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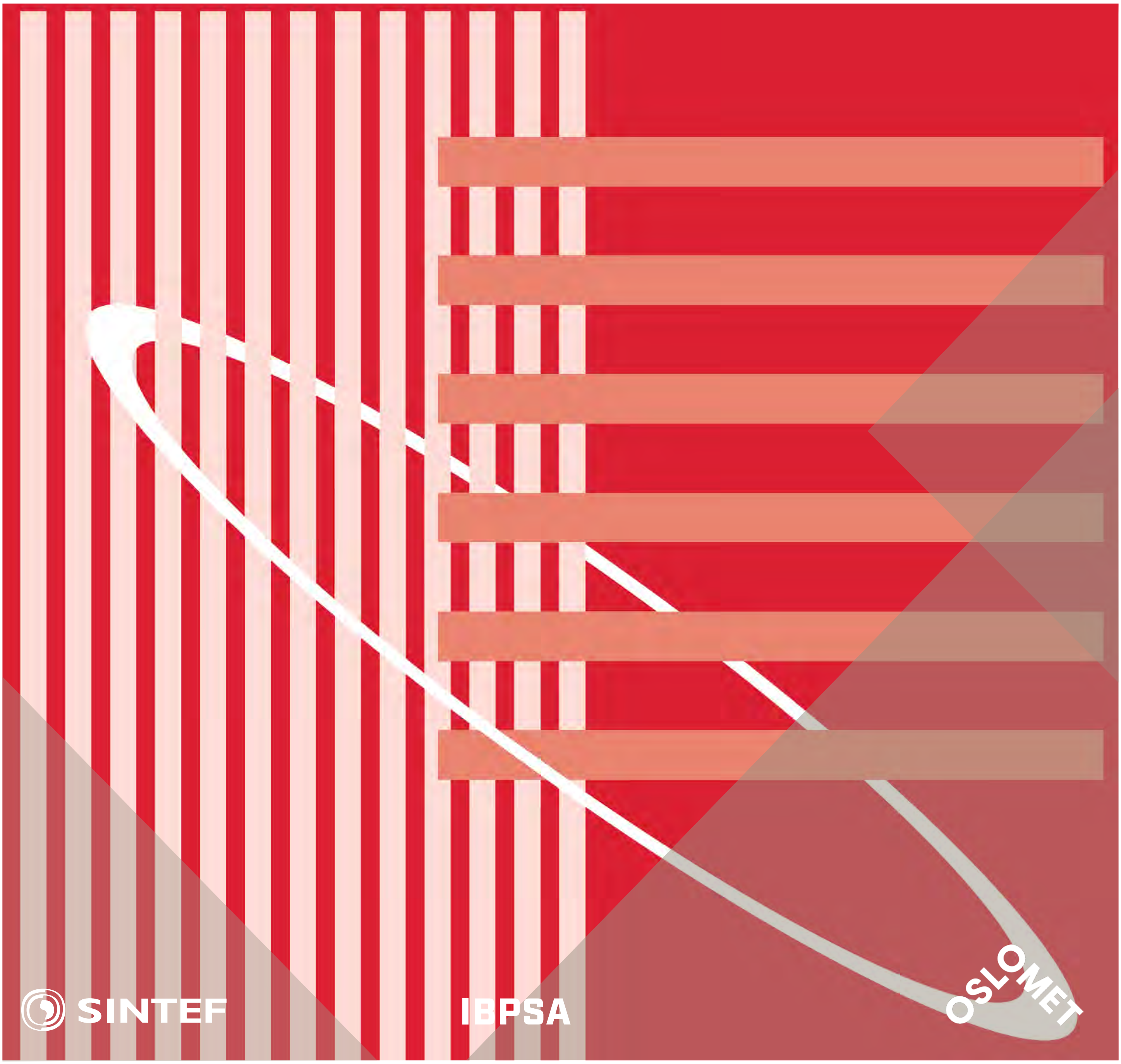

SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

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Experimental and numerical studies on thermal performance of an office cubicle having gypsum boards coated with PCM-enhanced spackling

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Abstract

PCM enhanced wallboards on internal surfaces of building spaces is an attractive solution for improvement of thermal performance in buildings. This work deals with using a novel spackling compound as a primer coating material, from Gyproc Saint-Gobain, Sweden AB, in the inner walls of building envelopes for passive cooling and thermal comfort management. The spackling compound contains fillers, rheological additives and binding agents together with micro-encapsulated PCM. Experimental measurements and numerical simulations are performed for an office cubicle having 14 m^2 floor area with and without PCM enhanced spackling material. PCM enhanced spackling has been applied on the internal walls and ceiling surface. The results show that a significant cooling effect could be achieved when covering walls and ceiling with PCM enhanced spackling directly exposed to the occupied zone. Furthermore, a parametric study shows that the PCM's thickness, and the nighttime ventilation airflow rate and supply air temperature have considerable impact on the cooling performance.

