Experimental Investigation of PCM System Improved with Nighttime Ventilation for Enhanced Solidification

Eva Zavrl [a,b], *Mohamed* El Mankibi [c], *Mateja* Dovjak [d], *Uroš* Stritih [a]

[a] Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia, eva.zavrl@fs.uni-lj.si and uros.stritih@fs.uni-lj.si

[b] Institute for Innovation and Development of University of Ljubljana, Ljubljana, Slovenia, eva.zavrl@iri.uni-lj.si

[c] National School of State Public Works (ENTPE), Vaulx-en-Velin, France, mohamed.elmankibi@entpe.fr

[d] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia, mateja.dovjak@fgg.uni-lj.si

Abstract. It is predicted that in EU-buildings by 2030, the energy used for cooling will increase by 72%. Simultaneously, the energy needed for heating will drop by 30%. Thermally well-insulated lightweight framed buildings prevent heat losses through their envelope and reduce the energy demand over the heating season. However, the heat capacity of the lightweight wall is relatively low, and in summer, the building lacks thermal stability and overheats. Phase change materials (PCM) are broadly investigated for their well-known benefits of improving indoor thermal comfort by decreasing indoor temperatures while reducing the energy needed for space cooling when melting. One of the possible application methods is to encapsulate the material and place it in the 'building's building assemblies, such as walls and ceilings. However, due to a low material density (insulation effect) and high indoor temperatures on summer nights, the material does not completely solidify in the night cycle, and does not fully perform (melt) in the day-cycle. Thus, the nighttime outdoor air ventilation has to accelerate the solidification. The system is investigated in an experimental chamber divided into two units (reference and PCM modified). Each unit represents an office located in a South-Eastern Europe region with an above-average sun hours. Both units are equipped with a ventilation inlet (on the bottom of the wall) and outlet (in the middle of the ceiling). The internal wall and ceiling are entirely covered by macro-encapsulated PCM plates (SP24E) placed in the wooden frame. The original wall and ceiling are forming the airtight ventilation gap. In the nighttime cycle, the plates are being solidified with the linear diffuser (placed at the bottom of the wall), distributing the airflow behind the plates upwards (direction wall-ceiling). The results show that under the current configuration, the active-passive system decreases the indoor cell air temperatures in the hottest daily scenario up to 5 °C. Also, the complete PCM plates solidification may be accomplished within the nighttime cycle (12 h), when the air-gap is ventilated, average inlet air temperatures of 15 °C and 16 °C at a flowrate of 500 m^3/h.

Keywords. Phase Change Materials, Cooling Application, Nighttime Ventilation, Passive system, Enhanced Solidification
DOI: https://doi.org/10.34641/clima.2022.249

1. Introduction

For heating and cooling of the building sector, 40 % of final energy is used. This sector is one of the largest energy consumers in Europe, and it is responsible for more than one-third of the EU's emissions [1]. Due to global warming, the outdoor air temperatures in the summertime are increasing and with it the energy demand for cooling [2], [3]. In Europe over the last decade, the number of heating days in buildings decreased by 13 %, while by 2030, 72% increase in energy cooling demand is predicted [4]. Lightweight prefabricated buildings are popular structural concept. They have a skeleton structure with low-density thermal insulation as the prevailing material in wall composition. Often, they are designed with large window areas. Event thought in the heating season, the indoor building spaces are kept warm. In the cooling season, lightweight buildings easily overheat due to low thermal accumulation, which results in instant cooling demand to establish healthy and comfortable indoor conditions [5]–[7]. Besides bioclimatic architectural design, the buildings can be heated or also cooled by passive or active systems.

Passive building systems do not require a drive power, moving parts and controls for their function and demand little maintenance. In contrast, active building systems include mechanical systems for heating, cooling and ventilation (HVAC), illumination and are managed by control systems [8]. Such passive solutions are also Phase Change Materials (PCMs) integrated into building component such as roof, ceiling, internal and external walls and floor. However, many studies showed that PCM integrated into building components did not completely solidified over the nighttime cycle due to heat discharge indoors which results in deteriorated daily performance.

