generally not suitable in situations with high latent cooling loads. Dehumidifying is generally not a big issue in residential and office buildings in moderate climates, therefore, passive cooling could be employed there rather effectively (alternatively in combination with air-conditioning). There are several passive cooling techniques that can be used in buildings in moderate climates. Most of these techniques employ ventilation as a way of removing heat from a building e.g. Breesch et al. (2005), Eicker et al. (2006).

The passive cooling technique that makes use of diurnal swing of outdoor temperature is called night ventilation or night-time ventilation. The principal is that a building is ventilated with cool outdoor air at night and the thermal mass of a building is employed for cold storage (that leads to reduction of indoor temperature the following day). An extensive analysis of the potential of passive cooling by night ventilation in Europe can be found in Artmann et al. (2007).

Passive cooling by night-time ventilation is generally considered a suitable technique for the buildings with available thermal storage mass. In case of heavy-weight building structures (brick walls, concrete slab floors, etc.) building structures themselves can be used as thermal storage mass. Modern building structures generally provide rather small thermal mass and that thermal mass is very often not directly exposed to the ambient air (e.g. sound attenuated concrete slab floors, suspended ceiling covering concrete slabs, etc.). The popularity of light-weight building structures in the housing sectors (wood-frame structures in particular) is on the increase even in the countries where masonry has been a traditional type of building material. As a consequence, new ways of providing thermal storage capacity in light-eight buildings are being developed. The latent heat storage in phase change materials (PCMs) seems to be quite promising since it offers high thermal storage capacity in a small temperature interval. A review on thermal energy storage with phase change materials can be found in Sharma et al. (2009). Though latent heat storage can be employed in many passive cooling techniques only night-time ventilation will further be discussed in this paper.

HEAT TRANSFER CONSIDERATIONS

Thermal storage in night-time ventilation cooling usually operates in 24-hour cycles (heat load is charged into and discharged from the thermal mass within the 24-hour interval). In an ideal case of latent heat storage for passive cooling the total latent heat storage capacity should be equal to the daily sensible cooling load of the space. If we suppose that proper solar shading is used in a building to minimize cooling loads from solar radiation we can assume that the heat exchange between thermal mass and ambient environment is primarily due to convection. The heat flux at the surface of thermal mass can be expressed by equation

$$Q = A\,h\,(t_a - t_s) \qquad (1)$$

where Q [W] is the heat flux, A [m^2] is surface area, h [W/m^{2}K] is heat transfer coefficient, t_a [°C] is ambient air temperature and t_s [°C] is thermal mass surface temperature. The equation (1) can also be used for combined heat transfer by convection and radiation, when the heat transfer coefficient h is replaced by the combined heat transfer coefficient h_{comb}. The three main factors influencing the heat flux into and out of thermal mass are the heat exchange area, heat transfer coefficient and temperature difference.

If thermal storage is integrated with building strictures then the heat exchange area is usually the same as the surface area of the heat storage structures exposed to the ambient air. The problem is that surfaces of many building structures are not directly exposed to the surroundings due to noise attenuation, room furnishing, suspended ceilings, etc. It is desirable to have large surface area for thermal storage not only for the sake of convective heat transfer but also for its contribution to mean radiant temperature. A human body exchanges heat with the surroundings not only by convection by also by radiation, and mean radiant temperature is an important factor influencing thermal comfort.

As for the heat transfer coefficient, its value generally depends on air motion (air velocities) in a room. The air motion in buildings is usually a product of both natural and forced convection and it is very difficult to estimate the exact value of heat transfer coefficients at internal surfaces. The value of combined heat transfer coefficient in the range of $5\ W.m^{-2}.K^{-1} < h_{comb} < 10\ W.m^{-2}.K^{-1}$ can be expected in most situations. One of the advantages of latent heat storage over sensible heat storage is related to temperature difference between heat storage mass and the surroundings. If sensible heat storage is used then the surface temperature t_s rises with the amount of heat stored in the thermal mass. Latent heat storage, theoretically speaking, is an isothermal process. However, the assumption of constant temperature of phase change material during the phase change is not very correct as will be documented by results of experiments.

LABORATORY EXPERIMENTS

A set of laboratory experiments with latent heat storage has been performed in order to investigate the advantage latent heat storage in comparison with sensible heat storage (represented by water in the study). Aluminium containers filled with Rubitherm® SP 25 PCM blend were chosen for passive cooling experiments because the containers can easily be fixed to the internal surfaces of existing building structures. Another reason for choosing aluminum containers (marketed as CSM panels) was high thermal storage capacity per square meter of the surface area.

