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DEVELOPMENT OF PHASE CHANGE WALL-LININGS TO ENHANCE THERMAL STORAGE OF BUILDINGS

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Summary

Research collaboration between University of Brighton and OMNOVA Wallcovering (UK) Ltd has successfully developed a thermal interactive wall-lining utilising sensible and latent heat storage through the inclusion of phase change materials. The current use of lightweight construction can result in large temperature swings and overheating in the summer. The PCM wall-lining functions to reduce overheating in buildings by storing the excess heat principally in the form of latent heat. By minimising overheating the PCM wall-lining can reduce and, in some climates, eliminate the need for air-conditioning. A direct result of the reduced overheating is the improved thermal comfort for the occupants.

A test laboratory has been set up at the University of Brighton, comprised of two thermally matched chambers, to evaluate the performance of the PCM wall-lining in a controlled environment. This paper describes the results of the experimental work which demonstrates the reduction of peak temperatures and improvement in thermal comfort. Factors affecting PCM wall-lining performance and future work to optimise the test facilities to enable greater analysis of the PCM wall-lining are also discussed.

1. Introduction

Global temperatures have increased by around 0.6°C over the last 100 years and there is continually new evidence showing most of the global warming that has occurred over the last 50 years is a direct result of human activities. The Intergovernmental Panel on Climate Change (IPCC) has predicted that during the 21st Century global temperatures will increase by between 1.4°C and 5.8°C, and that sea levels will rise by between 0.09 and 0.88 metres. This is an unprecedented rate of global warming, which is largely caused by the increased amount of man-made greenhouse gas emitted into the atmosphere (UNFCC 2004).

Buildings are responsible for over 40% of Europe's total energy consumption and consequently produce a huge amount of carbon dioxide (CO_2) emissions. In the UK almost half of all CO_2 emissions are from buildings, the largest proportion is a result of space heating (CIBSE 2004). The continuing trend of lightweight construction has not only reduced the thermal capacity for the storage of beneficial solar gain in winter, but also increases the occurrence of temperature swing and overheating in the summer. Innovative design and materials need to be developed that can work in conjunction with existing technologies to reduce the amount of overheating in summer by improving the thermal capacity of lightweight buildings. Appropriate use of energy saving design such as the PCM wall-lining being developed in the current research can reduce the need for energy intensive cooling systems, which has grown by 10% from 2000 to 2004 (BSRIA 2002). The application of PCM wall-lining can have significant impact to reduce global energy consumption, a preliminary analysis of the quantity of wall-lining products installed in new and refurbished buildings globally suggests there is the potential for installing up to 440 million square metres of PCM wall-lining in domestic and non-domestic buildings (Dyball 2004).

The aim of this research is to determine if PCM wall-linings can improve thermal comfort through the reduction of peak internal temperatures. The research has reviewed the use of thermal energy storage technologies for use in buildings and identified the environmental benefits of PCM wall-linings. This paper reports on the experimental setup, monitoring procedure and the preliminary results of the experimental investigations to determine the temperature reductions achievable by the prototype PCM wall-lining. The limitation and inference of the results to the future development are also summarised.

2. Development of Phase Change Wall-linings

Research collaboration between University of Brighton and OMNOVA Wallcovering (UK) Ltd has resulted in a project to develop a thermal interactive wall-lining, utilising OMNOVA's manufacturing technology, that can improve the thermal storage capacity of buildings, reduce overheating and reduce the demand for conventional cooling systems. This has been realised by including phase change materials in wall-linings.

2.1 Phase Change Technology

Phase Change Materials (PCMs) are materials that not only absorb sensible heat as the temperature increases but also absorb latent heat when melting and release the stored heat when freezing, both at an almost constant temperature. PCMs have a high latent heat storage capacity, high energy densities and are relatively low in cost. PCMs can be used in buildings to significantly improve the thermal mass as they have a much greater ability to store heat than conventional building materials such as concrete. Concrete has a sensible heat storage capacity of 1.0 kJ/kgK, whereas an inorganic phase change material such as calcium chloride hexahydrate can store up to 193 kJ/kg during phase transition. PCMs are able to reduce peak temperatures in buildings by absorbing excess heat during the day and releasing the heat at night when it is cooler. The storage and release of excess heat results in a narrower temperature band over a diurnal period therefore improves thermal comfort for the occupants.

