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Dynamic Thermal Behavior of Two Newly Developed PCM Cooling Ceiling Prototypes

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Abstract

In this work, two prototypes of PCM cooling ceilings were investigated regarding their dynamic thermal behavior. Both prototypes address the improvement of thermal contact between PCM, cooling fluid and the ceiling surface, but each with other priorities. The main difference between the two PCM cooling ceilings is the positioning of the PCM layer. In one cooling ceiling construction, macroencapsulated PCM is put on top of the water pipes of a conventional cooling ceiling panel. In the second ceiling construction the PCM containers are between the ceiling panel and the water pipes which are directly connected to the backside of the PCM containers. To characterize the thermal performance of both prototypes, temperatures and heat flows for the three occurring operation modes 'passive cooling', 'active cooling/regeneration' and 'active heating' were recorded. The measurements were performed using a novel measurement setup that enables dynamic thermal measurements on single building elements like wall elements or cooling ceiling panels. The results reveal the advantages and disadvantages of both ceiling constructions, one being a good compromise between passive and active operation modes, and the other emphasizing the passive cooling mode by reducing the thermal resistance between ceiling surface and PCM. Meanwhile, both ceiling types are integrated in the recently constructed Energy Efficiency Center and undergo a long term monitoring.

Keywords: phase change material (PCM), cooling ceiling, passive cooling, latent heat storage

1. Introduction

The conceivable shortage of fossil energy sources and the impact of the increasing CO_2 concentration in the atmosphere on the global climate led to increasing research effort in the field of renewable energy sources and energy efficiency in the last two decades. Especially in the building sector, as one of the main energy consumers, the application of technologies and materials that increase energy efficiency has a great potential for energy savings and is therefore of outstanding importance. A promising material class which got into focus of international research is Phase Change Materials (PCM). PCM can store and release a large amount of heat with very little change in temperature during a phase change between solid and liquid state and hence cater for a temperature stabilization effect. This property makes PCM suitable for building applications because a constant indoor temperature in the comfort range is preferable. There are several options to apply PCM materials into a building. In general, PCM can be applied in a central application (e.g. central heat or cold storage) as well as in a decentral application (e.g. implementation into the rooms). For the decentral approach a distinction can be made between passive and active systems. For room integrated PCM acting passively it is preferable to place the PCM at the inner surfaces for optimal thermal connection to the room air. The thermal connection determines the passive cooling or heating power and assures that the high heat capacity of the PCM is available. The needed heat fluxes have to be realized mainly by free convection which is the limiting factor for the passive systems. A common realization of passive PCM systems is the implementation of PCM wallboards. PCM wallboards can reduce the interior wall surface temperatures during the heat absorbing process, whereas during the heat releasing process the surface temperatures are higher than of an ordinary wall (Liu and Awbi, 2008). Liu and Awbi (2008) observed an enhancement of the heat flux density into the PCM wall compared to an ordinary wall of more than 100% during the melting

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process in their experiments in an environmental chamber. However, a passive regeneration of the PCM in the wallboards can be problematic, especially if no natural ventilation can be used.

In contrast to the passive systems, active systems involve the possibility of moving a heat transfer fluid (e.g. air or water) actively to enhance the heat transfer into or out of the PCM and to support the overall system performance. The PCM is then used to shift the cooling demand from daytime to nighttime when cold can be produced more efficiently or can even be obtained from regenerative source.

Active systems can complement the passive cooling effect of the PCM with active cooling and/or can assure PCM regeneration. Hence, active systems can overcome the drawbacks of passive PCM systems but, on the other hand, need a certain amount of electrical energy. To develop active PCM systems which still feature the advantages of passive PCM systems like energy efficient passive cooling or time shifting peak loads and additionally avoid system failures due to overheating because of the limitation of the passive cooling power, an accurate system design is necessary. Activated systems with PCM are highly focused in research. One promising approach for an active PCM system is the integration of PCM into the ceiling structure or cooling ceilings. This enables passive cooling or heating by stabilizing the surface temperature of the ceiling in the PCM’s melting range and at the same time ensures a stable system performance by switching into active mode if needed. Pomianowski et al. (2012) for example, investigated the heat storage and cooling capacity of a thermally activated concrete ceiling with PCM. In their work, they added a layer of PCM concrete (with a PCM weight fraction of 1%-6%) to the lower surface of the ceiling and did numerical and experimental investigations. They found out that their theoretical assumptions of the thermal properties of the PCM concrete overestimate the performance of this material. The authors also state that the PCM layer can lead to a decrease of the active cooling capacity of a thermally activated concrete ceiling. Koschenz and Lehmann (2004) developed a thermally activated ceiling panel with PCM. As PCM microencapsulated paraffin with a melting range of about 20°C to 24°C was used. It was bedded with a weight fraction of about 25% into gypsum which was then poured into a stable metal structure holding a capillary water tube system for active regeneration. In their experimental work, the authors found out that the melting range fits very well for passive cooling assuming a cooling load of 40 W/m². As a drawback it is mentioned, that the high fire load of the paraffin may be a problem for a broad system’s applicability.