For example, in numerical investigation, Prabhakar et al. used the natural ventilation for enhancing the nighttime solidification of macro-encapsulated PCM plates (Rubitherm RT24 - 15 mm thick) and showed that in temperate climate nighttime ventilation increased the PCM performance from 3.32% to 25.62% [9]. Furthermore, Memarian et al. in Teheran summer and autumn studied DuPont Energain (5 mm thick PCM panel) experimentally and BioPCM (21 °C, 23 °C, 25 °C, 27 °C and 29 °C) numerically [10]. Several NV rates were tested (0 ACH, 1 ACH, 3 ACH, 5 ACH, 7 ACH and 10 ACH), and the combination of NaV at 5 ACH and BioPCM with melting point temperature (MP) at 29 °C provided 15% reduction in yearly energy consumption. In addition, the cooling effect of nighttime ventilation coupled with 5 mm thick PCM celling (MP: 26 °C, 28 °C, 30 °C and 32 °C) was simulated in six different cities in Kazakhstan (Nur Sultan, Karaganda, Kokshetau, Almaty, Aktobe and Atyrau; extremely hot to cold) by Adilkhanova et al. [11]. The natural ventilation was set to 8 ACH operating when indoor temperatures are 2 °C or higher from the outdoor. In Almaty and Aktobe with PCM MP 28 °C and natural ventilation, the maximum operative temperature was reduced up to cca. 5 °C. Similarly, the application of a 0.02 m thick layer of BioPCM25 to the ceiling and/or wall of the rooms was investigated under the Melbourne (Australia) climate conditions by Jamil et al. [12]. When the nighttime outdoor air temperatures dropped to 22 °C or lower the windows were opened for 20% which successfully contributed to the maximum daily temperature of 2 °C and more. Under the summer conditions in Lativa, Sinka et al. experimentally tested the performance of two PCMs (DuPont Energain and BioPCMQ25M51) applied in five materially diverse test buildings coupled with various HVAC systems. During the night, nighttime mechanical ventilation rate was set to 0.76 ACH and by additionally opening the windows, the BioPCM completely solidified, which resulted in 2 °C lower daily indoor temperatures.

However, PCM may also be cooled by applying the air locally. Many studies reported beneficial effects on solidification by ventilating the PCM enriched building components.

For instance, in Tianjin (China), Hou et al. and Li et al. experimentally investigated the thermal performance of a composite phase change ventilated roof [13], [14]. The melting temperature of the outer PCM layer was 32.55 °C and inner 24.12 °C. 1. Among the studied cases, the system reduced the indoor air temperatures by 34.4–47.0% (3.74–8.2 °C). Additionally, Alizadeh and Sandrameli measured the indoor thermal parameters of a PCM-based storage system with MP of 27 °C integrated with ceiling fan ventilation for enhanced nighttime solidification [15]. During summer period in Teheran (Iran), the peak indoor temperatures is decreased by 2.5 °C. Similarly, Weinläder et al. introduced a ventilated PCM (MP: 24 °C) ceiling for cooling application and monitored it over the summer in Munich (Germany) [16]. The ceiling air-gap was free ventilated (300 m3/h) in the nighttime, which corresponded to daily indoor operative temperature drop of 2 K (to 28 °C). Moreover, Jiao and Xu used EnergyPlus energy simulation software to simulate a simplified ventilated PCM ceiling (MP: 26 °C, 27 °C and 28 °C) at various night ventilation rates (5–20 ACH) combined with several window opening ventilation rates (3-8 ACH) [17]. The most effective PCM was with the melting temperature of 27 °C, which could keep the indoor temperatures within the recommended summer indoor thermal comfort range. Nevertheless, Evola et al. evaluated the performance of nighttime ventilated air gap in contact with PCM placed on the internal wall using Energy Plus located in Catania (Italy) [18]. The presence of the ventilated air-gap improved the daily PCM storage efficiency from 42.4% to 78.2%.