Introduction

In recent years, the construction industry gained a worldwide attention towards improvement of energy efficiency and innovation. The global challenges for construction engineering encompass research areas in all phases of the building process, starting from planning to final disposal of the building (Casini (2016)). Progress in material science and technology can provide innovative, sustainable, and environmentally friendly solutions to meet such global challenges. Incorporation of phase change materials (PCMs) in building elements essentially increases the thermal mass and are used in latent thermal energy storage systems and thermal management systems (Madessa (2014), Vik et al. (2017)). PCMs are widely used in construction materials e.g. HVAC systems, floors, ceilings, roofs, concrete, drywalls, coating plasters blends etc. Among these, PCM enhanced wallboard in the interior side of the building envelope is the most common solution for implementing PCM into building elements (Kalnæs and Jelle (2015)). Microencapsulation is the most effective way to integrate PCM into building materials. Several researchers have studied the benefit of PCM incorporated gypsum boards (Feldman et al. (1991), Athienitis et al. (1997), Neeper (2000), Zhang et al. (2012), Borreguero et al. (2010)) in the interior. Nevertheless, dependencies of the thermo-physical properties and overall energy performance on different wt% of PCM incorporated in a composite material are the most important aspects toward the optimal and cost effective PCM loading. The key challenges are to improve the overall lower thermal conductivity and latent heat of a PCM incorporated composite as well as to meet the fire safety requirements.

However, bulk production of microencapsulated PCM (MPCM) incorporated gypsum boards incurs a high production cost. An interesting cost effective alternative is to make a suitable spackling mixture incorporated with MPCM. This work is motivated by the recent novel spackling compound produced by Scanspac (Saint-Gobain Sweden AB, 2020) as a primer coating material in the inner walls of building envelope (walls/ceilings about 1-3 mm thickness) toward efficient thermal management by passive cooling/heating. The coating could be applied on gypsum boards, plaster boards, concrete or bricks. It is to be noted that, spackling compounds are often used in the interior surface of building envelope to repair defects of the surfaces. These compounds are typically made of (Kurp (2003)) binders, clay, lubricant, stabilizer, thickeners etc. Spackling materials could be of different application types and densities. For example, "lightweight" spackling is suitable for minor repairs. On the other hand, "heavy duty" spackling is relatively denser and more suitable for covering nails, drywall screw holes, filling significant depressions and holes of wall board (Foster and Bonifas (2010)). US patent (Gozum and LaFleur III (2016)) reported the self-priming spackling compound which yields consistent and uniform appearance when painted. The spackling compound used in this study contains fillers, MPCM, rheological additives and binding agents. To the best of our knowledge, there is no literature about the MPCM enhanced spackling material and its usage for thermal management in building applications. In this work, we present an experimental and numerical analysis of the aforementioned novel spackling material towards efficient thermal performance in buildings. The work is organised as follows. In section Methodology, we first present the overall experimental setup followed by the numerical setup for the present work. The analysis is presented in sections Results and Discussions. Finally, conclusions are drawn at the end.

Methodology

The impact of the PCM spackling material on the operative temperature of an office cubicle is measured in a full-scale test room. The measurements are also used to validate a numerical model of the lab experiment in IDA ICE. Measurements of temperature in the test room were performed with and without PCM spackling on wall and ceiling surfaces.

