AN INVESTIGATION ON PHASE CHANGE MATERIALS TO REDUCE SUMMER OVERHEATING

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ABSTRACT

Phase change materials in rooms increase the thermal mass and help to reduce overheating. Two phase change materials were investigated in full scale experiments at the Bauhaus-University Weimar. Deducted from the experimental results, a numerical description of the phase change process with and without super-cooling was developed using temperature dependent functions for heat capacity and thermal conductivity. In the paper validation, stability and accuracy of the model are discussed and recommendations are made. Simulation results of PCM-plaster show the potential of a marketable material. Attention was put on the optimization of melting temperature and layer thickness.

INTRODUCTION

Modern architectural constructions with high glazing facades and light-weight constructions increase the overheating problem, in particular in office buildings with high casual loads. One way to overcome this problem is to use phase change materials (PCMs) in buildings. PCMs are heat accumulators that store and release heat during the phase change process. PCMs increase the thermal mass in buildings and reduce peak temperatures during hot spells.

EXPERIMENTAL RESEARCH

Former Research

The heat storing effect of PCMs and their possible use within the building sector has been investigated since the middle of the 20th century. While the first studies combined PCMs with heating systems and heat exchangers, in the 1980s the research turned towards a more passive application. The use of PCMs during summer periods has been the focus since the 1990s. Scalat et al. (1996) examined latent heat wallboards in full scale experiments with heating and cooling mode with an emphasis on possible peak load shifting. Feustel et al. (1997) saw the potential of using PCMs in light buildings with special attention on the necessary discharging. Lamberg et al. (2000) investigated paraffins and salt-hydrates with phase change temperatures between 23°C and 24°C and found a maximum temperature reduction of nearly 5 K. With the evolution of micro-encapsulation (Jahns, 2004) the development of new PCM-containing materials was carried out. Schossig et al. (2003) used paraffin filled capsules in spackle and plaster with layer thicknesses from 6 mm to 5 cm and measured a temperature reduction of 3°C.

"SFB 524" at the Bauhaus-University Weimar

Within the framework of the government funded project "SFB 524" (Bauhaus-University Weimar, 2005), which concentrated on the renovation of existing buildings by the use of new materials and constructions, the Department of Building Physics at Bauhaus-University Weimar undertook an experimental and numerical investigation of phase change materials. The focus lay on the passive application in extremely lightweight rooms, as they are typical for modern office buildings. In summer the indoor-temperatures in those rooms rise quickly and problems with thermal comfort are common. The moderate climate conditions in most parts of Europe should nevertheless allow for solutions without costly and energy-demanding air-conditioning.

The test rooms

For the experimental investigation, two similar test rooms made of a lightweight plaster board construction were erected in a former industry building. The construction of the inner partitioning and the ceiling was composed of a 20 cm layer of insulation with low thermal conductivity and low heat storing capacity. The insulation was covered with a gypsum plaster board which was plastered with PCM-plaster containing 20% microcapsules with paraffin in one room and with a conventional gypsum plaster in the other room. The building was orientated south-east with a large transparent area. Both rooms were equipped with 32 thermocouples each to measure indoor temperatures, surface temperatures and temperatures within different layers of the construction. Ambient temperatures were recorded via data-loggers and global solar radiation was measured by a pyranometer.

Temperature reduction in the test-rooms

The thickness of the plaster-layer varied from 1 cm in summer 2004 to 3 cm in summer 2005. Additional 10 m² gypsum-board with PCM-plaster and polyethylene tubes filled with salt-hydrate were added to the PCM-test room during 2004 in order to improve the effects. With a 1 cm layer of PCM-plaster the measurements showed a reduction of the peak indoor temperatures by 2°C when comparing the room with PCMs to the room without PCMs. A 3 cm layer improved the reduction by 3°C and with the salt-hydrate a maximum reduction of 5-6°C could be achieved (Waldhelm et al., 2005).

Properties of the PCMs used in the experiments

The PCM-plaster used in the experiments was a gypsum-plaster containing 20 % of PCM micro-capsules. These micro-capsules have a diameter of 5 – 10 μm and are filled with paraffin. The plaster can be plastered onto the walls like normal gypsum plaster and its appearance and surface properties do not differ significantly from those of conventional material. Since 2005 PCM-plaster with micro-encapsulated PCM has been available on the market.

