Macro-Encapsulated Phase Change Material (PCM) Ceiling Panels Performances as an Active Cooling System: Experimental Investigation

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ABSTRACT

Macro-encapsulated Phase Change Materials (PCM) can be used in buildings to increase their thermal inertia and dampen temperature oscillations. Coupling this technology with a night-active water circulation through embedded pipes can enable the system to store cold. This notion of storage allows shifting of the cooling load. However, when facing a high cooling load (e.g. an overcrowded room), the night-active circulation could become insufficient to maintain acceptable thermal comfort. This study aimed to investigate experimentally the performance of macro-encapsulated PCM panels (MEP) with occupancy water circulation in response to a high heat load.

The experimental investigation showed that ventilation parameters (supply temperature and ventilation flowrate) and water circulation parameters (temperature setpoints for activation) determined the MEP's behaviour. This behaviour could be similar to TABS (Thermally Activated Building Systems) when ventilation was dominant in terms of cooling power during occupancy: the setpoint for active water circulation in the panel was never reached. When the cooling impact of ventilation was reduced, the MEPs would behave as radiant ceiling panels.

By choosing the values of these parameters well, it was possible for the operative temperature to stay 96% of the time between 23 and 26 °C. This range is defined as comfortable in summer for office working in EN16798-1 (2019). It also showed that occupancy water circulation could improve panel heat absorption by 35% with deactivated ventilation (reaching 21 W/m² in average during occupancy).

1 INTRODUCTION

In recent years, climate change and its consequences have been the center of attention of many organizations such as the European Commission set a path to become climate-neutral by 2050 (2019). Energy use related to buildings has a significant importance with respect to these goals. Indeed, the International Energy Agency (IEA) (2024) states that buildings and building construction sectors account for 30% of total global final energy consumption and 26% of total energy sector emissions. Also, nowadays air conditioners and electric fans for cooling account for about 20% of total electricity used in buildings around the world. Their number is growing and the IEA (2018) also predicted that more than 60% of world's households could be equipped with a unit by 2050, leading the energy demand for space cooling to triple by that time.

Numerous studies have been conducted to lower the environmental impact of cooling in buildings without compromising on thermal comfort by either improving existing technologies or introducing new ones. Part of these technologies relies on the inclusion of Phase Change Materials (PCM). Due to their high energy density, they allow to enhance thermal mass of buildings by using a reduced amount of space compared to sensible heat storage. According to Baetens et. al. (2010), depending on the PCM type, their latent heat can lay between 120 and 250 kJ/kg. In comparison, water has a heat capacity of 4.2 kJ/(kg.K). As with other heat storages, they allow to shift the cooling load, to improve energy efficiency and to increase thermal comfort by reducing temperature fluctuations in buildings as respectively pointed by Alva et. al. (2017), Plytaria et. al. (2018) and Kuznik et. al. (2010). Another advantage of some integrated PCM technologies lies in their ease of installation. Allerhand et. al. (2019) demonstrated that macro-encapsulated PCM solutions are more interesting for building retrofitting compared to TABS (Thermally Activated Building System).

Many active systems integrating PCM have been studied already. Weinläder et. al. (2016) compared the thermal connection to a room of two designs of PCM radiant ceiling panels composed of two main layers (i.e. one of graphite and one of PCM) and a water circulation structure. The comparison was made for a difference between these designs in the vertical position of the layers. The researchers concluded that having the PCM below the graphite layer and the circulating water resulted in a better thermal connection between the PCM and the room. Gallardo and Berardi (2019) simulated the performance of a radiant panel system with integrated PCM in very hot and humid conditions. They showed that the system could save around 48% of operation energy compared to an all-air system in existing office buildings. These savings were mainly due to the operation of the plant at night. Mousavi et. al. (2023) designed and studied the performance of an experimental system composed of shape-stabilized PCM composite boards. They concluded that the system required 4-5h of water circulation during the night and that the panel system had a heat transfer coefficient of 8.48 ± 0.97 W/(m².K).