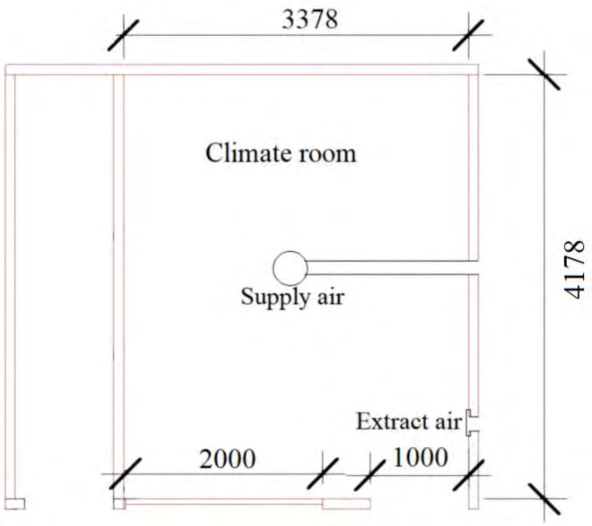
Experimental setup

The test room is located inside an indoor climate laboratory at OsloMet. The test room is separated from the laboratory room by roof, floor and walls. On one of the walls, there is a (1 x 2) m^2 door and a (2 x 2) m^2 window towards the laboratory room. The floor area of the test room is 14 m^2 and the room height is 2.34 m. The room height of an office cubicle is normally higher than in the test room, usually around 2.7 m. Due to stratification it can be assumed that the measured air temperatures in the occupied zone were slightly higher than what would have been in a room with a higher ceiling. Figure 1 shows sketches and a photo of the test room and the test setup. Table 1 shows the internal heat loads of the office cubicle, together with important design data. There is also some heat gain from measurement devices and electronic control equipment, amounting to approximately 40W.

The floor, ceiling and walls of the test room are made of sandwich elements consisting of 100 mm thick polyurethane foam covered with thin metal plates on both sides. Inside of ceiling and walls there is an uninsulated wood frame (between 48 and 73 mm thick) and 13 mm thick gypsum boards. The gypsum boards were covered with approximately 1.8 mm thick PCM spackling and a layer of white painting. The floor consists of a wood parquet on top of the polyurethane foam element.

The test room is equipped with a mechanical balanced ventilation system, a diffuser for supply air in the ceiling and exhaust at ceiling level on the wall.

Internal heat loads for the cubicle are listed in Table 1. Lighting load was provided by two fluorescent lamps. Occupants and equipment corresponds to two persons. As illustrated in Figure 1, heat load from occupants and equipment was provided by vertical cylindrical ventilation ducts with heating elements inside and matt black outside surface. Solar heat load corresponds to a south facing window of (2 x 2) m^2, with automatically controlled external solar shading, at midsummer at Oslo airport Gardermoen. A simplification is made by distributing the diurnal solar heating energy as a constant load of 200 W within the business hours of the office.



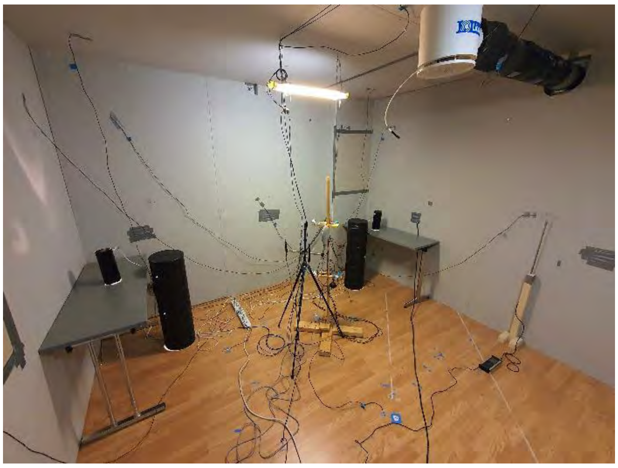


Figure 1: sketch (above) and a photo (below) of test room and setup (dimensions are in mm).

Table 1: Input data of the office cubicle

Parameter	Value
Supply air temperature for business hours [°C]	19
Supply air temperature for non-business hours [°C]	14
Supply airflow for business hours [m^3/h]	135 (3 l/sm^2)
Supply airflow for non-business hours [m^3/h]	230 (5 l/sm^2)
Heat gain from computers [W/m^2]	9
Heat gain from occupants [W/m^2]	13
Heat gain from lights [W/m^2]	4
Heat gain from sun [W/m^2]	14
Schedule business hours	08:00-18:00
Schedule non- business hours	18:00-08:00
Infiltration [ACH] @ 50 Pa	3.4
U-value (door/window) [W/(m^2K)]	0.6/0.8
U-value (wall/ceiling/floor) [W/(m^2K)]	0.20/0.20/0.21

This heat load was provided by an electric heating foil placed on the inside of the window. The window pane was covered with aluminium foil in order to reduce radiation heat loss from the heating foil through the window.