The second material investigated was Calcium Chloride Hexahydrate, which is already in use in commercial applications. It is a cheap, relatively low-toxic salt-hydrate with a specific latent heat higher than those of paraffin. For passive application in buildings the pure Calcium Chloride Hexahydrate has to be modified in order to decrease its melting point. Nucleators must be added to reduce the problem of super-cooling that occurs frequently with salt-hydrates (Lane, 1983). Though there are different possible measures, the risk of hydratization and segregation remains considerable. DSC-(Differential Scanning Calorimeter) measurements of the modified Calcium Chloride Hexahydrate at the end of the experimental period showed significant super-cooling and a higher melting-point than at the beginning.

Table 1 shows that the thermal properties of PCMs vary following the state of aggregation of the material. The most important differences can be found with salt-hydrates between the thermal conductivity and the specific heat in solid and liquid state. **Fig. 1a** and **1b** demonstrate DSC-curves of the PCM-plaster and the salt-hydrate, where the latter shows important super-cooling.

During the DSC-measurement a constant heating (~1- 2 K/min) is maintained. When the phase change occurs, the necessary heat flow must be increased in order to heat up the material regularly. The latent heat of the material corresponds to the area beyond the measured heat flow curve (**Equ. [1]**).

$$l = \int_{\theta_1}^{\theta_2} \frac{\dot{Q}}{m} \cdot \frac{1}{R}\, d\theta - c \cdot (\theta_2 - \theta_1) \qquad [1]$$

A number of DSC-measurements were done during the experimental period in order to check the reproducibility. While the behaviour of the PCM-plaster was very stable, there were great variations in the results of the salt-hydrate due to super-cooling. Super-cooling appeared when all the material liquefied before the PCM then cooled down. In this case the solidification process took place at a temperature that was significantly below the temperature where the melting process had finished. If the cooling started before all the PCMs liquefied there was no super-cooling found.

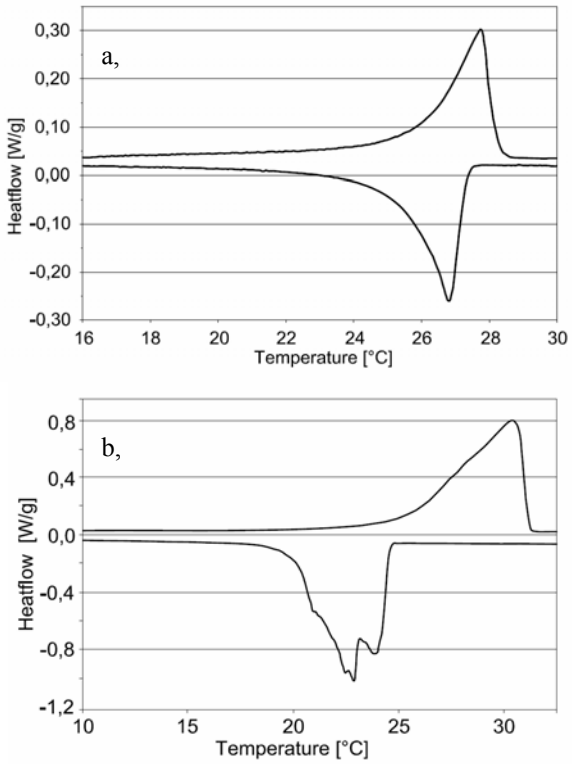

Fig. 1a and 1b: DSC-measurements of PCM (1a, PCM-plaster with microencapsulated paraffin 1b, Modified Calcium Chloride Hexahydrate)

Knowing the temperature range in which the phase change occurs is very important for the investigation of its efficiency when using PCMs as a passive heat storage medium in rooms. The ideal cycle would be melting during the day and solidification during the night. The next day the material could only store latent heat if at least parts of the PCM solidified again. If the solidification process needs lower temperatures than achieved during the night, the PCM will stay liquid and loses its latent heat storing capacity until the material will have solidified and "discharged" again.

Table 1
Properties of PCM.