The functionality of PCM in a building application is strongly dependent on the PCMs thermal properties, on the thermal boundary conditions the PCM is exposed to, as well as on the interaction with the influencing systems (e.g. cooling ceiling, cold source). Hence, it is important to perform test measurements of the PCM system under realistic boundary conditions. Taking possible subcooling effects of the PCM into account as well as the fact that the PCM is cycled in his melting range most of the time, the importance of such measurements before system implementation is getting clear. As measurements in test rooms are time consuming and expensive, especially during the product optimization phase, a small test chamber which can hold a single cooling ceiling panel was constructed. With this measurement setup two different PCM cooling ceiling prototypes were investigated. The two prototypes use PCM on a salthydrate basis to overcome the problems of a high fire load indicated in Koschenz and Lehmann (2004). The PCM was encapsulated into metal containers which allow a high heat transfer and a high PCM fraction thus enabling cooling ceiling structures that are low-weight compared to systems with microencapsulated PCM fractions of 30% or lower. The thermal characterization of both cooling ceiling types described in this paper was used for further optimizations of the ceiling construction before both ceiling types were implemented into the new R&D building of the ZAE Bayern, the Energy-Efficiency-Center (EEC, 2014), in June 2013.

2. Materials and Method

2.1. Measurement Setup

For the evaluation of the dynamic thermal behavior of the two PCM cooling ceiling prototypes a novel measurement setup was constructed. It is realized as a highly thermal insulated box which is situated in a temperature controlled surrounding. The setup is shown in figure 1. The idea of the setup is to simulate the conditions in a real test room in much smaller dimensions and well known and controllable boundary conditions. The most important feature is the realization of the heat transfer between room air and sample through an adjustable, well known thermal resistance instead of having an air layer with free convection and the corresponding uncertainties. The possibility to adjust the thermal resistance enables also to simulate different sample mounting situations, e.g. vertical and horizontal mounting, just by changing the thermal resistance. In general, not only cooling ceilings but also PCM building materials and components like plasterboards with PCM can be tested with this setup. Additionally, the small test chamber offers the advantage of easy sample mounting compared to real test rooms.

The outer envelope of the chamber is made of XPS foam (extruded polystyrene) with a thermal conductivity of $\lambda = 0.036$ W/(mK) and has a thickness of 0.10 m. For sample mounting the lid of the chamber can be removed. The inner horizontal dimensions of the chamber are (0.625 x 0.625) m².

The measurement setup can be subdivided into 6 layers shown in figure 1. The layers can hold the sample or measurement equipment or a thermal resistance and are interchangeable. The setup is hence customizable and can be adapted to the requirements.

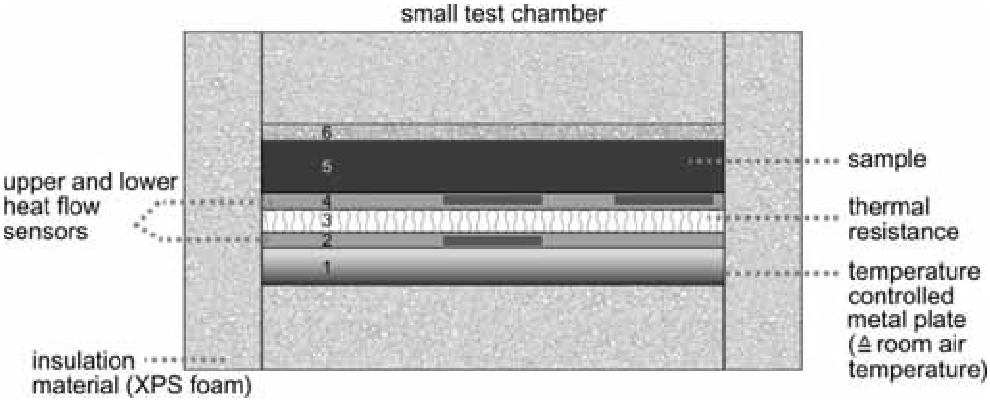

Fig. 1: Scheme of the experimental setup. The chamber is subdivided into 6 layers (number 1-6). For this work, the chamber holds a temperature controlled metal plate (1) representing room air temperature, a specific thermal resistance (3), several layers with heat flow embedded heat flow sensors (2 & 4), and the test sample (5).

For the cooling ceiling measurements the setup was as follows:

The interior of the chamber holds a temperature controlled metal plate in position 1 which is connected to an external thermostat. The metal plate is used to establish a fictive room air temperature which can be adjusted by the thermostat.

In layer 2 a heat flow sensor (HFS) is embedded in the center of a plastic template of the same thickness and thermal conductivity, which is important to prevent lateral heat flows. Hence, a one dimensional heat flux in vertical direction through the layer can be assumed during the measurement.