A significant development in phase change technology is the ability to microencapsulate PCMs. Microencapsulation is the packaging of micron-sized materials (both liquids and solids) in the form of capsules, ranging from less than 1μm to more than 300μm. Microencapsulated PCMs can be used to introduce high thermal storage capacity into conventional building materials. Examples of research developments using microencapsulated PCMs include gypsum plaster (Schossig et al. 2004), concrete (Cabeza et al. 2004), and wallboard (Hummel 2004; Khudhair et al. 2003).

An advantage of using a PCM wall-lining instead of the other developing products is its direct exposure to heat exchange within the room. Most PCM materials are located deep within the construction of a wall or ceiling and would have less effective heat transfer.

2.2 PCM Wall-linings

OMNOVA Wallcovering (UK) Ltd has undertaken laboratory experiments to develop a vinyl formulation that included microencapsulated organic PCMs in the wall-lining. Vinyl formulations are developed using the plastisol route, a suspension of finely divided polymer held within a plasticiser and modified using stabilisers, pigments and rheology control agents. The plastisol formulation is coated out and passed through a high temperature oven for a few minutes where the heated plasticiser penetrates the polymer and the plasticised polymers coalesce to produce a homogeneous wall-lining. A successful formulation was developed and a prototype PCM wall-lining was manufactured using the knife-over-roll coating technique. A 6mm PCM wall-lining was produced containing 20% microencapsulated organic PCM.

2.3 Preliminary Investigation

A theoretical analysis was conducted to determine the quantity of PCM that would be required in a standard office to prevent it from overheating. Dynamic thermal simulations were conducted of an intermediate floor in an office building that had north, east, south and west facing orientations. The maximum amount of PCM required in each office to absorb all of the excess heat in the day and be able to release the stored heat during the night in the UK was determined. The maximum amount of inorganic PCM with a latent heat storage capacity of 180 kJ/kg required in an office was 0.93 kg/m^2 and the maximum amount of organic PCM (150 kJ/kg) required was 1.12 kg/m^2 (Ip et al. 2003). The prototype PCM wall-lining developed contains 1.5 kg/m^2 microencapsulated organic PCM which indicates the PCM wall-lining would be able to reduce overheating in a standard office.

Detailed thermal analysis of the PCM wall-lining prototype was performed to determine its latent heat storage capacity and the melting point. A common method used to analyse the properties of PCMs is Differential Scanning Calorimetry (DSC). DSC measures the temperatures and heat flows associated with phase transitions in materials as a function of time and temperature in a controlled atmosphere. A DSC analysis of the microencapsulated PCM and an analysis of the PCM wall-lining were carried out. Theoretically the PCM wall-lining should have the same melting point as the microencapsulated PCM if it was undamaged during the manufacturing process. As the PCM wall-lining contains 20% PCM then the latent heat storage capacity of the PCM wall-lining should be around a fifth of the microencapsulated PCM result. The results of the DSC analysis during the heating and cooling cycles are shown in Figures 1 and 2 respectively.

The phase change temperature of the microencapsulated PCM and the PCM wall-lining is 25°C. This is the onset point of the melting transition that is displayed in Figure 1. The larger peak illustrates the quantity of latent heat absorbed during the phase change of the microencapsulated PCM and when integrated with respect to time gives the latent heat capacity of 95 J/g. The PCM wall-lining peak, the smaller peak, also has a melt point of 25°C and the latent heat capacity is 16 J/g. The same results were obtained for the thermal properties during the cooling cycle, Figure 2. The DSC results have demonstrated that a PCM wall-lining does change phase at the phase change temperature and is able to absorb and release latent heat under controlled conditions.