	THERMAL CONDUCTIVITY [W/mK]		SPECIFIC HEAT CAPACITY [kJ/kgK]		DENSITY [kg/m³]		LATENT HEAT [kJ/kg]	MELTING POINT (peak-temp.) [°C]	SUPER-COOLING [°C]
phase	solid	liquid	solid	liquid	solid	liquid		-	
PCM-Plaster Source:	0.23 1)	0.20 1)	1.10 1)	1.07 1)	957 1)	(957) 1)	16.5 2)	28.1 2)	0-1 2)
$CaCl_2$*6H_2O Source:	1.09 3)	0.54 3)	1.42 3)	2.1 3)	1562 3)	1802 3)	172.0 2)	29.0-29.5 2)	5-15 2)

Sources:
1) Measurements at the Bauhaus-University Weimar
2) DSC-measurements at the Friedrich Schiller University Jena
3) Lane (1983)

A NUMERICAL PCM-MODEL

Description

Within the SFB 524 project we examined the effects of phase change materials placed on the surface of inner partitioning, ceiling or floor that can be numerically treated as a separate layer with room-side heat transfer on the one hand and heat conduction to the next (opaque) layers on the other side. The thermal boundary conditions that determine the temperatures at the surface and within the PCM-layer are influenced by many parameters. The use of an integrated building simulation program is therefore recommended when it is intended to investigate the efficiency of PCMs in a specific room. For the numerical investigation the aim was to use the kernel of an existing program (ESP-r) and to add a PCM-tool that takes into account the properties of PCMs. The principle is based on former work from Heim et al. (2004). A useful numerical approach suggests consideration of the following points:

- specific latent heat
- different values for specific heat in solid and liquid state
- different values for thermal conductivity in solid and liquid state
- temperature range of melting and solidification
- super-cooling if the temperature range of melting differs significantly from solidification

The microencapsulated PCM-plaster was treated as a homogenous material. Due to the small diameter of the capsules and assuming that they are well mixed into the plaster, the heat transer within the PCM-plaster was supposed to be uniform. Therefore one value for thermal conductivity and one value for heat capacity was considered for the composed material.

Implementation

Assuming that there is no super-cooling, the heat storing process during phase change can be described by one temperature dependent function of heat capacity which is called $c_{latent}(\theta)$.

$$c_{latent}(\theta) = \frac{1}{m}\frac{dh(\theta)}{d\theta} \qquad [2]$$

$\theta < \theta_1$: $c(\theta)=c_{solid}$

$\theta_1 \le \theta \le \theta_2$: $c(\theta)= c_{solid} + c_{latent}(\theta)$

$\theta > \theta_2$: $c(\theta)=c_{liquid}$

$c_{latent}(\theta)$ can be derived from the DSC-curves, where an exponential or rational approximation was found most appropriate. Although the R^2 of the rational function was slightly higher, it was given preference to the use of an exponential function:

$$c_{latent}(\theta) = \exp(a + b \cdot \theta) \qquad [3]$$

Based on a large number of various approximations of DSC-measurements and under the assumption that $c_{latent}(\theta)$ follows **Equ. [3],** the coefficient a can be written as:

$$a = -b \cdot \theta_2 + d \cdot \ln(\frac{l}{l_0}) + e \qquad [4]$$

As the coefficients b, d, e are known constants, the coefficient a can be derived from b, d, e and from the latent heat l and the peak-temperature θ_2. The advantage of **Equ. [3]** becomes obvious: The value for $c_{latent}(\theta)$ can be calculated only from the latent heat

of the material and from the peak-temperature of phase change (θ_2), which means that the information of the thermal properties of the PCM is sufficient. The user does not have to know the details about approximation and coefficients.

In order to modify the value for heat capacity within the Fourier-equation for one-dimensional heat conduction, the value for c in solid phase is multiplied by a heat capacity-factor: c-factor = $c(\theta)/c_{solid}$.