The present research introduces an active-passive system for cooling application (APS) combining the PCM plates on the internal wall and ceiling coupled with a locally ventilated air gap for improved heat transfer during the nighttime cycle. The cooling potential of the APS in the daily cycle is assessed by measuring the indoor air temperatures in test cells and the required PCM 'plates' solidification time during the nighttime cycle is determined by measuring the PCM surface temperatures. The results show that the APS decreases the daily indoor temperatures. With the proposed configuration and sufficiently low inlet temperatures, the PCM plates may be completely solidified over the night.

2. Method

2.1 Operation principle

The proposed diurnal APS system for cooling application consists out of a passive and active operation cycle. The left side of **Fig. 1** represents the passive daily operation cycle when PCM plates are melting and cooling the indoor space by accumulating heat from the space. The right side of the figure shows the active nighttime operation, where the air gap is ventilated and the PCM plates are solidified by the cool outdoor air (arrows: blue – cool outdoor air, yellow – slightly heated air and red – air fully heated by the plates and exhausted outdoors).

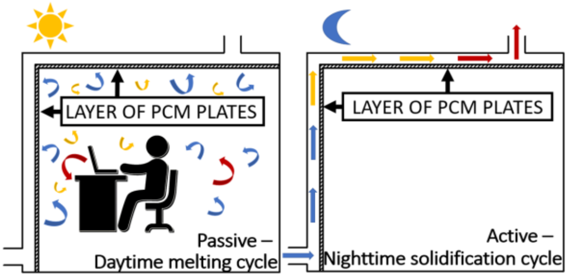

Fig. 1 – Principle of the APS for cooling operation

2.2 Experimental configuration

The APS system is located in the test facility named Hybcell at National School of State Public Works (ENTPE) in Lyon, France. Two identical test cells were monitored, cell A (PCM modified) and cell B (reference). **Fig. 2** shows the PCM modified cell.

Fig. 2 – Experimental facility (PCM modified cell)

The metal PCM plates are framed in the wooden substructure and form an airtight air-gap with the original wall (29 plates) and ceiling (38 plates) of the cell. The air-gap is nocturnally ventilated by the white linear diffuser inlet on the bottom of the wall. **Fig. 3** shows the main elements and dimensions of the PCM modified cell. The blue crosses in the figure represent the air temperature measuring points. The blue cross outlined with red represents the air thermometer positioned in the centre of the room (located in cell A and in cell B).

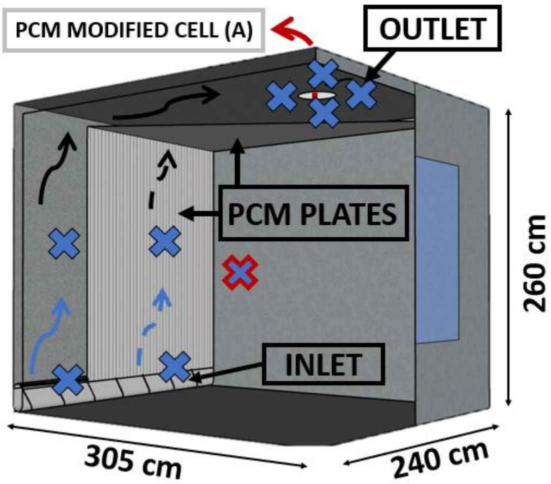

Fig. 3 – Sketch with elements of the PCM modified cell

The PCM plates are encapsulated in CSM aluminium cases (dimensions: 40x30x15 mm and weight: 2 kg) and filled with salt-hydrate SP24E (Rubitherm) [19]. The peak melting temperature is reached at 24 °C with storage capacity of 180 kJ/kg. The solidification occurs at 22 °C and 23 °C with storage capacity of 118 kJ/kg and 42 kJ/kg, respectively. The density of solid and liquid material is 1.5 kg/l and 1.4 kg/l, respectively with heat conductivity ~0.5 W/(mK). The melting point of the material is selected according to the thermal characteristics proposed for thermal comfort in hot summer periods in cooling season [20].

