Performance Analysis and Energy Saving Potential of Room Integrated PCM Wallboards for Passive Cooling Application

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Abstract. Phase Change Materials (PCMs) can enhance thermal mass and energy efficiency in lightweight buildings. In this work, the thermal behaviour of plasterboards with incorporated microencapsulated PCM is investigated. These PCM wallboards are mounted in office rooms of the Energy Efficiency Center (EEC) in Würzburg (Germany). The experimental results show that the PCM wallboards can provide a passive cooling power of up to 8.4 W/m². However, the regeneration behaviour of PCM during the night critically influences their thermal performance for the next day. In the period from April to September of the years 2015 and 2016, the average regenerated (solid) fraction of the PCM in the wallboards at the beginning of each day was only 20 %, even though the regeneration is supported by the nightly operation of cooling ceilings. In order to improve the thermal performance of the wallboards this problem has to be addressed. Therefore, a case study is performed with the thermal building simulation software TRNSYS 17. In this simulation, a night ventilation is used to enhance PCM regeneration, whereas active cooling by means of the cooling ceiling only takes place during the day. The simulations were carried out for two PCMs differing in the melting range. The simulation results reveal that the regeneration of the PCM wallboards could be increased by a factor of 2, which directly increases the latent heat storage capacity in rooms and reduces the temperature rise during daytimes. Compared to a reference room without PCM wallboards, the electrical energy demand for active room cooling is reduced by 30 %.

1. Introduction

Buildings account for approximately 40 % of the total energy use in Europe [1]. A significant amount of this goes to space heating and cooling. In order to increase the energy efficiency and the thermal storage capacity of lightweight buildings, phase change materials (PCMs) can be incorporated into buildings [2]. PCMs can reversibly absorb and release a high amount of heat in a narrow temperature range using the phase change between solid and liquid state. Room integrated PCMs can passively dampen temperature swings, ensuring better thermal comfort for occupants, while also reducing or eliminating the need for mechanical cooling. The integration of PCM can be achieved via separate building components, or as an additive to ordinary building materials, which makes them PCM-composite materials. Most commonly used PCMs in the building sector are paraffins (organic) and salt hydrates (inorganic). Unlike the inorganic PCMs, organic PCMs are available as microencapsulated material and can be integrated into building materials. Paraffins are chemically stable, non-corrosive (except for some plastics), and usually have low or no subcooling [2]. The most relevant drawbacks of the organic materials are flammability and low thermal conductivity. Wallboards used for our
investigations are plasterboards containing microencapsulated paraffins for latent heat storage [3]. In order to investigate the thermal behaviour of the PCM wallboards, experiments were carried out in office rooms of the Energy Efficiency Center (EEC) of ZAE Bayern in Würzburg, Germany [3]. The investigation addressed the passive cooling capacity of PCM wallboards and their regeneration behaviour [3]. Moreover, for comparison, measurements were conducted in a reference room with a standard gypsum board wall and a gypsum board/concrete wall, respectively, in order to evaluate the effectiveness of PCM wallboards. In addition to the experiments, a simulation was performed on an EEC building model with TRNSYS 17, with the aim to investigate the potential enhancement of the PCM regeneration using a night ventilation.

2. Experimental scenario and results
The Energy Efficiency Center is the R&D building of the ZAE Bayern in Würzburg, Germany [4]. The building uses several thermal energy storage technologies such as phase change materials (PCMs) in wallboards and cooling ceilings in rooms. A floor plan of the south-facing test rooms R110 and R112, which were used in the experimental investigation, can be seen in Figure 1. The area of each partition wall is 16.90 m², with a width of 5.93 m and a height of 2.85 m. The room R110 serves as a reference room and contains no PCM wallboards; it has a lightweight wall with conventional gypsum boards on the west side, while gypsum boards are mounted on a concrete wall (thickness of 15 cm) on the east side. In R112, east and west walls are equipped with Knauf Comfortboard-23 (PCM-A) from Knauf Gips KG, Iphofen, Germany. In addition, both test rooms are equipped with a cooling ceiling. R110 is equipped with a conventional cooling ceiling (Plafotherm E200 from Lindner Group KG, Germany), whereas in R112 a modified cooling ceiling with macroencapsulated PCM, described in detail in [5], is mounted.