This method is straightforward for homogenous volumes and room-side boundary volumes, but it poses problems if temperature nodes are set on the interface to the next layer like in the symmetrical nodal scheme used in ESP-r (Hensen et al. 1994). In this case the modification of the heat capacity applies to a mixed boundary volume as shown in **Fig. 2**:

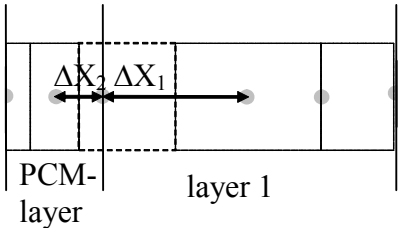

Fig. 2: Nodal scheme of heat conduction in ESP-r

Without touching the main source code of heat conduction in ESP-r, the inaccuracy made in the ESP-r PCM-module depends on the thickness of the following layer:

$$\left(\frac{\Delta x_1 \cdot \rho_1 \cdot c_1}{2} + \frac{\Delta x_2 \cdot \rho_2 \cdot c_2}{2}\right) \cdot \text{ c-factor } = \quad [5]$$
$$= \frac{\Delta x_1 \cdot \rho_1 \cdot c_1 \cdot c(\theta)}{2 \cdot c_{solid}} + \frac{\Delta x_2 \cdot \rho_2 \cdot c(\theta)}{2}$$

with: $c_2 = c_{solid}$ (PCM) and $c_1 = c_{solid}$ (layer1)

Equ. [5] shows that the part of layer 1 that belongs to the boundary volume is multiplied with the c-factor too. A very thin "fictional" layer between the PCM-layer and the next "real" layer in the construction helps to minimize the error by reducing Δx_1.

Validation

The numerical accuracy of the c-factor was tested by setting the phase change temperature range very high or very low so that only the correction c_{liquid}/c_{solid} happened. Then the simulation results of a reference wall without using the PCM-module were compared to results where the choice of c_{solid}, and c_{liquid} led to similar heat capacity as in the reference wall. The difference in the obtained temperatures (surface temperature and inner node temperatures) did not exceed 0.02 K.

The validation of the PCM-function is based on the comparison of measured temperatures in the test room and simulation with ESP-r. One of the main problems in modelling the test room was how to cope with solar radiation entering the room. The global irradiation measured by the use of a pyranometer on the roof of the buiilding had to be transformed in its direct and diffuse parts as ESP-r requests this information. Different algorithms were tested where the Page's correlations (Heidt, 1985) were found most appropriate. The second area where important errors must be assumed is the relatively low accuracy in the measurement of ambient temperature in combination with the chosen high ventilation rate during the night (air change rate ~ 3-5 1/h from 7pm to 7am). Despite these inconveniences, the correspondences achieved between the experimental results and the calculated temperatures is sufficient.

Super-cooling

In order to assess the effects of the above mentioned super-cooling, this problem was adressed in a separate explicit finite difference scheme. The difficulty in describing a super-cooled phase change process is knowing the history of the material. If the material liquefies before it cools down, then super-cooling will occur. Otherwise the PCM will solidify immediately and nearly symmetrically to its melting process. As a consequence the heat capacity $c_{latent}(\theta)$ during solidification corresponds either to the known function or to a new super-cooled function. While the phase change during melting and non-super-cooled solidification occurs between θ_1 and θ_2, the super-cooled solidification takes places between $\theta_2^*=\theta_2$-*sub* and $\theta_1^*=\theta_1$-*sub* (with sub-temperature differences between non-super-cooled and super-cooled solidification).

The method used to keep the information about the previous behaviour of the PCM is to store the maximum and minimum temperatures of each node in the PCM for the previous and present timestep. At each extremum the melting degree *h* will be calculated to know how much of the material is liquid, thus the melting degree describes the percentage of melting. The melting degree results from the integration of $c_{latent}(\theta)$ or $c_{super\text{-}cooled}(\theta)$ respectively between the previous and the present extremum, where the limits of integration depend on the temperature at which these extremums occur. Thirty cases need to be considered separately and for six of them the previously calculated melting degree will give the information if the PCM was in an undercooled state at the previous extremum or not. In order to ensure that at no point of the calculation the specific latent heat of the PCM will be exceeded, a factor is introduced to modify $c_{latent}(\theta)$ during the next time step. This factor depends on the actual value of h, the previous and the present extremum and it considers the possible maximal or minimal temperatures that can be achieved in the next future time step.