2.3 Experimental mechanical features and measuring equipment

Fig. 4 shows the schematic sketch of the experimental mechanical features for the establishment of the experimental conditions and locations of the air temperature, PCM surface temperature on the front (room side) and back (air-gap side) of the plates and velocity sensors. The air-gap was ventilated with conditioned and mechanically supplied air. The required air temperatures for nighttime solidification of the PCM were lower than indoor temperatures in test facilities, so the air had to be cooled and thermally stabilised by the air chiller located in the duct before the inlet fan. Two axial fans (300-3000 m³/h, 1500

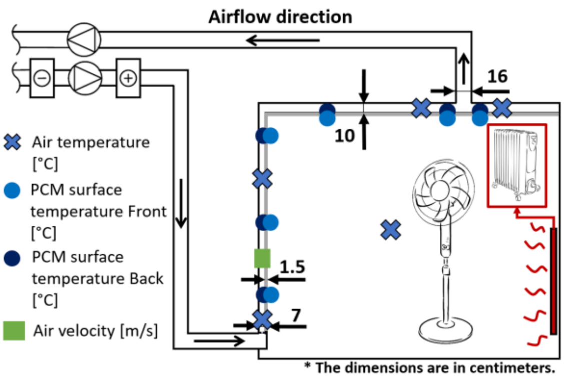

Fig. 4 - Experimental features and measuring points

Pa, 50/60 Hz) were located on the inlet and outlet duct, operating simultaneously. The cooled air was additionally conditioned with the spiral heating coil located after the inlet fan. The linear inlet diffusor was made by establishing a 1 cm thick opening along the entire 2 m long oval 5 cm wide duct component. It distributed the air along the air-gap separated into 5 channels.

The air temperature was measured in the air-gap determining inlet temperature, mid-air-gap temperature, outlet temperature using PT 100 sensor (DeltaOHM HD_35EDWH data accusation) in two points per height and in the centre of cell A and B with DeltaOHM HD_35EDG_1NB (acc.: ± 0.2 °C, range: 0…+60 °C) on 1.1 m height. The plates were monitored by measuring the front (cell side) and back (air-gap side) surface temperature in three points per height protected by aluminium tape to avoid the effect of radiation. The velocity was sampled at 1.3 m height in each channel and in the middle of the gap (average value of the channels is 0.9 m/s) with DeltaOHM HD403TS and DeltaOHM HD2903TO1 anemometers (acc.: ± 0.05 °C, range: 0.05…25 m/s). The volume flow rate was estimated to 500 m^3/h. Both cells were equipped with 2000 W heaters for simulation of the summer conditions and room fans for the establishment of the sufficient mixing of the air the cell.

2.4 Experimental protocol

The study presents two different sets of experimental results. The first set is purposed to show the cooling effect of the plates during the daily cycle when the PCM is melted. The heater in cell B was navigated to maintain the required set point cell temperature based on the air temperature measured in the centre of the room. The exact same amount of power was provided by the heater in cell A. The temperature difference between the measured values of air temperature in cell A and B was the cooling effect of the PCM plates. Three different set point temperatures were tested 26 °C, 30 °C and 35 °. Prior to the experimental case, the plates were cooled to 20 °C, to ensure the complete PCM solidification. The case was completed when the cell air temperature in cell A reached the cell air temperature in cell B. The room fans in cell A and B were switched ON during the entire test.

The second set of experiments aims to reveal the PCM solidification time required during the nighttime cycle. Prior to the experimental case, the plates were heated to 28 °C to ensure the completely melted PCM material and obtain the predicted indoor temperatures in summer. Afterwards, the plates were cooled with the average inlet air of 15 °C, 16 °C and 17 °C. The indoor temperatures were selected based on the Central European outdoor temperatures in summer (cooling season). The case was finalised, when the average PCM surface temperatures on the front and on the back of PCM plates' surface dropped to 18 °C or lower.

3. Results and Discussion

The results present daily operation of the APS during the PCM melting cycles and its nighttime operation during the application of the ventilation for enhanced PCM solidification.