The PCM spackling consists of an ordinary spackling to which encapsulated micro size PCM spheres is added. Key data of PCM and spackling are listed in Table 2.

During the test, air temperature was measured in the supply air duct, and in the middle of the test room at 0.6 m above the floor. The test room's internal wall surface temperatures, as well as the top surface of the PCM in the suspended ceiling and the surface of the PCM in the wall were also measured. Both the air and surface temperatures were measured by T-type thermocouples, having +/- 1.5 °C uncertainty. The thermocouples were logged by an Intab PC-logger 3100i which was operated by Intab EasyView software version 5.6. Most of the measurement points are shown in Figure 2.

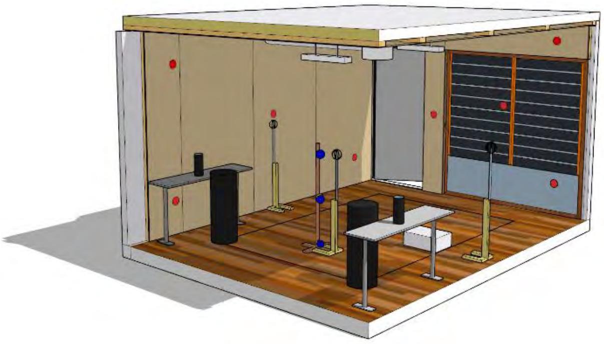


Figure 2: Measurement points (red and blue circles).

The air velocity during the experiment was measured lower than 0.2 m/s. Thus, the operative temperature can be calculated as an average of the calculated mean radiation temperature and the measured values of air temperature at 0.6 m above floor level. The mean radiation temperature is calculated from measured surface temperatures and view factors of the surfaces exposed to a person sitting in the middle of the room:

$$\overline{T_r^4} = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots T_N^4 F_{p-N} \qquad (1)$$

Where $\overline{T}_r$ is the mean radiation temperature (K), T_N is the surface temperature of surface N (K), and $F_{p\text{-}N}$ is the view factor between a person and surface N (Standard Norge, 2001).

Numerical simulation

In the numerical analysis, IDA Indoor Climate and Energy 4.8 (IDA ICE) software (Equa, 2020) was used to study the performance of the PCM enhanced spackling. First, the PCM wall extension in IDA ICE was validated against measurement data. Then, parametric analysis was conducted in order to study the effect of different design parameters on the spackling performance.

PCM wall model validation

The measured average indoor air temperature of the office cubicle was used to validate the PCM wall model behaviour in IDA ICE. The PCM wall model has been developed for years and is now available in the Expert edition of IDA ICE. The wall model uses an enthalpy formulation method, considering the temperature dependence of the enthalpy of a PCM during melting and solidifying phases, and solves the heat transfer equation using the finite difference method.

The cubicle was considered as a single thermal zone, as shown in Figure 3, and all the design parameters used in the experimental test, including air flow rate, ventilation schedule and supply air temperatures, and internal heat loads were employed as input data for the validation. Since the cubicle is placed inside a laboratory room, the surrounding conditions are represented by the temperature of the laboratory room. This varied between 22.2 °C to 22.6 °C.

In the simulation, the heating mat that approximate the solar heat load was replicated by placing an electric radiator of the same surface area as the heating mat. Moreover, in our numerical analysis we approximated the internal heat load from measuring devices to 3 W/m^2.

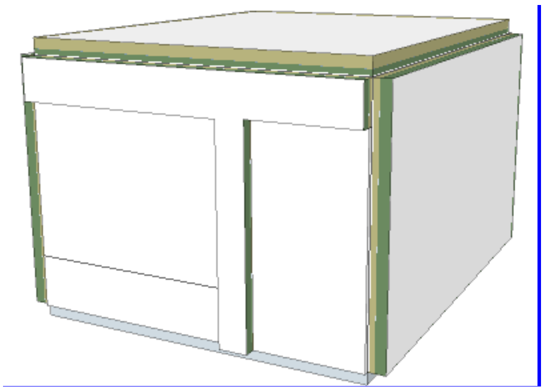


Figure 3: Office cubicle designed in IDA ICE

Consistent to the PCM layer implemented in the experimental test, 2.10 mm and 1.75 mm PCM layer thickness was applied on the ceiling and the wall surfaces respectively. Variation of specific heat capacity of the PCM with temperature, as shown in Figure 4, was also employed in the PCM wall model. The model uses discrete points to approximate the temperature dependency of the specific heat capacity curve within the temperature range of the curve. Other thermo-physical properties of the PCM are shown in Table 2.