Fig. 3 shows the temperatures within a 3cm layer of PCM without super-cooling. The dotted line shows the melting degree for the surface temperature (black line) calculated at each extremum. The peak-temperature of phase change is 28°C and as long as the night temperatures are cold enough to discharge the PCM, the average temperature of the PCM-construction does not exceed 28°C. On July 26 the PCM could not solidify anymore and the temperature closely follows the air temperature (assumed heat transfer coefficient of 8 W/m²K on the one side and adiabatique boundary on the other side).

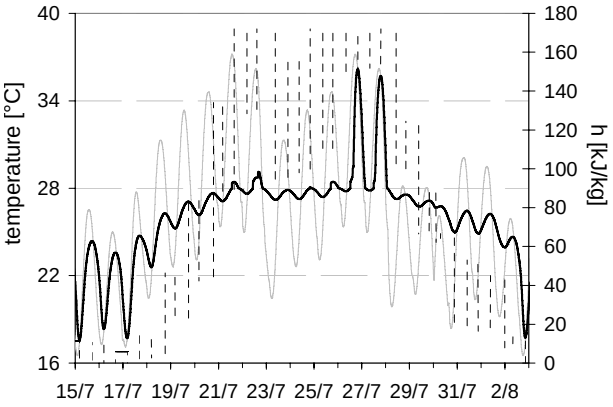

Fig. 3: PCM with peak-temperature θ_2=28°C, Latent heat 172 kJ/kg

*(dashed line: melting degree * latent heat , grey line: air temperature, black line: surface temperature)*

Fig. 4 shows the behaviour of a super-cooled PCM under the same conditions, but with a solidification temperature of 22°C for the super-cooled solidification. The material properties correspond to those of the salthydrate in Table 1 and a 3 cm layer with a room-side convective heat transfer and an adabatique boundary on the other side. When the PCM first achieved a complete liquid state on July 22 it could not solidify anymore until the air temperature fell clearly below 22°C. During the hot days from July 23 to July 28 the PCM could not act as a heat storage medium.

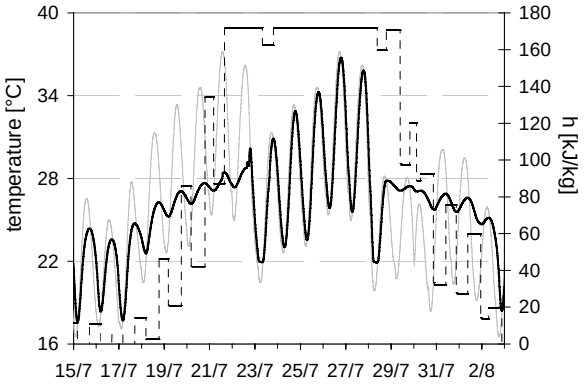

Fig. 4: Super-cooled PCM with θ_2=28°C and solidification temperature $\theta_{2super\text{-}cooled}$=22°C

*(dashed line: melting degree * latent heat , grey line: air temperature, black line: surface temperature)*

Stability and time step requirements

The stability of the explicit difference scheme depends on time step and spatial discretisation and on the material properties in pure solid or pure liquid state. Small Fourier numbers Fo < 0.01 are needed to avoid oscillation. Therefore the high values of heat capacity calculated for $c_{latent}(\theta)$ during the phase change are favourable. Problems occur when the whole construction reaches temperatures above or below the phase change region. As long as parts of the construction are in the temperature range of phase change, larger time steps can be used.

The ESP-r-tool was tested for implicitness degrees between γ=0.5 (Crank-Nicholson) and γ=1 (fully implicit) and there were no stability problems found using the PCM-module. Concerning the accuracy of the calculations special care has to be addressed to the choice of time step and spatial discretisation. The chosen distance between temperature nodes does not influence the calculated results as long as the time step is small enough. If time-steps >5min is used a node grid with Δx>5mm leads to an over estimation of the achieved temperature reduction by the PCM. Equally large time steps, even with small PCM-layers, lead to errors that are in the same order of magnitude as the attainable temperature reduction. The importance of a small time step can be seen in **Fig. 5**. While the errors due to different time steps in case of a constant thermal diffusivity within an implicit or mixed implicit/explicit model are minor, they become important when they occur in the region of the peak-temperature of phase change. Due to the high values of c(θ) around the end of the melting process the temperatures in the PCM-layer increase slowly. When the construction exceeds θ_2, the temperature rise is important. Hence PCMs are most useful as long as they nearly achieve their peak-temperature without surpassing it.