3.1 Daily PCM melting cycle performance

The cooling effect of the APS system is determined based on the cell air temperature drop measured in cell A (PCM modified cell) in comparison to the cell air temperatures measured cell B (reference cell without PCM). **Fig. 5** shows the cell air temperature fluctuations (T_{a}) depending on the time during three different investigated cases (set point temperature in cell B 26 °C – light grey line, 30 °C – dark grey line and 35 °C - black line) where temperatures obtained in cell A are marked with dashed line and in cell B with solid line.

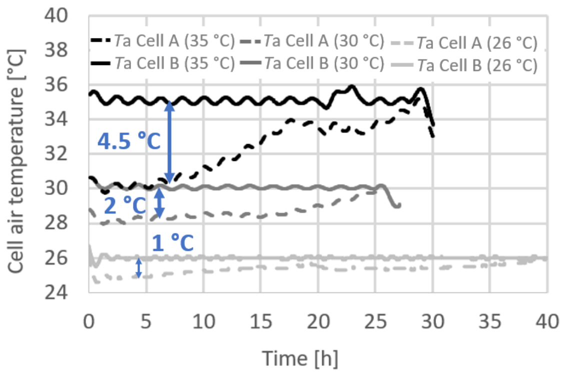

Fig. 5 – Cell air temperatures obtained during the daytime melting cycle in cell A and cell B

The results showed, that in all investigated cases, APS system with PCM plates decreased the daily cell air temperatures. The cooling effect of the plates is the strongest during the first hours of the experiment.

In the simulation case where air in cell B was heated to 26 °C ($T_{\mathrm{a\,CELL\,B\,26\,°C}}$), the cell air temperatures in cell A ($T_{\mathrm{a\,CELL\,A\,26\,°C}}$) dropped for 1.5 °C in first 3 h, for 1 °C between 3-10 h and later gradually increased from 1 to 0 °C in the last 10-40 h of the test. Since the heat added to the space is relatively little compared to the other cases, the $T_{\mathrm{a\,CELL\,A\,26\,°C}}$ are kept at cca. 25 °C during the entire time which is within recommended summer indoor air temperatures for thermal comfort (between 22 and 26 °C). Therefore, no additional space cooling systems need to be applied.

In the simulation case where air in cell B was heated to 30 °C ($T_{\mathrm{a\,CELL\,B\,30\,°C}}$), the cell air temperatures in cell A ($T_{\mathrm{a\,CELL\,A\,30\,°C}}$) compared to the reference cell differed for 2 °C in first 15 h and for 1.5 °C to 0 °C in 15-25 h. During the first 12 h, the $T_{\mathrm{a\,CELL\,A\,30\,°C}}$ were kept at 28 °C.

In the simulation case where air in cell B was heated to 35 °C ($T_{\mathrm{a\,CELL\,B\,35\,°C}}$), the cell air temperatures in cell A ($T_{\mathrm{a\,CELL\,A\,35\,°C}}$) dropped for 5 °C in first 5 h, from 5 to 2 °C in 5-15 h and later on increased from 2 -0 °C in

15-30 h. In this case, the cooling effect is the highest among all investigated cases. The indoor air temperatures $T_{a\ \mathrm{CELL\ A\ 35\ °C}}$ are kept between 30 °C and 31 °C during the first 12 h.

Since the cell air temperatures ($T_{a\ \mathrm{CELL\ A\ 30\ °C}}$ and $T_{a\ \mathrm{CELL\ A\ 35\ °C}}$) are higher from the recommended summer values for indoor thermal comfort, additional cooling devices such as air-conditioning device are required to decrease the indoor air temperatures. In cases with set point temperature in cell B fixed to 26 °C and 30 °C, the $T_{a\ \mathrm{CELL\ A\ 26\ °C}}$ and $T_{a\ \mathrm{CELL\ A\ 30\ °C}}$ are kept at constant decreased value where the melting cycle lasts more than 12 h. These results indicate, that the amount of PCM plates could be decreased for. However, the decreased amount of PCM plates could negatively affect the $T_{a\ \mathrm{CELL\ A\ 35\ °C}}$, which is kept at 30 °C in first 5 h and later starts to increase to 32 °C by the end of the daytime cycle at 12 h.