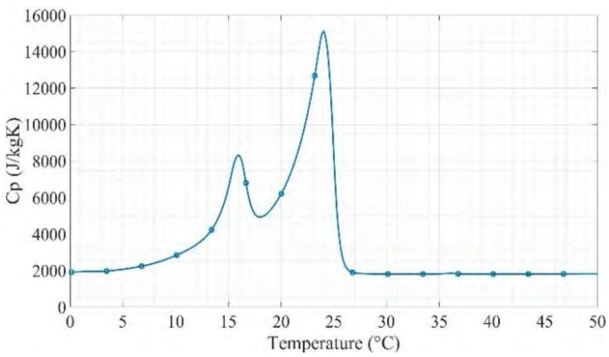


Figure 4: Specific heat capacity vs temperature of the PCM spackling measured using differential scanning calorimetry test (Saint-Gobain Sweden AB, 2020).

For validation purpose, a simulation was run for three days and the result was compared with the measurement as shown in Figure 5. The result showed that the simulated mean air temperature corresponds well with the measured mean air temperature, and the maximum relative error is about 6.6 % around at 19:00. It is important to note that the measured mean air temperature represents the average air temperature of the air temperatures measured at different heights of the cubicle.

Table 2: Thermo-physical properties of the PCM spackling (Saint-Gobain Sweden AB, 2020)

Property	**Value**
Density [kg/m^3]	970
Total heat storage capacity[KJ/kg]	88.4
Thermal conductivity, solid[W/m K]	0.08
Thermal conductivity, liquid [W/m K]	0.08
Onset melting point [°C]	20
Peak melting point [°C]	24

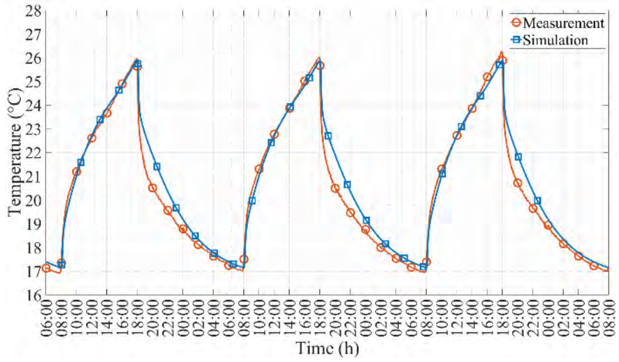


Figure 5: Comparison of measured and simulated data

Figure 5 shows a qualitative comparison of the measured and simulated values of the mean air temperature of the cubicle. An R^2 value of 0.976 implying that the variation in simulated temperature strongly corresponds with the measured temperature.

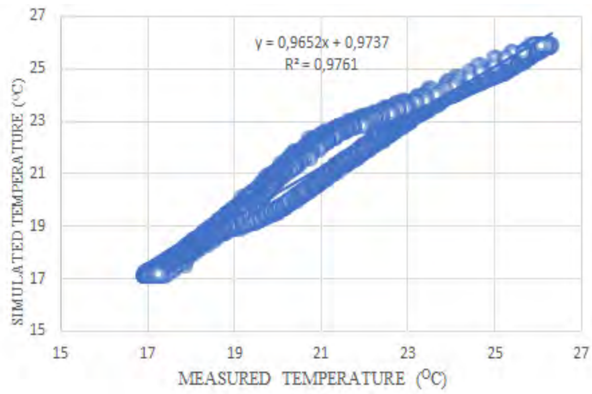


Figure 6: Scatter plot of measured and simulated indoor air temperature

Moreover, Coefficient of Variation of the Root Mean Square Error (CV_{RMSE}) approach using Equation 2 is adopted to check the deviation of the measured data from the simulated result. The CV_{RMSE} showed a 1.12 % error, which also indicates good accuracy of the model.

$$CV_{RMSE} = \frac{1}{y_m}\sqrt{\left(\sum_{i=1}^{n}\frac{(\hat{y}_i - y_i)^2}{n}\right)} \quad (2)$$

Where y_i is the simulated/predicted value, $\hat{y}_i$ is the actual/measured value, y_m is the mean of measured values, and n is the number of data points.