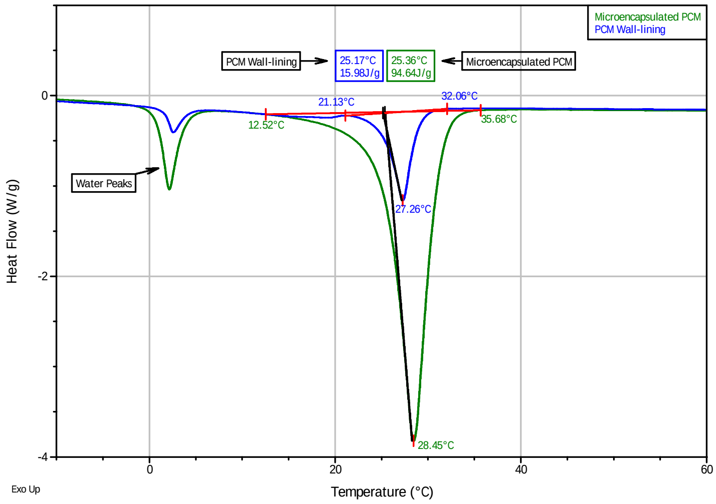

Figure 1 Thermal properties of PCM and PCM wall-lining during heating cycle

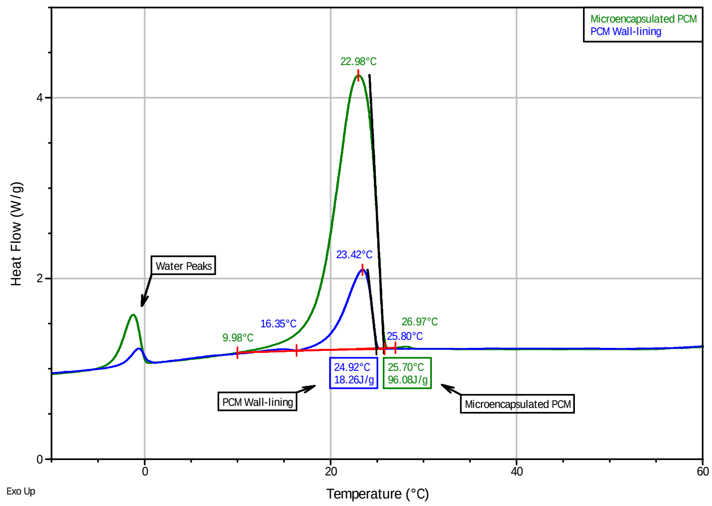

Figure 2 DSC cooling curve of PCM and PCM wall-lining

3. Experimental Investigation

The experimental investigation aims to determine the ability of the PCM wall-lining to reduce internal temperatures of a room to improve thermal comfort. To do this two identical chambers were constructed; the first chamber is fitted with PCM wall-lining while the second chamber is used as a reference chamber for comparison. The chambers were heated and measured using different amounts of heat input and air flow conditions.

3.1 Test Chambers

Two highly insulated, identical chambers, 2.4m^3, were constructed within a laboratory at the University of Brighton. The chambers were fitted with a total of 18 surface temperature sensors, 6 air temperature probes and 2 room temperature sensors, as illustrated in Figure 3. The room radiant temperature, as part of the indication of thermal comfort, is measured using a 36mm black globe thermometer (Humphreys 1978).