These results are in agreement with the results obtained from the other studies. For example, Weinläder et al. [16] used salt-hydrate with MP of 24°C attached only to the ceiling of the room and decreased the daily indoor tempeartures for 2 °C (to 28 °C), which corresponds to tempertures $T_{a\ \mathrm{CELL\ A\ 30\ °C}}$ obtained in cell A. Hou et al. and Li et al. used two PCM layers in the ventilated roof (MP external: 32 °C and MP internal: 24 °C) and thus, reached higher drop in indoor tempeartures [13,14]. Prabhkar et al. specified, that by adding the nighttime ventilation to PCM with MP of 24 °C, the daily indoor temperatures droppedfrom 3.3% to 25.6 % [9].

3.2 Nighttime PCM solidification cycle performance

The duration of the nighttime solidification is presented in **Fig. 6 –8**. The figures show average surface temperatures measured on the front (cell side) surface of the PCM plate (solid line), average surface temperatures measured on the back (air-gap side) surface of the PCM plate (dashed line) and inlet air temperature (dotted line) measured in the inlet of the air-gap depending on the time. The results are presented in separated figures during three different cases with average inlet air temperatures of 15 °C (light grey), 16 °C (dark grey) and 17 °C (black). The selected PCM material transfers to sensible phase at 21 °C. During the solidification cycles, a non-uniform temperature distribution along the PCM wall and ceiling in size of 1 °C was observed. Therefore, the blue dashed line designates the end time of the solidification cycle determined at 20.5 °C In all investigated cases, average surface temperatures measured on the front of the PCM plates strongly correspond to the average surface temperatures measured on the back, which indicates that the phase change quickly overcame the thickness of the plate.

Fig. 6 shows the average surface temperature on the front and backside of the PCM plates during the solidification with inlet air temperatures of 15 °C. The results show that under stable inlet temperatures the PCM was fully solidified already in first 5 h of the case, which is the shortest period among all investigated cases. In this case, the energy consumed for the fan operation could be decreased by reducing its power and volume air flowrate.

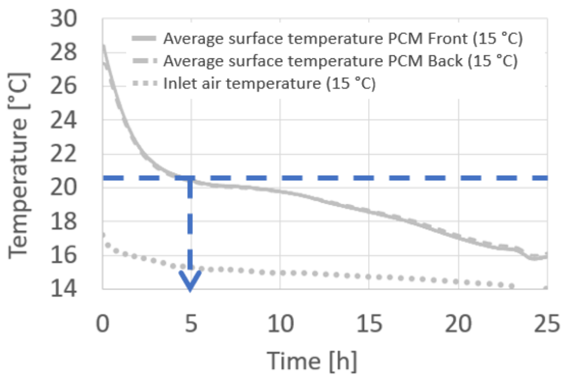

Fig. 6 – The average PCM surface temperatures and inlet air temperatures obtained during the case solidified with average inlet air of 15 °C

Fig. 7 shows that the average surface temperature on the front and back side of the PCM plates during the solidification with average inlet air temperatures of 16 °C. The complete PCM solidification was obtained after 14 h, which is 2 h longer than the nighttime solidification cycle. However, it must be noted, that due to the experimental conditions, in the first 10 h the inlet temperatures was higher than 16 °C (18 °C – 16 °C, on average 17 °C) which notably affects the solidification time in first 12 h. Based on this note, the inlet air with temperatures of 16 °C is conditionally sufficient for the complete nighttime PCM solidification.