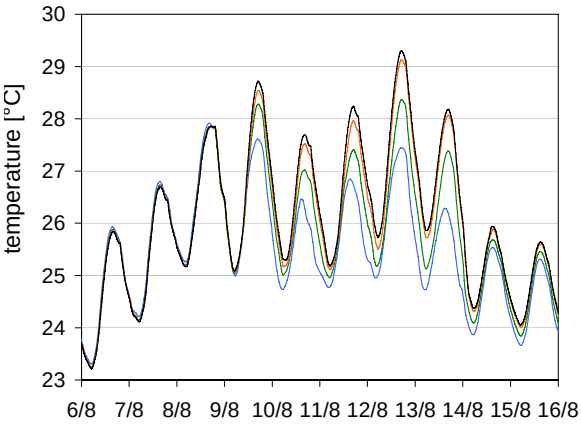

Fig. 5: Simulated temperatures with different time-steps

(blue line: time-step 1 h, green line: time-step 30 min, orange line: time-step 15 min, black line: time-step 5 min)

SIMULATION OF PCM-PLASTER

Peak-temperature of phase change

Due to the limited latent heat of the PCM-plaster (l=16.5 J/g) a maximum reduction of ~3K can be achieved. To make best use of the heat storing capacity, the peak-temperature θ_2 of the PCM should be chosen 2-3K below the temperatures that occur without PCMs. **Fig. 6** shows surface temperatures of a 3 cm layer of PCM-plaster with peak-temperatures θ_2 at 24°C, 26°C and 28°C compared to the surface temperature of a conventional gypsum plaster (black line). During the hottest day (June 8) the highest reduction was achieved with a peak-temperature θ_2 of 28°C (blue line). The next day was less hot and therefore a peak-temperature of 26°C (green line) was most favourable. During the coolest day (June 10) a peak-temperature of 24°C (orange line) was most efficient.

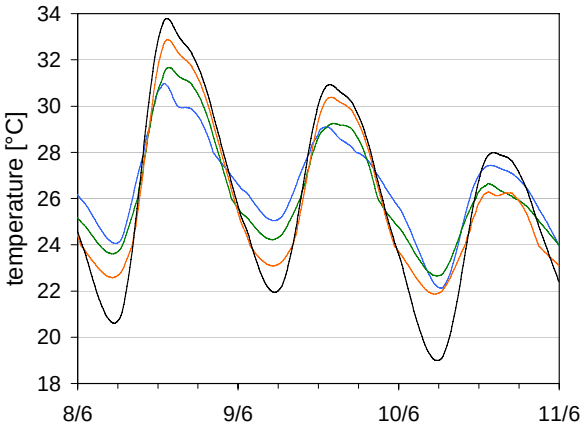

Fig. 6: Simulated surface temperatures of a 3cm PCM-plaster

(black line: plaster without PCM, orange line: θ_2 = 24°C , green line: θ_2 = 26°C, blue line: θ_2 = 28°C)

Although the temperature range of human thermal comfort suggests that temperatures should not exceed ~28°C, one has to be careful with low peak-temperatures. To ensure a sufficient discharging of the PCM, the material should attain a temperature of at least 3 K below θ_2 during the night. If this discharging temperature is not reached (e.g. see green line on June 9 and orange line on June 10), the PCM cannot use its full latent heat and the achieved reduction stays beyond the maximum reduction of 3 K.

Effective thickness of PCM

Recommendations for the thickness of the PCM-plaster also depend on the ambient conditions in combination with the peak-temperature θ_2. **Fig. 7a** shows the surface temperature for thicknesses of 1, 2, 3 and 5cm at a peak-temperature of 28°C while **Fig. 7b** shows the same thicknesses at a peak-temperature of 26°C.

A 3 cm layer (blue line) of the PCM-plaster at 28°C brings good results and further extension of the layer up to 5 cm does not have recognizable effects. In contrast to the PCM-plaster at θ_2 = 26°C it is reasonable to use thicker layers. While soon the room-side part of the PCM gets completely liquid, deeper layers at lower temperatures can be activated due to the heat conduction. The heat transfer into the construction makes a 5 cm layer still work as a heat storing medium even if the surface has already surpassed the peak-temperature of phase-change.