The validation results revealed that the PCM wall extension in IDA ICE replicates the measured data and it can also be used for further investigation of PCMs performances. However, it is important to note that the validation process investigated conditions typical for the summer season, and the validity of the model under other conditions is not guaranteed by this validation process. Future study should be devoted to extend the validation of the model.

Parametric design analysis

In order to study the effect of the spackling layer thickness, supply air temperatures, and the air flow rate on the performance of the spackling PCM, a parametric analysis was conducted for the same office cubicle designed for experimental test. In the analysis, only one of the design parameters was varied while the other design parameters were kept constant. Hence, in the first scenario, three PCM layers, with thicknesses of 2 mm, 3 mm and 4 mm were considered when the PCM was applied on internal walls and ceiling surfaces. The supply air temperatures and air flow rate for both business hours and non-business hours, schedules, and internal heat loads mentioned in Table 1 were used as input data.

In the second case, the thickness of the PCM layer was set to 3 mm and the supply air temperature for the non-business hours was varied between 14°C and 17°C, while the other design parameters were held constant.

The third scenario investigate the effect of the ventilation air flow rate during the non-business hours. The air flow rates were set to 135 m^3/h, 180 m^3/h, 225 m^3/h and 270 m^3/h. Again, a 3 mm PCM layer thickness was chosen, and all the other design parameters were kept constant.

All the three scenarios were identical in terms of construction materials, dimensions and configuration, and the parametric analysis focused on the temperature reduction potential of the PCM enhanced spackling compared to a reference case without PCM enhanced spackling.

Results and discussion

Experimental results

The experimental study was focused on the performance of the PCM enhanced spackling, in terms of reduction of operative and surface temperatures of the office cubicle.

Operative temperature

The operative temperature which is calculated from the measurements is depicted in Figure 7. The result revealed that adding the PCM spackling to the ceiling and wall surfaces reduced the operative temperature with 0.9-1.1°C, e.g. from 27.0°C to 25.9°C at day 1. The temperature reduction seems to be relatively constant between 14 and 16:00. It is also interesting to observe that the cooling impact of the PCM seems to start around 9:00 in the morning, at an operative temperature of about 20°C. The operative temperature during non-business hours is almost equal with and without PCM spackling. This indicates that the ventilation airflow rate during non-business hours is abundant in order to remove heat released from the PCM when the temperature in the cubicle drops.

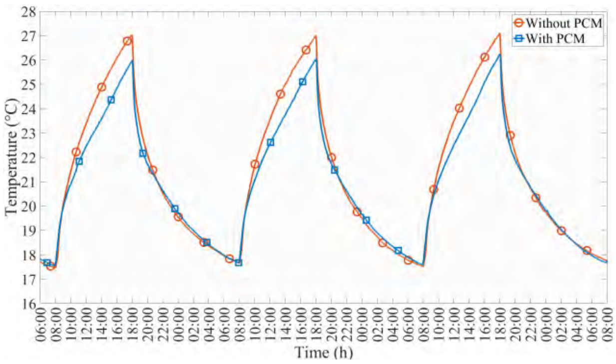


Figure 7: Operative temperature.

Surface temperature

Surface temperatures with and without PCM, in the ceiling and at the walls, are shown in Figure 8.