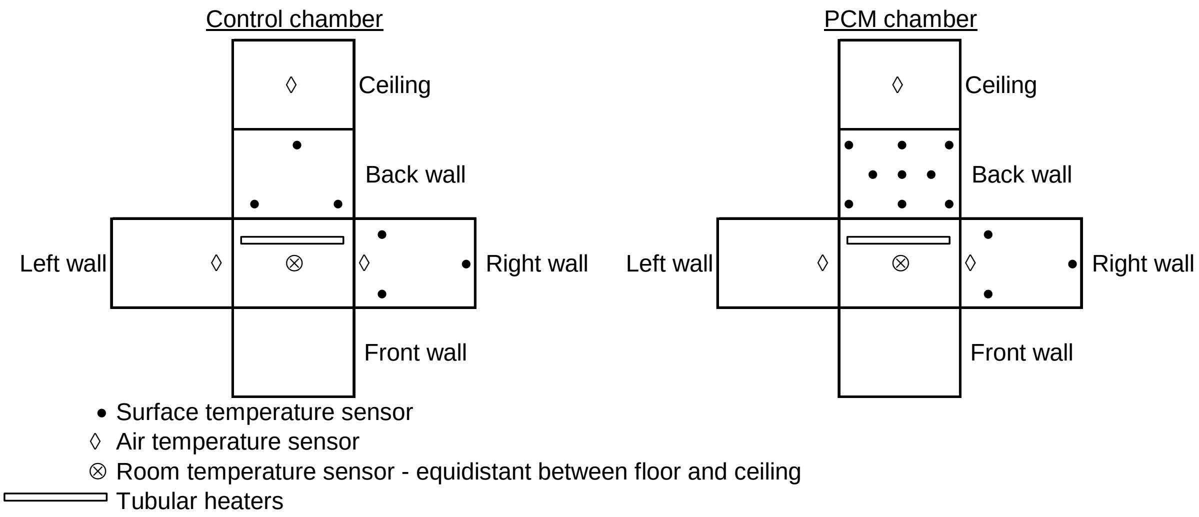

Figure 3 Layout of temperature sensors in test chambers

The heaters used to supply heat to the test chambers were connected to power meters to ensure the heat input to each chamber was identical. All the monitoring devices were wired to an Agilent Benchlink data logger and the data were recorded at timed intervals.

The PCM wall-lining was fitted to the walls of the first chamber, as shown in Figure 4, providing a latent heat storage capacity of 1663 kJ. No materials were fitted to the walls in the Control chamber, so latent heat was only available in the PCM chamber.

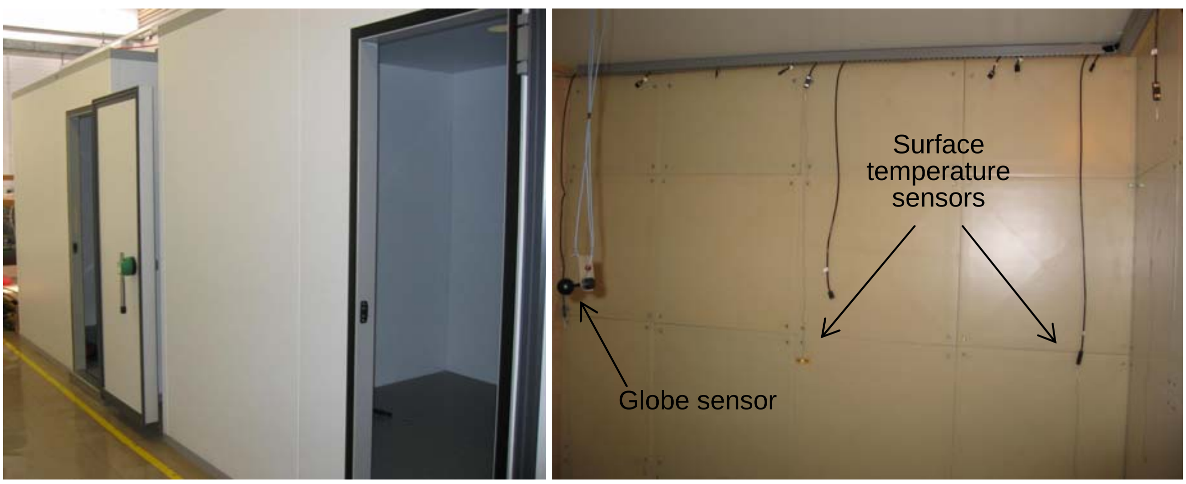

Figure 4 Test chambers (left) and fitted PCM wall-lining with temperature monitoring sensors (right)

3.2 Experimental Procedure

A range of experiments were conducted in the test chambers using different amounts of internal heat inputs and air supply rates. The results reported focus on two experiments, one with ventilation and one without, to quantify the temperature reduction that can be achieved using the PCM wall-lining under two test conditions. The test chambers were heated using a 360W heat source in each chamber and programmed to operate from 14:00 to 22:00 hours. The temperature data were recorded every 5 minutes for at least one heating and cooling cycle.

3.3 Results and Discussion

The room temperature results after heating the test chambers for 8 hours and allowing to cool without refrigeration are shown in Figures 5 and 6. Figure 5 shows the room temperature results when using no ventilation and Figure 6 shows the results using constant ventilation.