The melting temperature of the Rubitherm® SP 25 blend is 26°C, congealing temperature is 25°C and heat storage capacity in the temperature range 15/30°C is 180 kJ/kg. Since the dimensions of the panel are 453 mm x 303 mm x 10 mm and each CSM panel contains approximately 1 kg of Rubitherm® SP 25 blend the thermal storage capacity of the panels is around 1.3 MJ/m^2 in the temperature range 15/30°C when the panels are mounted side by side on the surface. Figure 1 shows the aluminium containers (panels) inside of an environmental chamber.

Figure 1: CSM panels in the environmental chamber

The results of one of the experiments can be seen in Figure 2. The air temperature in the chamber was increased to 29°C at the rate of 0.1 K per minute and afterwards it was maintained at 29°C for 10 hours. Then the air temperature in the chamber was decreased to 20°C (at the rate of 0.1 K per minute) and kept at that level for another 10 hours.

As can be seen, the temperature of water-filled container followed very quickly the air temperature in the chamber while it took almost 12 hours for the container filled with Rubitherm® SP 25 blend to reach temperature of 29°C.

The phase change is not distinctly visible in the melting period. There is a distinct change in the slope of the temperature curve at about 26°C (apparently caused by the phase change) but there is no temperature plateau so well known from the theory. The phase change is much better recognizable in the congealing period. A slight supercooling (subcooling) at the initialization of congealing can be seen in the chart but it is rather small. The air velocity inside the environmental chamber was monitored by a CTA probe. The average air velocity was 0.36 m.s^{-1}.

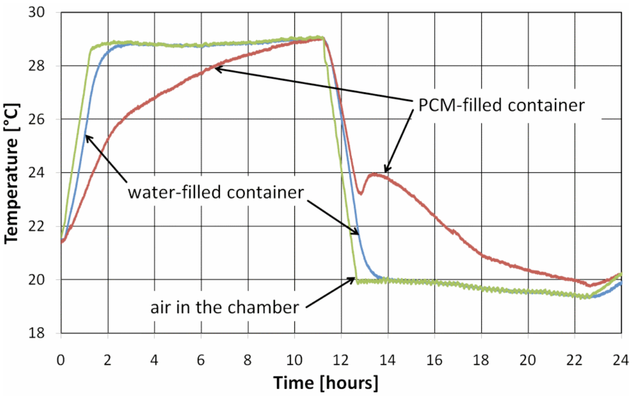

Figure 2: Panels in the environmental chamber

As can be seen in the photo in Figure 1, the panels were exposed to the air in the chamber on both sides. This is not the case when the panels are mounted on a wall or a ceiling. Therefore, thermal insulation was put on one side of the panels in order to investigate the performance of the panels when exposed to the ambient air only on one side. The thermal insulation consisted of 20 mm of polysterene. The result of this experiment can be seen in Figure 3. The air temperature in the chamber was 30°C during melting period and 19°C during congealing period. The increase and decrease of the air temperate in the chamber was at the rate of 0.1 K per minute. It took longer for the PCM to melt and solidify in this case.

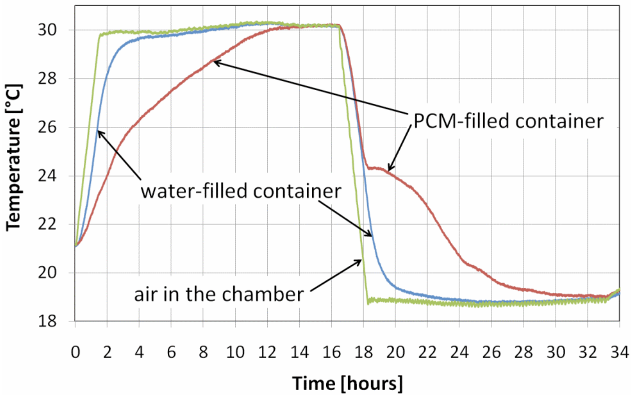

Figure 3: One-side insulated panels

FULL SCALE EXPERIMENTS

The full scale experiments with passive cooling have been performed in an experimental house. The experimental house is a two-story wood-frame house with the heated floor area of just over 100 m^2. The house is fitted with a demand controlled hybrid ventilation system that can operate in passive cooling mode. The floor plans of the house with indication of the main components of the hybrid ventilation system are in Figure 4.