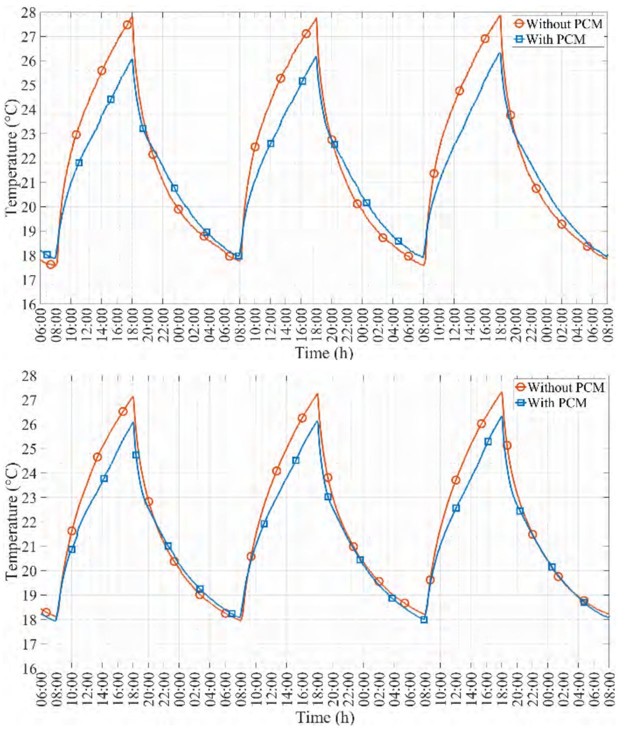


Figure 8: Surface temperature of ceiling (upper) and walls (lower).

The surfaces with PCM reached peak temperatures of between 26.0°C and 26.4°C, which is around the upper end of the transition area of the PCM, as shown in Figure 4. The impact of the PCM is significantly stronger in the ceiling than at the walls; the PCM reduces the surface temperature with about 1.6°C in the ceiling compared with about 1.0°C at the walls. This means that more of the cooling potential in the PCM in the ceiling has been utilized. The lowest temperatures in the morning varied between 17.8°C and 18.1°C. This is close to the lower end of the transition area of the PCM (see Figure 4). At the walls the temperatures measured with and without PCM are almost similar. In the ceiling, however, the temperatures measured with PCM are 0.2-0.3°C higher than without PCM. It is also interesting to observe that the cooling impact of the PCM seems to start around 8:30 in the morning, at a surface temperature of about 19°C. This corresponds well with the start of the transition period (see Figure 4).

Numerical results

The effect of the PCM layer thickness

Figure 9 shows compared results of the simulation run for a reference case without PCM and with three different spackling PCM layers applied on the ceiling and wall surfaces. The simulation is run for summer climate conditions in Oslo. The mean air temperatures of the cubicle increases from 08:00 until 18:00 following activation of internal heat gains. At about 09:00, the PCM starts to melt when the air temperature is 20°C, initiating a drop in the mean air temperature compared to the reference case. It is important to note that the maximum drop in mean air temperature happened at different hours for different PCM layer thicknesses. For the 4 mm thickness, the maximum temperature drop happened at 18:00, while for 2 mm PCM layer it happened at 14:00.

It has also been observed that the number of hours for the mean air temperature above 26ºC is zero for 3 mm and 4 mm layer PCM, while it was 4 hours for the reference case. This indicates that the PCM enhanced spackling has demonstrated the capability to sink peak indoor temperature.

In the non-business hours, it was also observed that the mean air temperature drop is more sluggish for the cases with PCM than for the reference case without PCM. This indicates that the PCM releases the absorbed latent heat to the surrounding by radiation and convection heat transfer.

This also indicates that the spackling layer thickness play an important role for the dampening effect of the temperature fluctuation, reduction of the cooling energy load of buildings and thermal comfort of occupants.

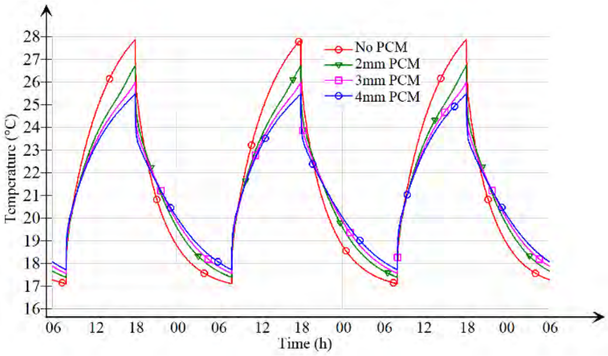


Figure 9: Air temperature variation with PCM layer thickness.

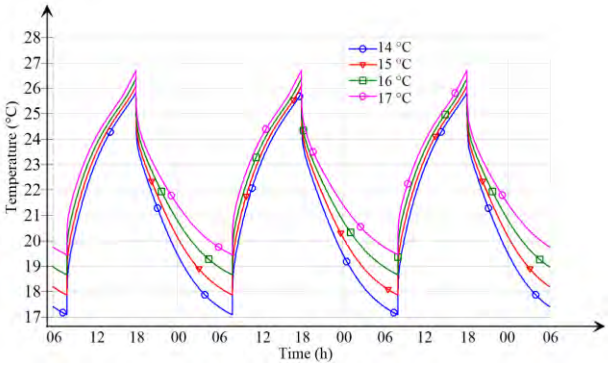


Figure 10: Air temperature variation with supply air set point.