A thermal resistance was placed at position 3. The thermal resistance realizes a certain heat transfer coefficient h between “room air” and the sample. By changing the thermal resistance, it is possible to simulate the conditions in a real test room for different systems, for example for wallboards with $h \approx 7$ - 8 W/(m²K) or ceilings in cooling or heating mode with $h \approx 10$ - 11 W/(m²K) or $h \approx 7$ - 8 W/(m²K), respectively. In this work, the material used as thermal resistance is cellular rubber with a thickness of 8 mm with the aim to establish a heat transfer coefficient h of 10 W/(m²K).

On top of the thermal resistance again a plastic template holding two HFS was placed at layer 4. One HFS is situated in the center; the second is located in a corner of the layer. By implementing the additional sensor in the corner it is possible to check if the assumption of a one dimensional vertical heat flow through the whole horizontal plane is reliable or if unwanted differences occur. Possible reasons for heat flow differences can be different contact resistances and small air gaps between the layers, or inhomogeneities of the materials used, or the sample itself.

At position 5 the sample is placed. The cooling ceiling panels examined in this work are connected to a second thermostat. Thus, not only the passive cooling mode but also the case of active cooling and heating can be measured.

Layer 6 was left empty in this work. An option is to place a template with further HFS onto the top of the sample to measure heat gain/loss at the sample’s backside. This is especially important if the measurement setup is used for calorimetric measurements.

Between each layer temperature sensors can be placed.

2.2. Cooling Ceiling Prototypes

In this work, two newly developed PCM cooling ceilings were examined with the measurement setup described above. Both cooling ceilings were prototypes which were developed during the project DEENIF (EEC, 2014) by Lindner Group KG in cooperation with the ZAE Bayern. Both systems had to be characterized before being implemented into the offices of the new R&D building of the ZAE Bayern in Würzburg, the Energy Efficiency Center. The development addressed the improvement of the thermal contact between the cooling ceiling surface and the PCM as well as between the water pipes and the PCM. These improvements should increase the energy efficiency of the systems by increasing the passive cooling power of the PCM as well as decreasing the time span needed for active PCM regeneration. Both prototypes differ from the placement of the PCM layer and hence set different priorities concerning the passive cooling mode, the regeneration of the PCM and the active controllability.

Figure 2 shows a scheme and a photo of the two cooling ceiling prototypes. In ceiling type I the PCM is situated on top of the water pipes and is contacted by a layer of pressed graphite. The graphite layer improves the thermal contact between the water pipes and the PCM as well as between the PCM and the ceiling surface which is important for passive cooling situations. As the water pipes are situated beneath the PCM, ceiling type I should provide a good active controllability, which can be beneficial if the cooling demand exceeds the passive cooling capacity of the PCM. In ceiling type II the PCM is directly attached to the cooling ceiling panel and the water pipes are fixed to the top of the PCM. This construction addresses the optimization of the passive cooling and the PCM regeneration but at the expense of the active controllability. Whereas ceiling type I falls short in terms of PCM regeneration as the room is cooled simultaneously, ceiling type II will show slower response to active room cooling as the PCM will decrease the cooling power until it’s completely regenerated.

In both ceiling types the PCM is encapsulated in metal containers. The PCM and the containers (“CSM-modules”) are from the company Rubitherm Technologies GmbH and have the dimensions (0.30 m x 0.45 m x 0.015 m). The containers of ceiling type II have one plane surface for the attachment of the water pipes and can hold 20% more PCM than the containers used in ceiling type I. The PCM consists of a composition of salt hydrates and organic compounds and was sold under the label “SP22”. The PCM has the majority of its melting enthalpy in the range of 22°C to 24°C. The dimensions of ceiling type I specimen were (0.625 x 0.625) m² (being half of the size of the standardized panel) and the dimensions of ceiling type II specimen were (0.600 x 0.450) m².

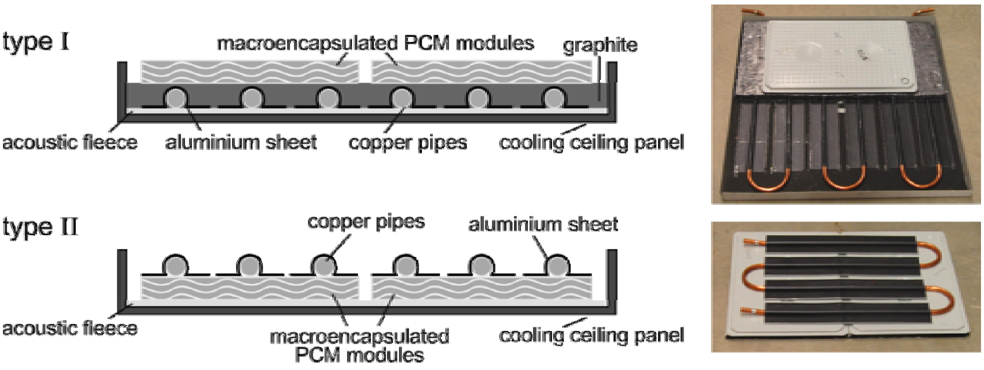

Fig. 2: Scheme and pictures of cooling ceiling type I and type II. In ceiling type I the PCM is on top of the water pipes and thermally connected by pressed graphite whereas in ceiling type II the PCM is directly attached to the cooling ceiling panel. For the picture of ceiling type I, half of the graphite layer and the second PCM module was removed.