Figure 2 shows the enthalpy H(T) and a picture of PCM-A wallboard (Knauf Comfortboard-23); it has a thickness of 12.5 mm and contains 80% gypsum and 20% microencapsulated paraffin. As one can observe from Figure 2, the phase change temperature range is between 17.5 °C and 23.5 °C and within this range, the latent heat storage capacity of this wallboard is 200 kJ/m². Thermal conductivity of this wallboard is 0.23 W/(mK). During the melting process (red line in figure 2a), the material changes its phase from solid to liquid while storing heat. During the solidification process (blue line) it releases the stored heat to the environment and the material becomes solid again. PCM-A exhibits almost no subcooling and its solidification starts at 23.5 °C. The main goal of the experimental work was to investigate the effectiveness of PCM wallboards in lightweight buildings. The experimental setup, measurement strategy, and results are comprehensively described in [3]. The experimental results showed that PCM-A wallboard can provide a passive cooling power of around 8.4 W/m² [3], which equals to about twice the cooling capacity of conventional gypsum boards with measured 4 W/m².
In addition, PCM-A provides a passive cooling power which is comparable to a concrete wall (with up to 9 W/m²) with a thickness of 15 cm [3]. As stated before, rooms are equipped with cooling ceilings, and these ceilings can be used to actively cool the rooms during nights to support PCM regeneration. During summer, cold water circulated in the cooling ceilings with an inlet temperature of 16 °C to 17 °C to support and accelerate PCM regeneration in the wallboards. Additionally, all office rooms in the EEC are connected to the central ventilation system with the standard air change rate for office rooms. To evaluate the regeneration behaviour of the PCM in the wallboards, the lowest PCM temperature after the active cooling period (generally between 06:00 to 07:00 am throughout summer) was identified for every day between April and September of the years 2015 and 2016. After finding the initial, i.e. lowest, PCM temperature in the morning, the enthalpy $H_i$ at that point can be derived using following equation:

$$H_i = \frac{(H_1 - H_0)}{(T_1 - T_0)} \cdot (T_i - T_0) + H_0$$

where $T_i$ is the PCM wallboard temperature in the morning after regeneration, $T_0$ and $T_1$ are the next lower and higher temperature point after $T_i$ in enthalpy temperature graph in Figure 2(a) and $H_0$ and $H_1$ are the corresponding enthalpies at the temperature points $T_0$ and $T_1$. Then the total amount of solid PCM in the wallboard can be calculated using the following relation:

$$\text{Percentage of solid (\%) } = \frac{\Delta H - H_i}{\Delta H} \times 100$$

where $\Delta H$ is the total enthalpy of PCM wallboard in the melting range.

In R112 with PCM-A, the average obtained regeneration was only 19 % for both years [3]. It indicates that the cooling power during the night from active cooling ceiling is not sufficient to regenerate the PCM in the wallboards. Hence, only a small part of the latent heat storage capacity of the PCM wallboard is actually used. This “regeneration problem” must be addressed in order to use PCMs in such passive cooling applications.
3. Simulation model validation

3.1. Building model
The investigated regeneration behaviour of PCM-A in R112 shows that the regeneration of PCM-A wallboard is problematic, and complete regeneration was never achieved. Hence, in order to investigate different techniques, which can enhance the regeneration, thermal building simulations were carried out using TRNSYS 17. The building model used for simulation is shown in Figure 3. The model is a typical building segment of the Energy Efficiency Center with a north and a south facing room. For this research, only the south facing room was used, which is identical to the reference room R110 (explained in section 2) and can be seen in Figure 3(b). The total area of the two windows is 6.44 m² with triple glazing (4-16-4-16-4) and an Ug-value of 0.7 W/(m²·K).

![Figure 3](image)

**Figure 3.** (a) Simulation building model of the test room within the EEC building; (b) South facing room for analysis.

3.2. Validation model and results
The presented simulation validation is based on the test room R110, which is a reference room with a standard cooling ceiling and whithout PCM (explained in section 2.1). In the simulation, weather data of Würzburg, Germany was used. For the validation, real measurement data were imported in the simulation to define the boundary conditions of the simulated room. The boundary temperatures of the walls, the floor and the ceiling in the zones were also applied from the measured data. Ventilation, infiltration, internal heat gains, as well as position and angle of the outer blinds were given from the actual data as well. The total validation period was two weeks in summer 2015. The first twelve days were used as a preliminary lead time for the transient response of the building, whereas the last two days were used for the validation. During these two validation days, the room behaviour was measured under defined boundary conditions such as constant heat loads in room, without users influence and with closed window blinds. One of the validation objectives is to assess the thermal capacity of the real test room. The thermal capacity of the room is a combination of the heat capacity of zone air node and all the thermal storage masses in the room. The heat capacity was set to a value of 600 kJ/K. The response of the model was compared to real measurement data and the results for the operative room and wall temperature are shown below in Figure 4. The root mean square error (RMSE) indicator is used to evaluate the validation model using (eq. 3).

\[
RMSE = \sqrt{\frac{\sum_{r=1}^{n}(A_r - S_r)^2}{n}}
\]  

where \(A_r\) are actual measurement results, \(S_r\) simulation results and \(n\) is the total number of results.
A perfect match between simulation and measurement data would provide an RMSE value of 0. Achieved RMSE values in this study are 0.241 and 0.052 for operative room and wall temperatures, respectively. As a consequence, it is proven that the simulation building model represents the thermal behaviour of the real office room R110 of the Energy Efficiency Center in good approximation.