The effect of the supply air temperature set point

The second scenario was to investigate the effect of the ventilation supply air temperature set point during the non-business hours. In this study, the air flow rate during the night was maintained at 230 m^3/h, while the supply temperature varied from 14°C to 17°C. It should be noted that 14 °C as a supply temperature is somewhat lower than what could be expected when applying night ventilation on a hot summer day.The result in Figure 10 depicts that having a lower supply air temperature assists the PCM to perform better. PCM loses heat and solidifies between 00:00 and 08:00.

During the daytime, 08:00-18:00, the PCM spackling absorb the heat available inside the cubicle, store it as latent heat and release it later in night to be ready to absorb heat on the next day. By doing so, the PCM can help to keep the room at a comfortable temperature.

The effect of the air flow rate during the night

In this scenario, the effect of the air flow rate of 135 m^3/h, 180 m^3/h, 225 m^3/h and 270 m^3/h were investigated for the non-businesses hour ventilation. As expected, Figure 11 shows that an increase in the airflow rate has assisted the PCM to reduce the air temperature during the day. This is, actually, due to an increase in the convective heat transfer coefficient between the exposed surfaces and the circulating air. The non-business hours or night time ventilation is important to remove the heat from the PCM, in order to make the PCM active for the next day operation.

It is evident that the parametric study showed that the PCM enhanced spackling has an effect on cooling energy saving during summer season. Therefore, for the PCM to have a better performance, it is vital to optimize its design parameters. For instance, an increase in the PCM layer thickness, does not necessarily reduce the air temperature accordingly. The amount of PCM applied on the walls and ceiling should be designed properly so that all the PCM can melt during the business hours and solidify during the night.

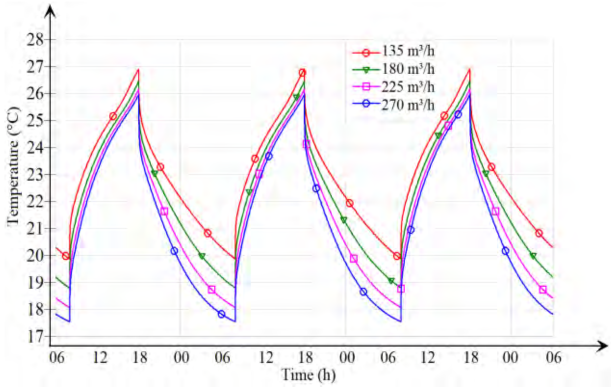


Figure 11: Air temperature variation with air flow rate.

Conclusion

In this study, experimental and numerical simulations were adopted to study the cooling potential of a PCM enhanced spackling manufactured by Scanspac. The spackling was applied on internal ceiling and wall surfaces of an office cubicle (14 m^2 floor area) exposed to Oslo summer climate. Initially, the PCM performance was tested in a full scale test room, then the measurement data were used for validating a simulation model in IDA ICE. Finally, a parametric study was conducted by varying the PCM's thickness as well as the nighttime ventilation airflow rate and supply air temperature. The following is a brief account of the findings:

- The results of the experiments showed that the PCM enhanced spackling has a significant potential for cooling.
- The experiment also showed that the cooling impact starts when the temperature of the spackling surface reaches 19°C.
- The simulation model works well and can be used to study performance of PCMs.
- The parametric study revealed that the PCM layer thickness, as well as the nighttime ventilation airflow rate and supply air temperature, play important roles for the positive impact of the PCM. This indicates that further research with multi-objective optimization is important.

Acknowledgement

This study utilized a novel spackling material supplied by Gyproc (Saint-Gobain, Sweden AB) and the authors of OsloMet greatly appreciate the successful collaboration with Gyproc. Mr. Håkan Söderblom deserves a special mention for his skilful work on building the walls and ceiling, and spackling and painting the surfaces. The authors would also like to thank Mr. Øystein Anderson (Senior Engineer) and Mr. Ernst Erik Hempel (Staff Engineer) of OsloMet for their support during the experimental work.

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