2.3. Measurement Scenarios

The measurement setup allows for calorimetric as well as dynamic measurements. This paper attends to the dynamic behavior of the cooling ceiling prototypes being exposed to a temperature change. The temperature change can be a temperature leap as well as diurnal temperature profiles for example.

The cooling ceiling prototypes were tested in their three most common operation modes: passive cooling (no water flow), active cooling/PCM regeneration (cold water flow) and active heating (warm water flow). Before starting the actual measurements, the sample was preconditioned to a certain steady state within the measurement setup. To keep things simple and to bring out the differences of the two prototypes more clearly, the ‘room air’ (metal plate) temperature was then set and kept at a certain constant value during the measurements. The three measurement scenarios are described below in detail.

Before starting the measurements for the passive cooling mode (mode I), it had to be ensured that the PCM is completely in its solid state. Therefore, the cooling ceiling was actively cooled with an inlet temperature of 16°C for several hours while the room temperature was kept at 22°C. With starting the measurement, the active cooling was switched off and the room temperature was set to 26°C, representing a warm room in summer. The measurement lasts until the PCM is completely melted and the temperatures are in a steady state again. The passive cooling power density which can be achieved depends on the heat transfer coefficient between the “room air” and the ceiling panel $h_{a\text{-}c}$, the heat transfer coefficient between the ceiling panel and the PCM $h_{c\text{-}P}$, as well as the available temperature difference ΔT between the “room air” and the PCM. The correlation is expressed by equation 1:

$$\frac{1}{A}\cdot\frac{dQ}{dt} = h \cdot \Delta T \qquad \text{(eq. 1)}$$

where the left side is the cooling power density (heat flux respectively) and h is defined as follows:

$$h = \frac{1}{\frac{1}{h_{a-c}} + \frac{1}{h_{c-P}}} \qquad \text{(eq .2)}$$

The active cooling/PCM regeneration mode (mode II), requiring the PCM in its liquid state, can directly follow on the passive cooling measurements, which then act as the preconditioning phase. Hence, the room air temperature is changed from 26°C to 22°C and the cooling is switched on with an inlet temperature of 16°C at the beginning of the measurement. The room air temperature of 22°C represents a realistic boundary condition for regeneration over night. The mentioned temperature profile is kept until the PCM is completely in its solid state again. The thermal performance during mode II is mainly affected by the heat transfer coefficient between the water pipes and the PCM as well as the water pipes and the cooling ceiling surface.

Both ceiling constructions can also be operated in active heating mode (mode III). To characterize the dynamic thermal behavior in mode III, the PCM needs to be regenerated at the beginning of the measurements. In the preconditioning phase the active cooling is running with an inlet temperature of 16°C. The room air temperature stays at 22°C during the whole measurement. With starting the measurement the inlet temperature of the ceiling is changed from 16°C to 35°C. The measurement lasts until the phase transition of the PCM is completed and a steady state is reached. An overview of the three measurement scenarios gives figure 3.

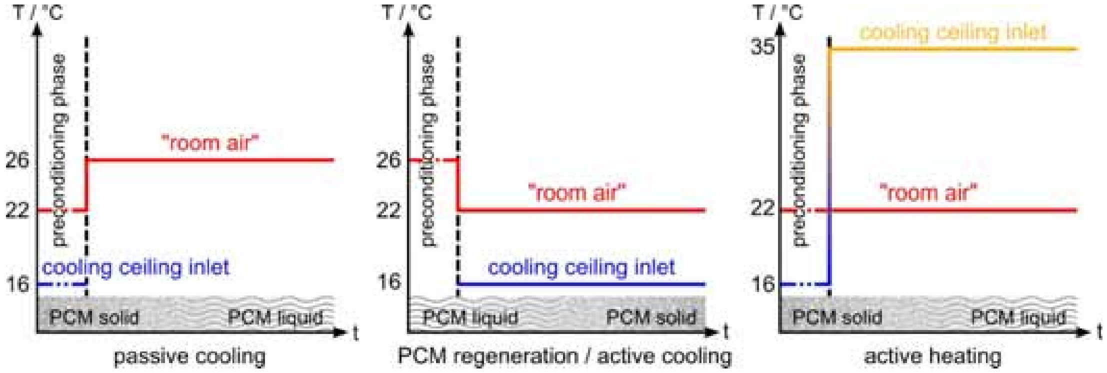

Fig. 3: Temperatures and PCM states during the measurements for the three operation modes “passive cooling”, “PCM regeneration / active cooling” and “active heating”.