**Figure 4.** Comparison of validation model outputs and measurement results (a) operative room temperatures and (b) wall temperatures for typical summer days (11th–12th July 2015)

### 4. Simulation with PCM wallboards

In order to overcome the problem of PCM solidification with PCM-A in R112, in the simulation, a scheduled night ventilation with different air changes is used. The simulation was carried out for the whole summer from 1st May until 30th August. Besides that, the simulations were carried out with internal gains of 800 W (400 W of radiative gain and 400 W convective gain) from 8 am to 6 pm. In the simulation model an equivalent cooling ceiling is used as in the real building. However, the cooling ceiling is only used during the daytime and only starts when the room temperature is above a specific set point. Hence, we compare the behaviour of PCM wallboards for four different setpoints in the simulation (24 °C, 25 °C, 26 °C and 27 °C). External blinds are also implemented in the model room and kept close if the total solar radiation on the glazing exceeds 180 W/m². In the model, the east and west wall are equipped with PCM wallboards and are modelled with the TRNSYS PCM-Type 399 as a passive component. In the simulations, two different wallboards are used. The first wallboard is PCM-A the second wallboard is PCM-B. The latter is a hypothetical PCM-A board with a shifted latent heat storage range between 20.5 °C to 26.5 °C. The material starts to store latent heat at 20.5°C reaching its maximum heat storage capacity at 26.0 °C. This range indicates that the PCM material is fully solid below 20.5 °C and completely melted above 26.5 °C. The other technical properties of this PCM-B board are identical to PCM-A, as explained in section 2.1 except for the shift in the temperature range.

The following simulation scenarios are investigated:

1. both walls with PCM-A, with enhanced night ventilation,
2. both walls with PCM-B, with enhanced night ventilation,
3. one wall with PCM-A, one wall with PCM-B (Mix PCM), with enhanced night ventilation,
4. without PCM wallboards, with enhanced night ventilation and
5. without PCM wallboards, with standard night ventilation (without enhanced night ventilation)

In simulation scenarios 1 to 4 (PCM-A, PCM-B, Mix PCM and no PCM) the night ventilation uses outside air and is set to monthly changing air change rates. In detail, the air change rates are 3/h and 4/h for the months May and June, respectively, while in July and August the value 5/h is used. For comparison reasons, simulation 5 was carried out without PCM wallboards and without enhanced night
ventilation only standard ventilation (unoccupied time of the office 18:00 to 08:00, with air change rate of 0.24/h according to the German norm DIN 1946-6).

4.1. Simulation results
One of the purposes of this simulation is to quantify improvements of the PCM wallboard regeneration behaviour by employing a night ventilation. For this purpose, the time-dependent PCM temperatures of the whole simulation are analysed. The ventilation boosts the heat discharge from the wallboards and reduces the PCM wallboard temperature significantly. For each day, the lowest PCM temperature after ventilation was identified (explained in section 2). The resulting data as a whole for simulations 1 and 2 is depicted in Figure 5. The box plot shows the solid PCM percentage in wallboards after regeneration with an enhanced night ventilation for the whole simulation period. The upper and lower whisker show the absolute maximum and minimum achieved regeneration. The box itself stretches from the 25 percentile to the 75 percentile and thus represents 50 percent of the values. The line represents the median of the data and the red point shows the achieved average regeneration percentage. The regeneration behaviour was investigated for the scenario with a cooling ceiling setpoint of 26 °C). As shown in the Figure 5, the regeneration of PCM-A is significantly improved compared to the experimental results. The average regeneration reached approx. 45 % to 50 % for PCM-A. This corresponds to an improvement of a factor 2.5 compared to the measured value of 19 % [3]. Besides that, the modified wallboard PCM-B exhibits a significantly higher regeneration with an average of approx. 90 %. Therefore, the higher melting range compared to PCM-A translates well to an expected higher regeneration value.