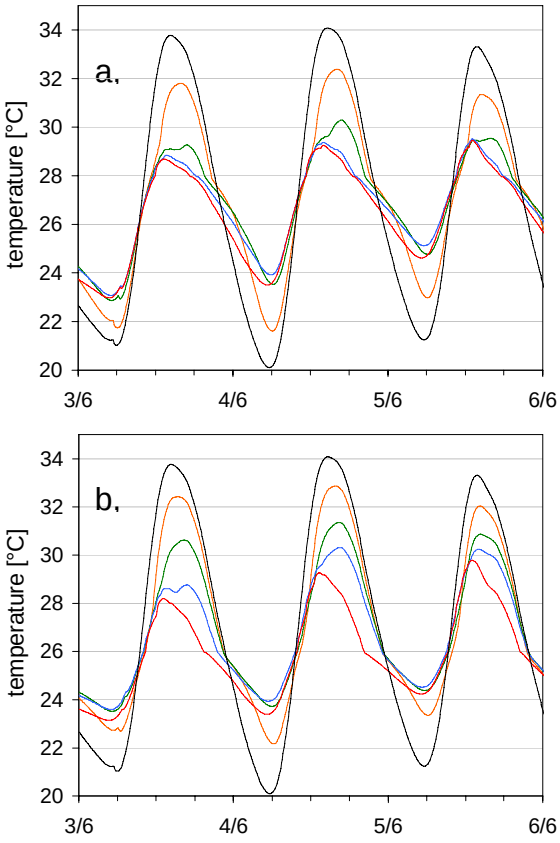

Fig. 7a, and 7b,: Simulated surface temperatures with different thicknesses

Fig.7a,: θ_2 = 28°C; Fig.7b,: θ_2 = 26°C;

(black line: 1 cm plaster without PCM, orange line: 1 cm PCM-plaster, green line: 2 cm PCM-plaster, blue line: 3 cm PCM-plaster, red line: 5 cm PCM-plaster)

Although the PCM at θ_2 = 28°C may lead to slightly lower maximum temperatures, it is less efficient if the temperature reduction is regarded over time. During the three days indicated, the surface-temperature of a 5cm layer of plaster without PCMs exceeded the comfort limit of 28°C over 41h, a 5cm layer of PCMs with θ_2=28°C surpassed 28°C over 27h and the PCM with θ_2=26°C only over 21h. Thus overheating hours (hours at which a specified temperature is exceeded) should be considered in the investigation of PCM-efficiency beside the maximum temperature.

Potential of PCM-plaster under moderate climate conditions

For a great number of simulations under various ambient conditions (different European climate files – Hoffmann et al. 2005), different construction details and room orientation, overheating hours that occur with a 3cm layer of PCM-plaster (peak-temperatures θ_2 between 23°C and 26°C) were compared to those that occur with conventional plaster.

Fig. 8 gives a rough indication of the potential reduction of overheating hours depending on the overheating hours occurring without PCMs. The reference temperature that must not be exceeded varies from 25°C to 27°C in accordance with German regulations (DIN 4108-2, Hoffmann et al. 2004). (Germany is divided into three different climate regions with each being subject to a different reference temperature.)

For rooms with moderate overheating a linear correlation was found. The lower limits should be taken for heavier construction that already dispose of a significant thermal mass while the upper limits apply to lightweight buildings. If during more than 400 hours in the year the room-temperature surpasses the reference temperature, the absolute values of reduction do not increase any more and correspondingly the relative reduction decreases.

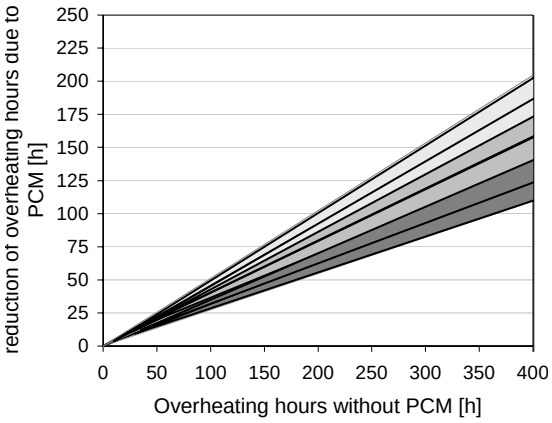

Fig. 8: Reduction of overheating hours with different reference temperatures

(dark grey region: overheating hours above 25°C, grey region: overheating hours above 26°C, light grey region: overheating hours above 27°C)

The potential of PCMs becomes evident if one considers that the German regulation allows overheating hours for 10% of the occupied time which is about 200 h in the case of an office. The use of a 3 cm layer of PCM-plaster with an adjusted peak-temperature θ_2 can help to fulfill the requirements.