3. Results

With the measurement setup described above, both cooling ceiling prototypes were characterized by dynamic thermal measurements. The dynamic measurements involve temperature as well as heat flux measurements. The positions of the HFS can be taken from figure 1; figure 4 shows the placing of the temperature sensors for both cooling ceiling types. For a proper characterization, the three typical operation modes described above (mode I – III) were examined. The results are described below.

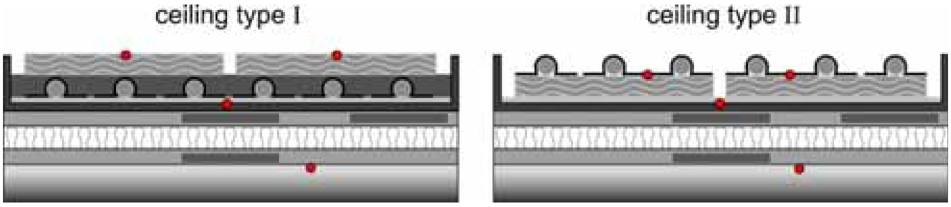

Fig. 4: Temperature sensor (red dots) placement for ceiling type I and II.

3.1. Passive cooling mode (mode I)

The passive cooling mode is designated to take place during daytime, while the room air is heated up by internal and external heat gains. Hence, the achieved passive cooling power during the loading cycle of the PCM is the subject of mode I measurements. It is also of interest, how long the PCM can provide a reasonable cooling power. The obtained results for ceiling type I and II are shown in figure 5. As ceiling type II prototype was smaller than type I (see 2.2.) the HFS in corner of layer 4 couldn't be used.

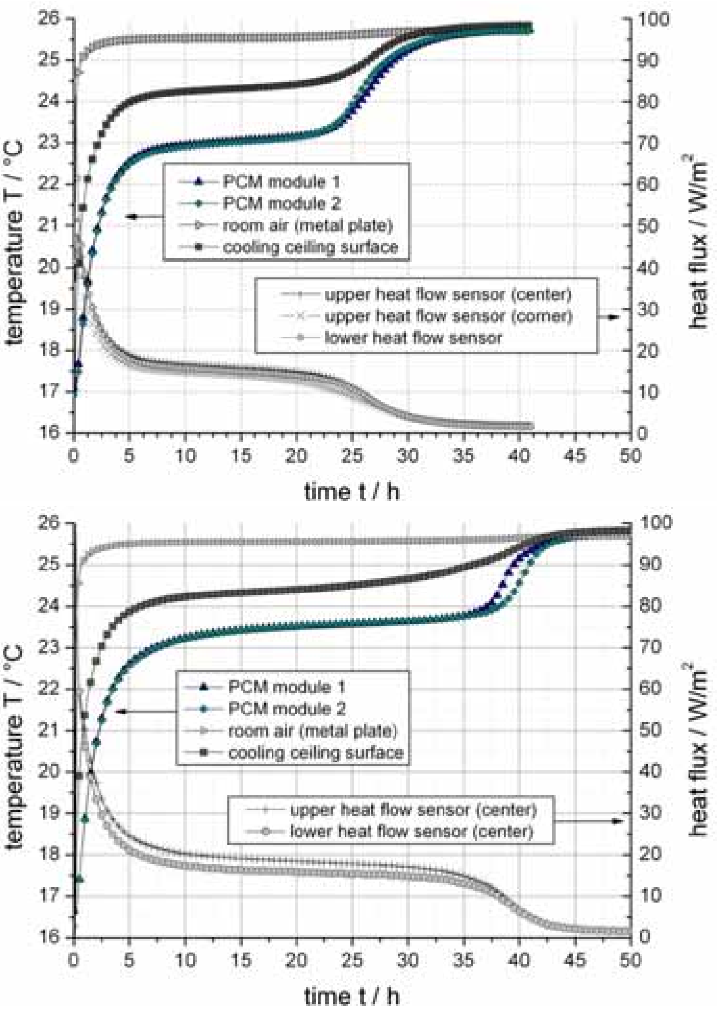

Fig. 5: Temperature curves and heat fluxes for the passive cooling mode of ceiling type I (top) and ceiling type II (bottom).

The results of the mode I measurements of ceiling type I are presented in figure 5 on the top. The PCM was preconditioned to a steady state at about 17°C and is hence completely solid at $t = 0$. Then the active cooling is stopped and the inlet temperature of the metal plate was set to 26°C, leading to a metal plate surface temperature or a room air temperature respectively of 25.5°C. As long as the PCM is out of its melting range, the temperature of the cooling ceiling surface and the PCM is rising. After about 4 hours the PCM begins to melt and the temperature is kept constant at 23°C over a period of about 16 hours. For $t > 25$ h the PCM is in its liquid state and the temperature rises until it reaches the room air temperature and a steady state. The measured heat fluxes at the three different positions are in a narrow range, but still show some deviations.