5. Thermal cooling energy saved by using PCM wallboards
The results indicate that regeneration is significantly improved using an enhanced night ventilation. In this section the effect on the active cooling power consumption in the room is evaluated for all scenarios with the different combinations of PCM wallboards Figure 6 shows the thermal cooling energy demand in the rooms with different cooling setpoints. The cooling energy consumption indicates the thermal cooling energy demand in the room to maintain the setpoint temperature hence the lower energy consumption clearly shows the effectiveness of PCM wallboards for room applications. As one can observe from the Figure 6, rooms without PCM wallboards (with night ventilation and without night ventilation) always consume more cooling energy than a room with PCM wallboards. At setpoint 27 °C and setpoint 26 °C, room with PCM-B and mix PCM wallboards are more efficient than PCM A, because of a higher melting range of PCM-B. In contrast, at setpoint 24 °C the room with PCM-A is more effective because the latent heat storage capacity of PCM-B is hardly used.
Figure 6. Total cooling energy consumed from cooling ceiling during the day with different setpoints and different PCM configurations throughout the simulation.

6. Electrical energy saved using PCM wallboards

It is now clear that night ventilation can improve the PCM regeneration and decrease the cooling energy demand. To evaluate the actual impact of the PCMs, the electrical energy saved using PCM in rooms was calculated. This includes electrical consumption for compression chillers and pumps. The cold generation during the day from compressor chiller was calculated with EER of 3.5, which is a typical value of the installed cooling system at ZAE Bayern. After calculating the electrical energy demand of the compression chiller, the electrical pump power was calculated according to DIN V 18599-7 using equation 4 [6].

\[ P_{el.pump} = \left(1.25 + \left(\frac{200}{P_{hydr}}\right)^{0.5}\right) \times 1.2 \times P_{hydr} \]  

(4)

Where, \( P_{el.pump} \) is the electrical pump power, and \( P_{hydr} \) is the hydraulic pump power in W.

Table 1. Electrical energy consumption for cooling energy generation with different setpoints during the whole year in kWh

|                     | Setpoint 24 °C | Setpoint 25 °C | Setpoint 26 °C | Setpoint 27 °C |
|---------------------|---------------|---------------|---------------|---------------|
| PCM-A – With Night Ventilation | 182.0         | 115.2         | 65.5          | 29.8          |
| PCM-B – With Night Ventilation | 215.1         | 121.8         | 53.9          | 20.2          |
| Mix PCM – With Night Ventilation | 189.8         | 113.5         | 57.4          | 21.1          |
| No PCM – With Night Ventilation | 231.0         | 148.3         | 81.1          | 36.2          |
| No PCM – Without Night Ventilation | 271.6         | 197.5         | 131.9         | 81.8          |

As one can observe from Table 1 and Figure 7, rooms with PCMs always reduce the electrical energy consumption for the cold production and distribution during the day time. Figure 7 shows the percentage electrical energy savings in a room using PCM wallboards compared to a room without PCM wallboards (all scenarios with night ventilation). These energy savings are electrical energy savings to generate and to distribute the cold during the day. PCM-A shows higher relative energy savings than PCM-B for cooling setpoints of 24 °C and 25 °C, PCM-B is clearly favorable at cooling setpoints of 26 °C and 27 °C. Additionally, the Mix PCM is a good compromise for all cooling setpoints. Hence, it is evident that the PCM-wallboards can reduce the electrical cooling demand.
7. Conclusion and recommendations

The primary goal of this work was to investigate the effectiveness of PCM wallboards in lightweight buildings and the improvement of the regeneration of PCM wallboards by using an enhanced night ventilation. Therefore, an experimental investigation has been carried out on a PCM-A (Knauf Comfortboard-23). The analysis of monitoring data from the years 2015 and 2016 revealed that the regeneration behavior of the PCM inside the wallboard is problematic. The average regeneration of PCM-A wallboard during the summer months was below 20%. To investigate measures to boost the regeneration, a thermal building simulation was carried out with TRNSYS 17. Simulation results show that by using proper night ventilation, average regeneration values can achieve 45% to 50%. The fictive wallboard PCM-B with the melting range shifted to higher temperatures shows an average regeneration of about 90%. In terms of electrical energy savings, a room with PCM-A wallboards can decrease the electrical energy demand for active cooling by a cooling ceiling by approx. 30% at cooling setpoints of 24 °C and 25 °C, while it is less favorable at higher cooling setpoints. A room with PCM-B is very efficient in reducing the energy demand at higher cooling setpoints, while it is less favorable at lower cooling setpoints. A mix of both PCMs showed very promising energy savings properties for all investigated cooling setpoints.

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