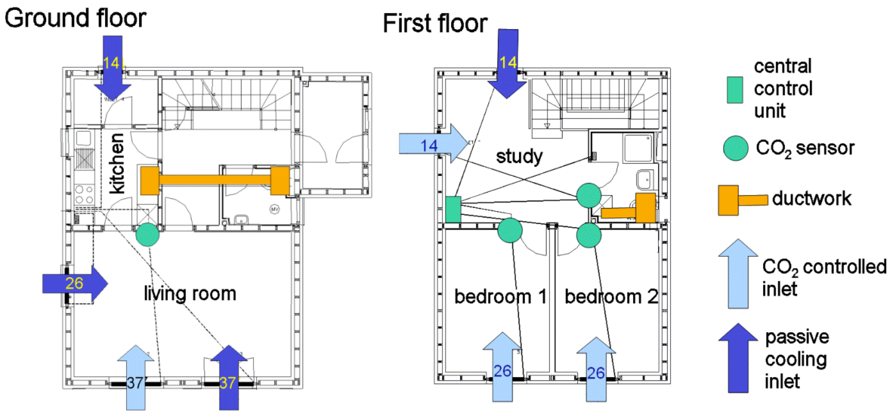

Figure 4: Floor plan of the experimental house

The PCM-filled panels were installed in Bedroom 2 in August 2008. Figure 5 shows the result of passive cooling experiment in Bedroom 2 in late August 2008. Unfortunately, outdoor temperature was relatively low in late summer 2008. It can be seen that the difference between the surface temperature of the PCM panels and ambient air temperature during night-time cooling was relatively low and did not exceed 2.5 K. The amount of heat discharged from 1 m^2 of PCM panels is about 57 kJ/hour when the temperature difference is $t_s - t_a = 2$ K and the heat transfer coefficient $h = 8$ W.m^{-2}.K^{-1}. It would take some 20 hours to discharge latent heat from thermal storage panels under such conditions.

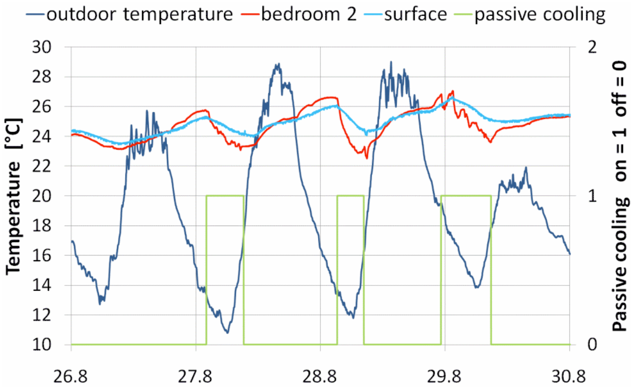

Figure 5: Passive cooling with latent heat storage

It would be really premature to draw conclusions about the performance of latent heat storage in night-time ventilation cooling based on this experiment. As can be seen in Figure 5, the indoor air temperature barely exceeded 26°C, which is the melting temperature of the PCM blend in the panels.

CONCLUSIONS

Night-time ventilation cooling is an energy-saving measure that can reduce energy consumption for air-conditioning of buildings. Thermal storage capacity of building structures plays a crucial role in night-time ventilation cooling. The phase change materials seem to be a good option for cold thermal storage in night-time ventilation cooling. Lab scale experiments performed with the PCM-filled panels confirmed better performance of latent heat storage for passive cooling in comparison to sensible heat storage represented by water-filled panels. Ability of phase change materials to absorb and discharge huge amount of heat in a rather narrow temperature band is a big advantage for passive cooling of buildings, where the thermal comfort requirements do not allow indoor temperature to change very much during the day. Thermal storage in phase change materials could effectively be used in air-conditioned building for reduction of peak cooling loads. Many air-conditioned buildings employ water/ice thermal storage systems to take advantage of cheaper off-peak electricity. Latent heat storage integrated with building structures could be employed in a similar manner in the buildings with multi-split air-conditioning systems, variable refrigerant volume (VRV) systems and other air-conditioning systems that do not use chilled water.

NOMENCLATURE

A	surface area, m^2
Q	heat flux, W
h	heat transfer coefficient, W/m^2K
t	temperature
Subscripts	
s	surface
a	ambient

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