The biggest difference appears between the lower HFS (layer 2) and the two upper HFS (layer 4) in the short period after the temperature step is applied. The difference is caused by the sensible heat storage of the thermal resistance. During the melting process of the PCM, the heat fluxes show only small deviations, which are due to small lateral heat flux effects. The lateral effects are caused by the inhomogeneous ceiling construction and eventually minor differences in the thermal contact in the horizontal plane between the different layers. The cooling power density during the melting process of the PCM is between 19.6 W/m² (t = 4 h) and 12.6 W/m² (t = 23 h). This cooling power is achieved with a temperature difference ΔT between the room air and the PCM of 3.3°C to 2.2°C.

With the heat flux and the correlated temperature difference, the heat transfer coefficient between the room air and the PCM $h_{a\text{-}P}$ can be calculated with equation 3:

$$h_{a-P} = \frac{heat\ flux}{(T_{room\ air} - T_{PCM})} \qquad \text{(eq. 3)}$$

This calculation is valuable only in steady state where sensible heat storage effects are negligible. Figure 6 shows the $h_{a\text{-}P}$-value during the melting process of the PCM. The heat flux used for the calculations is the mean value of the centered HFS in layer 2 and 4. As PCM temperature T_{PCM} in equation 3 the mean value of both PCM modules is taken into account. The rectangles in figure 6 indicate the period where the steady state requirement is fulfilled in a first approximation, i.e. the temperature change $dT(PCM)/dt$ of the PCM is minimal. These periods are used for the evaluation of the heat transfer coefficients by calculating the mean value during the period.

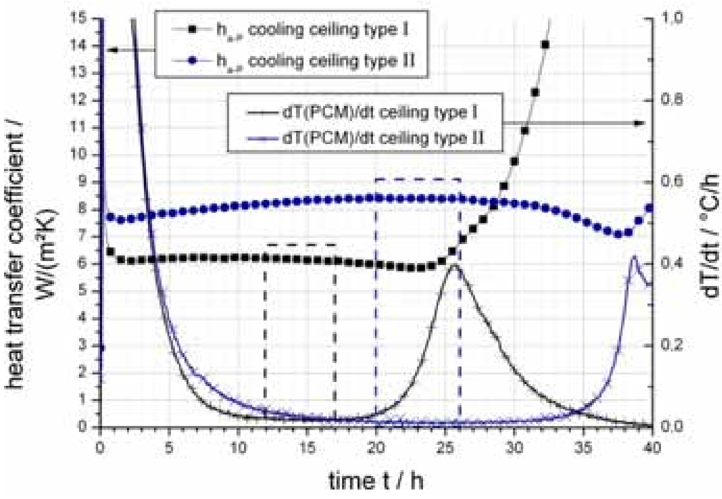

Fig. 6: $h_{a\text{-}P}$-values calculated with equation 3 and time derivation of the mean PCM-temperatures for cooling ceiling type I and II in passive cooling mode. The rectangles define the period used for the evaluation of the heat transfer coefficient.

The heat transfer coefficient $h_{a\text{-}P,I}$ between room air and PCM could be determined to 6.2 W/(m²K) for ceiling type I.

The results of the mode I measurements for ceiling type II are shown in figure 5 on the bottom. The measurement procedure was equal to the one for ceiling type I and temperature and heat flux curves show qualitatively the same behavior. However, the PCM in ceiling type II shows a temperature plateau shifted to a higher temperature. The temperature is stabilized at about 23.5°C instead of 23°C for type I. Ceiling type II was constructed some month after type I and the “SP22” material therefore wasn’t from the same batch. The melting process lasts for about 30 hours. The increased duration compared to type I is first of all due to the higher PCM amount as mentioned at 2.2. The higher PCM temperature during melting leads of course to lower temperature difference between the room air and the PCM which decreases the passive cooling power of the ceiling. But still, with ceiling type II a higher heat flux during melting was measured (24 W/m² at t = 5 h and 13.5 W/m² at t = 35 h) which is due to the better thermal connection of the PCM to the room air. The better thermal connection becomes evident when calculating the heat transfer coefficient $h_{a\text{-}P,II}$. Figure 6 shows the calculated $h_{a\text{-}P}$-value using equation 3, while again the mean values of the two centered HFS (layer 2 and 4) and PCM temperatures T_{PCM} (module 1 and 2) are taken into account. The heat transfer coefficient $h_{a\text{-}P,II}$ between room air and PCM could be determined to 8.4 W/(m²K) for ceiling type II, which is an increase of more than 35% compared to ceiling type I.

3.2. PCM regeneration / active cooling mode (mode II)

In the application the PCM regeneration takes place over night if the PCM isn't entirely in its solid state. Hence, for the measurements a room air temperature of 22°C is assumed, which simulates the room air temperature at night after warm days. To regenerate the PCM, the inlet temperature of the ceiling is set to 16°C. The results for both ceiling types are shown in figure 7.