The different slopes of the two curves in Figures 5 and 6 shows the different rates of temperature changes of each chamber when both are subjected to the same amount of heat input. In both experiments, without and with ventilation, the PCM chamber heats up at a slower rate than the Control chamber and the final temperature achieved is lower in the PCM chamber.

3.3.1 Without mechanical ventilation

Figure 5 shows that after heating the test chambers for 8 hours the PCM wall-lining kept the room temperature of the PCM chamber almost 4°C cooler than the Control chamber. This is due to the PCM wall-lining absorbing the heat and storing it in the PCMs. At the beginning of the heating cycle the graphs (section a-b) show the rooms began to heat at the same rate until 21°C was reached. This is due to the rapid sensible heating of the air in both chambers. After 21°C the heating rates of each chamber changed as a result of the different heat transfer processes. The temperature rise in the PCM chamber was clearly slower than in the Control chamber.

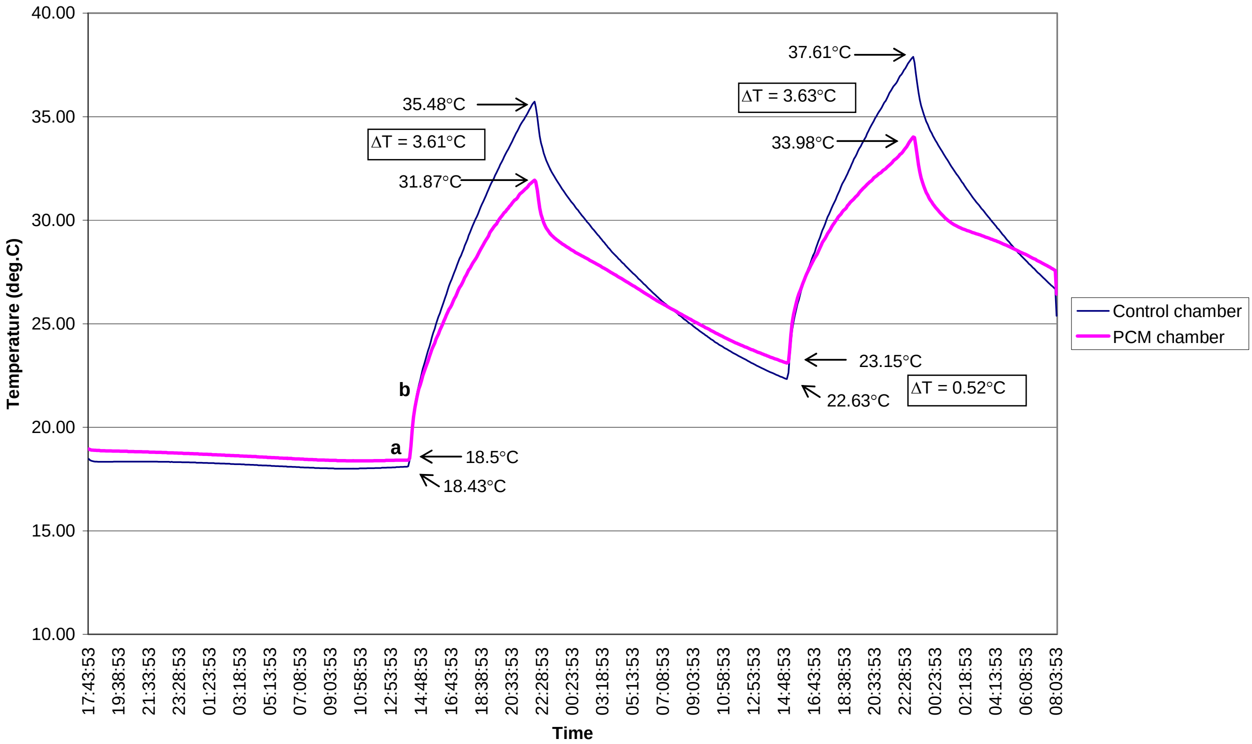

Figure 5 Room temperature results of testing PCM wall-lining with 8 hour heating cycles and no air flow

When the heaters were switched off in both chambers at 22:00 the chambers began to cool naturally. The initial sharp temperature drop of the cooling curve in Figure 5 is due to the rapid cooling of the air in the chambers. The room temperature in the Control chamber drops by 1.75°C whereas the PCM chamber only has a temperature reduction of 1.58°C during the 30 minutes after the heaters were switched off. The subsequent change in the curves is related to the thermal capacity of the materials in the chambers. The PCM wall-lining cools at a significantly slower rate, due to the release of latent heat from the PCMs. As the chambers were not ventilated the internal temperature in both chambers remained high during the cooling cycle.