However, the literature lacks research on PCM applications in buildings facing a high heat load. Bogatu et al. (2020) studied the cooling and load-shifting performance of a set of macro-encapsulated PCM panels (MEP) with embedded pipes for night water circulation integrated in an office building with an occupancy of two people (translating into 21.4 W/m² of internal heat gains during occupancy). This work aims to assess the performance and impact on thermal comfort of the same system using occupancy water circulation for an overcrowded room (i.e. 6 occupants translating into 34.6 W/m² of heat gains during occupancy). In other words, the work tries to determine if MEPs can be used as an active cooling solution in off-design conditions during occupancy when coupled to a ventilation.

2 METHODOLOGY

The experiments took place in the International Centre of Indoor Environment and Energy (ICIEE), Technical University of Denmark (DTU). This section presents the PCM and its integration technology as well as the different test chamber configurations and instrumentation.

2.1 PCM and Integration Technology

The panel used in this study was the MEP developed by Bogatu et. al. (2020). The PCM used was paraffin. It can be categorized as an organic PCM. Sharma et. al. (2007) pointed that this type of PCM does not induce corrosion and has a high heat latent capacity while allowing a stable performance. The material changes phase between 21 and 25 °C which overlaps the targeted room temperature range (20 - 26 °C). Each panel consisted in a steel case with aluminum profiles (enhancing PCM conductivity) and copper tubes to allow water circulation in which 3kg of PCM was poured. These panels were instrumented with either a temperature or a heat flux sensor. Figure 1 shows the cross-section of a panel.

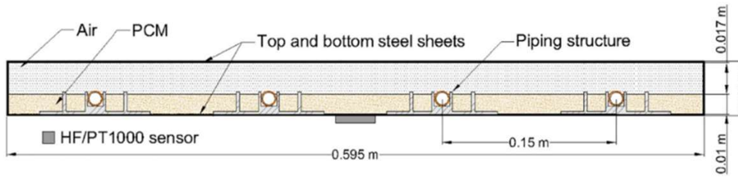

Figure 1: Cross-section of a MEP with its instrumentation (from Bogatu et. al. (2020)).

A picture of the ceiling and a schematic of the panel set are shown in Figure 2. The first consisted of 48 MEPs that were placed on the suspended frame of the test chamber, covering 76% of the ceiling area (17 m²). The rest of the ceiling was covered with polyurethane foam plates. The panels were connected to each other using flexible piping (in the plenum between the test chamber ceiling and the panel set) forming the four circuits shown in Figure 2. This ensured a homogeneous temperature of the panels during operation.

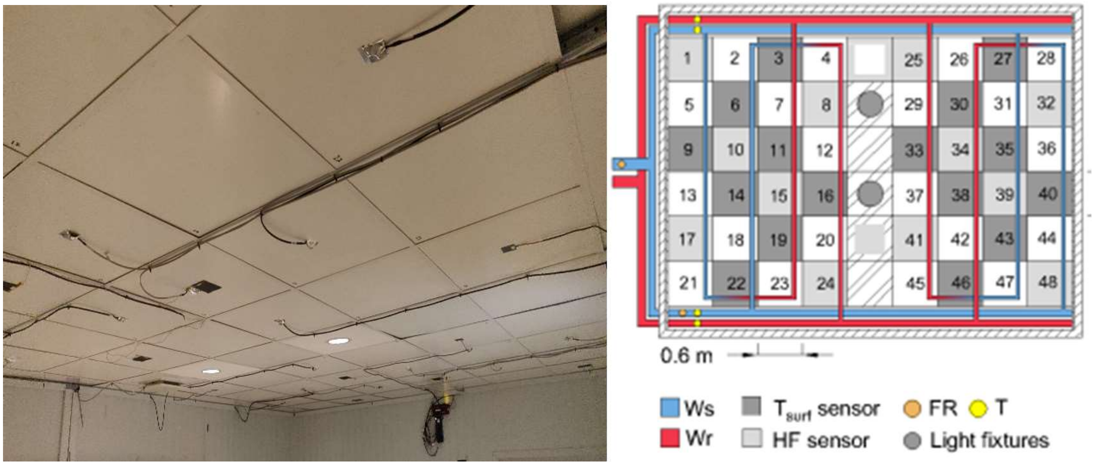

Figure 2: Picture and schematic of the panel set.