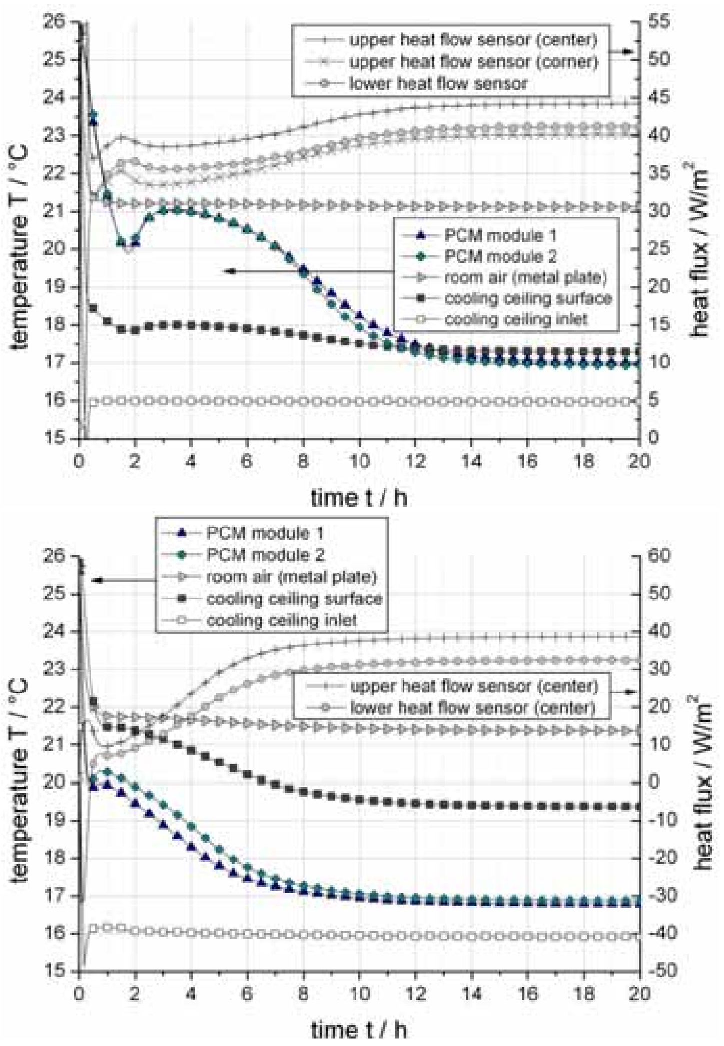

Fig. 7: Temperature curves and heat fluxes for the PCM regeneration / active cooling mode of ceiling type I (top) and ceiling type II (bottom).

Considering the PCM regeneration, it is important that with the chosen inlet temperature the nucleation of the PCM can be started. Especially when the PCM is a salthydrate and shows a certain degree of subcooling, this has to be tested. Additionally, it is of interest, if the PCM can be regenerated completely in a certain time span, e.g. over night, when the building is not occupied.

The measurements show that with an inlet temperature of 16°C the nucleation of the PCM can be triggered in both ceiling types. The crystallization starts at a PCM temperature of about 20°C, indicated by a PCM temperature rise. The PCM temperature curve is blurred in the measurement of ceiling type II, as the PCM temperature sensors also are in very good thermal contact with the water pipes (see figure 4). The time needed for the complete regeneration of the PCM with an initial temperature of 26°C is about 13 hours for type I and about 10 hours for type II, even though type II has more PCM. Ceiling type II hence shows a better performance in regeneration mode. In ceiling type I the cooling fluid is in thermal contact to the room and the PCM, causing a higher heat gain to the cooling fluid which in consequence reduces the cooling power. The water pipes of type II only take up heat from the PCM as the other side can be assumed adiabatic in good approximation. Furthermore, the thermal contact between cooling fluid and PCM is better for type II than for type I.

Considering the active cooling mode, the surface temperature of the cooling ceiling defines the cooling power towards the room. The active cooling mode is supposed to start operation if the heat gains of the room exceed the cooling power of the PCM and the room temperature in consequence exceeds the comfort range. Figure 7 reveals the differences in the ability of active room cooling between the two cooling ceiling types. After starting the cooling, ceiling type I reaches ceiling surface temperatures of about 18°C at the start of PCM crystallization and of about 17.3°C in steady state. Ceiling type II reaches ceiling surface temperatures of about 21.4°C at the beginning of the PCM crystallization and of about 19.4°C in steady state. Ceiling type I provides a good active controllability whereas type II offers superior performance during regeneration.

3.3 Active heating mode (mode III)

The active heating mode is similar to the active cooling mode but with an inlet temperature of 35°C instead of 16°C. As shown in figure 3, the PCM is preconditioned to 16°C at the beginning of the measurement. The results of the measurements are shown in figure 8.

As in the mode II measurements, ceiling type I shows the better active controllability. The temperature of the ceiling surface immediately rises to 30.7°C and stays there until the phase change of the PCM is completed. In the steady state the temperature reaches 32.5°C. Under the given boundary conditions the heating power amounts to 76-83 W/m² during the phase change and to 93 W/m² in the steady state.