After 9 hours and 50 minutes both chambers reached 25.65°C, illustrated in Figure 5 where the curves cross. Although the chambers have reached the same temperature the PCM Room only reduced 6.22°C whereas the Control Room cooled by 9.83°C, a much larger temperature range.

At the end of the cooling period there was a 0.5°C difference in room temperatures between the two chambers; such difference will increase if the cooling cycle continues. It can be estimated from the graph that it would take an additional 3 hours for the PCM Room to cool to the same temperature of the Control Room at 14:00.

3.3.2 With mechanical ventilation

The room temperature results of the test chambers when ventilation was used, in Figure 6, show that a smaller temperature reduction is achieved in the PCM chamber than when no ventilation was used, Figure 5. As a result of using ventilation in the chambers the room temperatures do not rise as quickly or as high as the experiment with no air flow.

Section a-b in Figure 6 demonstrates the initial heating of the air in each chamber from the start at 19.9°C to 21°C. There is a deviation in the heating rate due to the thermal capacity of materials in the chambers. The use of mechanical ventilation resulted in lower room air temperatures than the previous experiment and consequently a much lower surface temperature on the PCM wall-lining. The difference in surface temperatures of the PCM wall-lining and the plain wall in the Control chamber is only 0.89°C, whereas the surface temperature difference of the experiment without ventilation is 4.5°C. As the heat transfer is related to the air mass flow rate, surface heat transfer coefficient and the temperature difference, the results indicated that an optimum balance of ventilation and room temperature is necessary to achieve best heat transfer performance in a real building room.