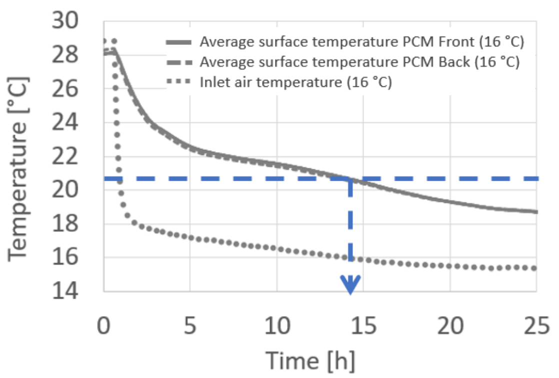

Fig. 7 - The average PCM surface temperatures and inlet air temperatures obtained during the case solidified with average inlet air of 16 °C

Fig. 8 shows that the average surface temperature on the front and back side of the PCM plates during the solidification with average inlet air temperatures of 17 °C. The results show, that the solidification is completed after 16 h of the experiment. Compared to the other two cases, the initial plate temperature was higher (30 °C instead of 28 °C) and thus, slightly affecting the total solidification time. Similarly, also in this case, the average inlet temperatures needed 5 h to completely stabilise from 18 °C to 17 °C, which may also affect the time needed for solidification.

Considering these two anomalies, it is expected that the total solidification time would decrease. However, it is expected that the solidification time would still exceed the nighttime solidification cycle for 12 h. Therefore, at current conditions, the average inlet air temperatures of 17 °C is insufficient (too high) to completely solidify the PCM plates. Nevertheless, the solidification time may be improved by increasing the air flow rate in the air-gap, although compared to the airflow size used by Weinlader et al. (300 m³/h), the amount of air supplied in present stuy is rather high [16].

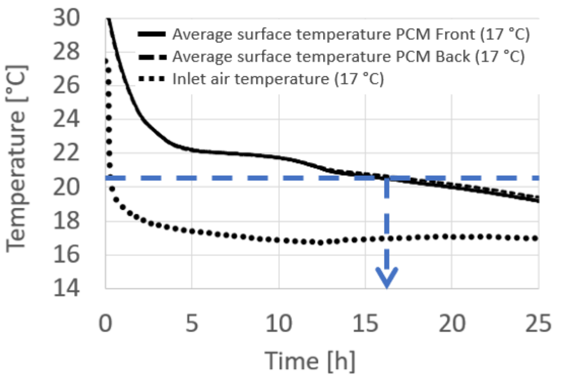

Fig. 8 - The average PCM surface temperatures and inlet air temperatures obtained during the case solidified with average inlet air of 17 °C

4. Conclusions

The research investigates the active-passive system (APS) for cooling application of buildings. It shows that the system indeed provides cooling to the indoor space during the daily cycle with the melting of the PCM plates. At cooler investigated indoor conditions (reference cell air temperature of 26 °C) no additional mechanical cooling systems are required. However, at warmer tested indoor conditions (reference cell air temperature of 30 °C and 35 °C) the system alone cannot sufficiently cool the indoor space and thus, requires additional cooling sources. The additional cooling provided by active mechanical systems increases the daily cooling energy demand. In such case, the expediency of APS system application could be questionable. Also, the electrical energy consumed by the fans for the nighttime air-gap ventilation 'shouldn't be exceed the total energy needed for the daily operation of active cooling systems. The investigated cases showed, that with the air-gap flow rate of 500 m³/h and average inlet temperatures of 15 °C and 16 °C, the PCM plates may be solidified in the predicted nightime cycle (12 h).

In the future, such system should be tested for lower amount of PCM plates, different air-gap flowrates and temperatures and optimise them, transient conditions for different climate types, determine the energy removed from the space by APS and the energy needed for additional cooling of the plates. The APS system should be investigated in combination with daytime ventilation for IAQ and nighttime natural ventilation for improved solidification from the cell-side.

5. Acknowledgement

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0158, Structural engineering and building physics and No. P2-0223, Heat and Mass Transfer) and Région Auvergne-Rhône-Alpes. The authors would also like to thank EU Comission for its financial contributions in the framework of Horizon 2020 project named Driving decarbonization of the EU building stock by enhancing a consumer centred and locally based circular renovation process (DRIVE0) with Grant agreement ID: 841850.

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