CONCLUSION

The positive effects of PCMs on indoor temperature during hot spells were subject to an experimental and numerical investigation at the Bauhaus-University Weimar. In full-scale test-rooms and DSC-measurements the behaviour of a PCM-plaster with micro-encapsulated paraffin and a salt-hydrate was looked at. The thermal conductivity and the specific heat of the materials depended on their state of aggregation. In the case of the salt-hydrate super-cooling was found as a major problem.

In order to model the PCM-behaviour correctly, the requirements for a numerical model were deducted from the experimental findings. A heat capacity factor as well as a factor to modify the thermal conductivity were introduced to define material properties in solid and liquid state as well as during phase change. After the implementation of a PCM-tool in ESP-r, the measurement results were used for the validation of a PCM-tool implemented in ESP-r.

Within a symmetrical nodal scheme with temperature nodes on the interface between PCMs and conventional layering, the heat capacity factor leads to inaccuracy. The introduction of a small layer between PCMs and conventional material is recommended. During simulation small time-steps ≤ 5 min and a spatial discretisation ≤ 5 mm is necessary to get reliable results.

Super-cooling is a major problem of salt-hydrates but may also occur with other PCMs. The hysteresis of melting and cooling was investigated in a separate model where two additional features had to be considered. The history of the material must be known in order to determine if the PCM is in a super-cooled state or not. The melting degree is necessary to keep the model consistent during its changes from super-cooled state to normal state and vice-versa.

Due to the super-cooling of the examined salt-hydrate, which imposes a massive discharging problem, the PCM-simulations concentrated on the PCM-plaster with micro-encapsulated paraffin.

The choice of the melting point (peak-temperature of phase change) influences the efficiency of PCMs to a great extent. A maximum reduction of 3 K for a 3 cm layer of PCM-plaster can be achieved if the peak-temperature of the PCM is about 2-3 K below the temperature that would occur without the PCM. If the peak-temperature is chosen too high, the PCM cannot use its full latent heat. With low peak-temperatures discharging problems may occur if the PCM-temperature during the night cannot be lowered to 3 K below its peak-temperature.

The recommended thickness of PCM-plaster depends on the peak-temperature of phase change. With optimized peak-temperatures a thickness of 3cm

brings the best reduction of maximum temperatures. In this case thicker layers will not improve the results. With lower peak-temperatures, thicker plaster layers might be useful because the deeper layers of the PCM can be activated by heat conduction.

Besides the maximum temperature, the most important criterion of PCM-efficiency is the number of overheating-hours that can be reduced. For a European climate a 3 cm layer of PCM-plaster with optimized peak-temperature can reduce overheating hours by 25 - 50%. The use of a PCM-plaster instead of a conventional plaster can help to fulfill the German requirements for indoor temperatures during summer.

NOMENCLATURE

l:	latent heat [J/kg]
l_0:	reference latent heat: $l_0 = 1$ J/kg
θ:	temperature [°C]
θ_1:	temperature [°C] where the melting process starts / solidification ends
θ_2:	temperature [°C] where the melting process ends / solidification starts
R:	heating rate [K/s]
c:	specific heat capacity [kJ/kgK]
c_{solid}, c_{liquid}:	specific heat capacity in solid / liquid state [kJ/kgK]
$c_{latent}(\theta)$:	temperature dependent function of heat capacity to represent the phase change process [kJ/kgK]
λ:	thermal conductivity [W/mK]
λ_{solid}, λ_{liquid}:	thermal conductivity in solid / liquid state [W/mK]
$\lambda_{latent}(\theta)$:	thermal conductivity during the phase change process [W/mK]
h:	enthalpy [J]
m:	mass [kg]

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