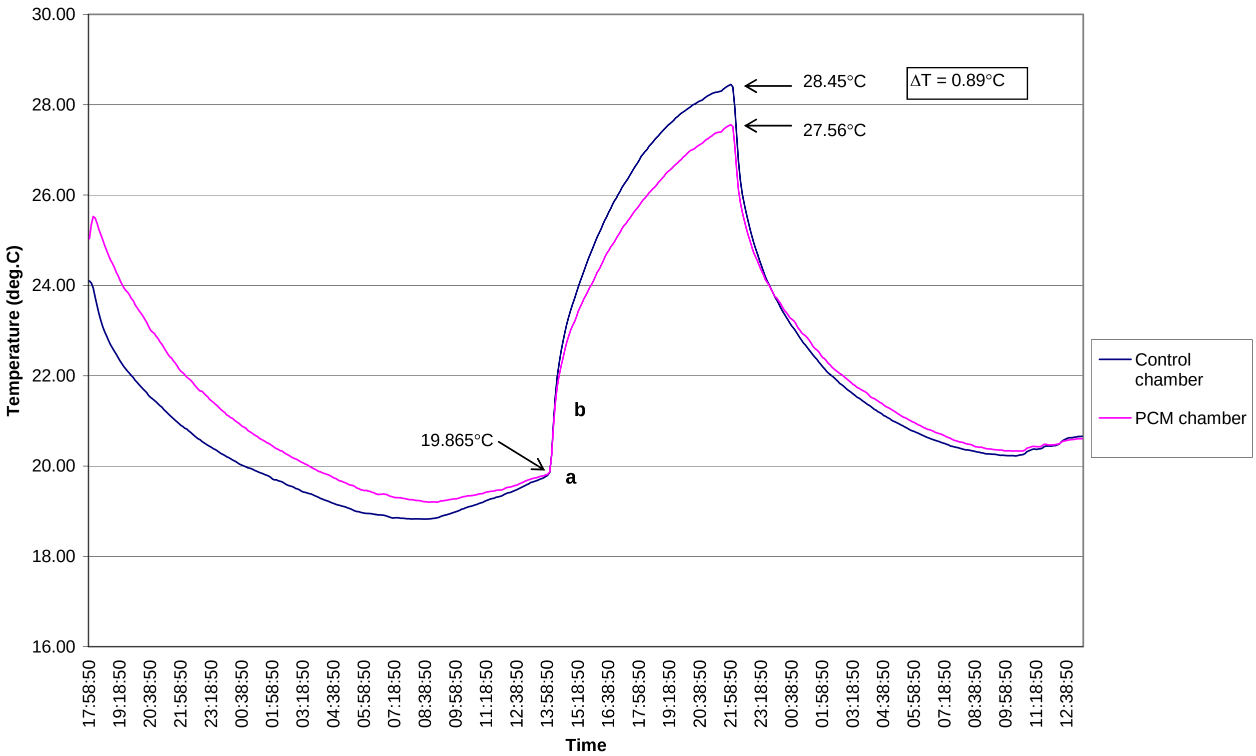

Figure 6 Room temperature results of ventilated test chambers after 8 hours heating

Figure 6 shows after the heating in both chambers is turned off at 22:00 the temperatures in both chambers immediately begin to reduce. The slope of the cooling curve is steeper than in Figure 5 demonstrating the effective removal of heat from the chambers when mechanical ventilation is used. During cooling it took only 1 hour and 50 minutes for the two chambers to reach the same temperature of 23.75°C, although the Control Room had a larger temperature range to reduce.

The experiments described have shown that a PCM wall-lining can successfully reduce the temperature of a room and improve the thermal comfort conditions. The results showed that the non-ventilated chamber with PCM wall-lining is more effective in minimising the temperature swing. It may be necessary to have a variable flow ventilation system to improve the PCM wall-lining's performance such as a low ventilation rate during the heating period to enable the heat to transfer into the PCM wall-lining and a high ventilation rate to discharge the PCM wall-lining during the cooling cycle.

3.3.3 Limitations

The experimental investigations are limited in the ability to simulate conditions consistent with real office environments. Whilst every effort is made to subject the PCM wall-lining to realistic temperature and ventilation conditions it is not possible to simulate a real in-use room environment.

The temperature of the PCM wall-lining may not be the accurate phase change temperature to keep a room 'comfortable'. The results of the experimental investigation showed the room temperature of the test chambers became much higher than would be comfortable for an occupant, even when the PCM wall-lining successfully reduced the peak temperature. A microencapsulated PCM with a lower melting point may be required to maintain lower room temperatures or a blend of PCMs with different phase transition points.

4. Conclusions

The experimental investigation has shown that the PCM wall-lining prototype can reduce the internal temperatures of the test chamber. The PCM wall-lining also delays the time taken to reach the extreme temperatures, which results in a narrower temperature band for the room throughout a 24 hour period. A reduction in peak temperature fluctuations by the PCM wall-lining could improve the thermal comfort environment for the occupants.

The difference in the PCM wall-lining's performance dependent on air flow and air temperature across the surfaces demonstrates that further work needs to be done to understand how optimal heat transfer into the PCM wall-lining can be achieved.

The successful development of PCM wall-linings will play a significant role in tackling the growing problem of overheating in buildings due to global warming, leading to a global reduction of energy consumption and demand for air-conditioning.

5. Future Work

Further work needs to be done to quantify the variables that affect the thermal performance of the PCM wall-lining. An air-conditioning system is currently being installed in the test chambers so air temperatures and air flows can be controlled more accurately than currently available. This will enable the heat transfer rates into and out of the PCM wall-lining to be determined and how they are affected by temperature and the air exchange rate.

The temperature monitoring of the chambers needs to be more sophisticated. The next phase of experiments will have surface temperature sensors located at every layer of the wall so the heat transfer rate and amount of heat stored in the PCM wall-lining during experiments can be quantified. These results will be used in finite element analysis along with air flows and conductivity of PCM wall-lining to determine the optimum thickness of the PCM wall-lining to operate at maximum efficiency.

The results from experiments in the upgraded test chambers will be used to validate the developing thermal simulation models in TRNSYS, a building simulation program. This program will help to identify if the phase change temperature of the PCM wall-lining is correct, to be able to absorb the necessary heat from an office in different buildings, and to evaluate the dynamic thermal performance of PCM wall-lining under different climatic and operating conditions.

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