The surface temperature of ceiling type II rises quite slowly after starting the heating. After 1 hour a surface temperature of 22.7°C can be observed. Then the PCM enters its melting range and a further temperature rise is retarded. After about 2 hours the PCM is completely melted and the surface temperature reaches 27.8°C in the steady state. The heating power of ceiling type II is below 21 W/m² until the phase change of the PCM is completed and reaches 72 W/m² in the steady state.

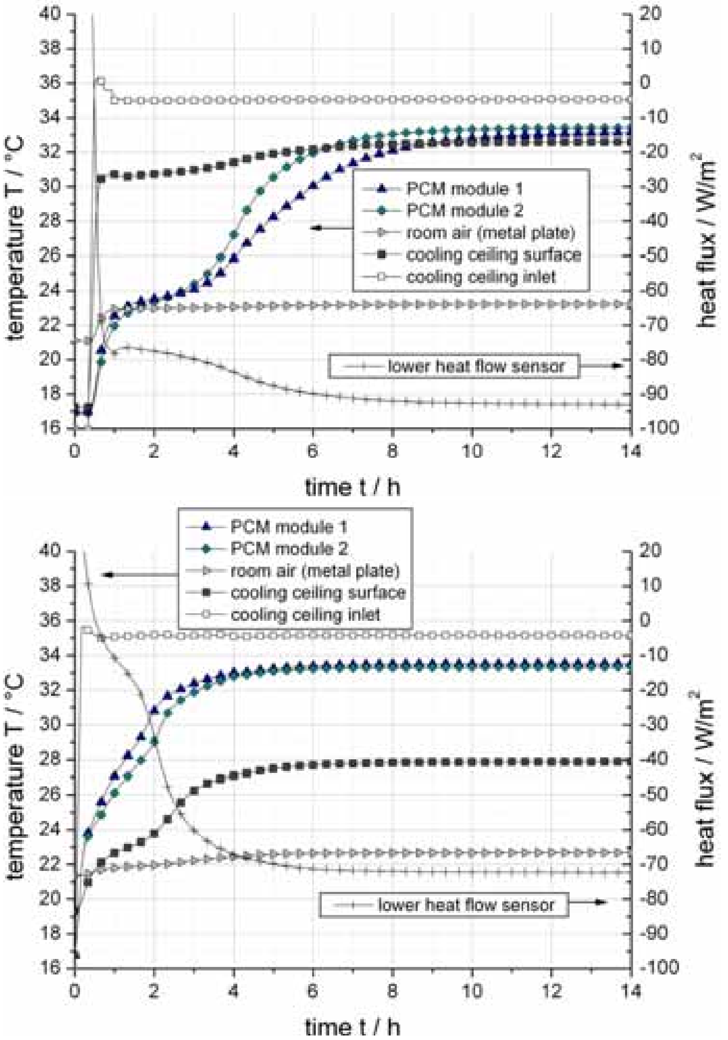

Fig. 8: Temperature curves and heat fluxes for the active heating mode of ceiling type I (top) and ceiling type II (bottom).

4. Conclusion

In the presented work the dynamic thermal behavior of two newly developed PCM cooling ceiling prototypes was examined. For characterization a new measurement setup was constructed which can hold single cooling ceiling panels. With this setup, the thermal conditions and typical heat transfer coefficients of a real test room can be simulated. As the combined heat transfer coefficient (convection + radiation) between the room air and the ceiling in a real test room is realized with a thermal resistance between the metal plate acting as room temperature and the sample, stable and well defined boundary conditions could be established in the measurement setup.

Both cooling ceiling prototypes address the improvement of the thermal contact between the room air and the PCM as well as between the cooling agent and the PCM, but with other priorities. In ceiling type I the PCM is placed on top of the water pipes. The thermal connection between the cooling ceiling surface and the water pipes is improved by a layer of extruded graphite which is pressed onto the pipes. The approach of ceiling type I is a compromise between a good performance during passive cooling and a good active controllability. As shown in the measurements, ceiling type I reaches low or high ceiling surface temperatures respectively very fast. If the heat gains during the day exceed the passive cooling power of the PCM, this system can support cooling actively with only little drawbacks compared to a regular cooling ceiling.

Ceiling type II concentrates on the enhancement of the passive operation mode and the PCM regeneration. In both tasks ceiling type II showed better results than ceiling type I. The measurements revealed an increase of the passive cooling power of about 35% during the melting process of the PCM compared to ceiling type I. The time needed for PCM regeneration could approximately be halved. As the surface temperature of cooling ceiling type II doesn’t reach such low temperatures during the regeneration process, less heat from the room is taken up from the cooling fluid. This leads to a better regeneration performance and reduce the cooling capacity requirements in a system. Otherwise, an active support of the cooling and heating during the day is not reasonable as the PCM has to be regenerated or melted respectively before the cooling or heating power is available to the room.

5. Acknowledgement

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