2.2 Climatic Chamber

Two different configurations were tested in a 5.4 × 4.2 × 3.2 m (L × W × H) highly insulated climatic chamber. The first configuration of internal heat gains (IHG1) was for testing a reference case with two occupants as if they were in an office with their equipment. This reference case allowed to check the operation of the system and to have a basis for comparison. The second configuration (IHG2) was put into place to test the MEPs operation under a higher cooling load consisting in a 6 occupants office space. Both configurations are shown in Figure 3. Two stands, S1 and S2, were equipped with a globe temperature sensor to measure the operative temperature for sitting people at a height of 0.6 m as mentioned in ISO 7726 (2001). Other sensors on these stands measured the temperature at 0.1, 1.1 and 1.7 m to establish the temperature stratification inside the room. For both configurations, a 2 m wide heating net emulated solar heat gains. The chamber did not have any window as it was inside a hall. The walls consisted of a sandwich of mineral wool between two metal sheets with a thermal conductivity of 0.25 (W/m².K) as determined by Toftum et. al. (2004).

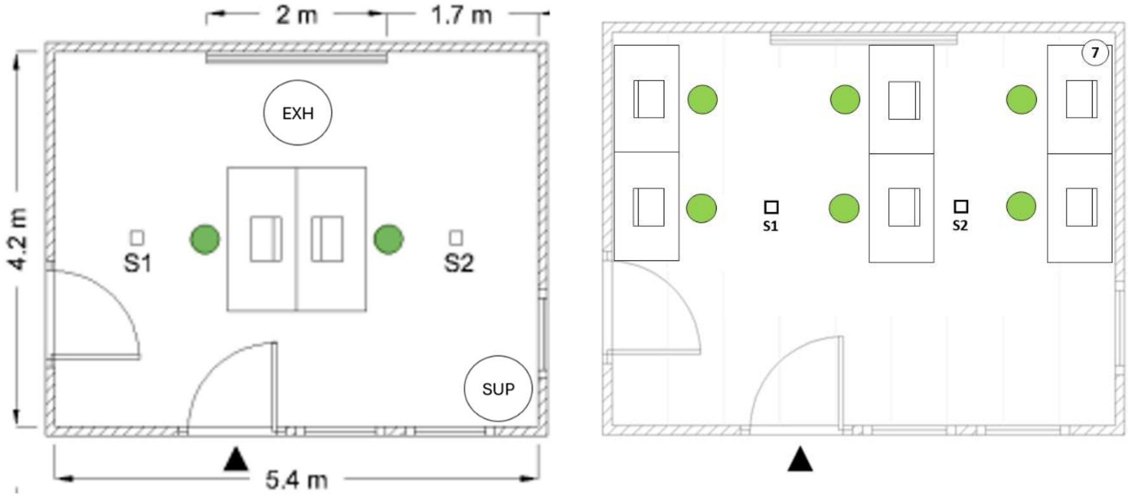

Figure 3: Representation of IHG1 and IHG2 configurations.

A displacement ventilation system was used. It induced a controlled airflow (in terms of temperature and flowrate) near the floor from an unoccupied zone (SUP in Figure 3) to the occupied zone. The air then displaced the hot and contaminated air to the ceiling where an exhaust was placed (EXH in Figure 3). This leads to a uniform air movement from the floor through the functional space towards the ceiling.

2.3 Heat Gains

The climatic chamber was equipped with two lights, occupants (emulated using steel dummies) and equipment (computers or heated steel cases). Table 1 shows the internal heat gains data for both configurations represented in Figure 3.

Table 1: Internal heat gains for the IHG1 and IHG2 configurations.

Device	Number		Unit heat rate input [W]	Total heat rate input [W]		Total heat rate input per floor area [W/m²]	
Lights	2	2	18	36	36	1.6	1.6
Dummies	2	6	75	150	450	6.6	19.8
Computers	2	6	50	100	300	4.4	13.2
TOTAL	/	/	/	286	786	12.6	34.6

The heating net was controlled to produce generate solar heat gains for a south facing window in Copenhagen, Denmark during the cooling season (between May and September). The heat input thus ranged from 0 to 150 W. The heating net power was gradually increased between 5:36 and 12:00 (reaching the maximum power of 150 W) before decreasing until 19:12 in steps of 25W. Figure 4 shows the evolution of total heat gains throughout the day for both scenarios. It shows that solar heat gains are much less important for the overcrowded scenario. The work of Bogatu et. al. (2020) provides more details on the choice of the heat gains values.

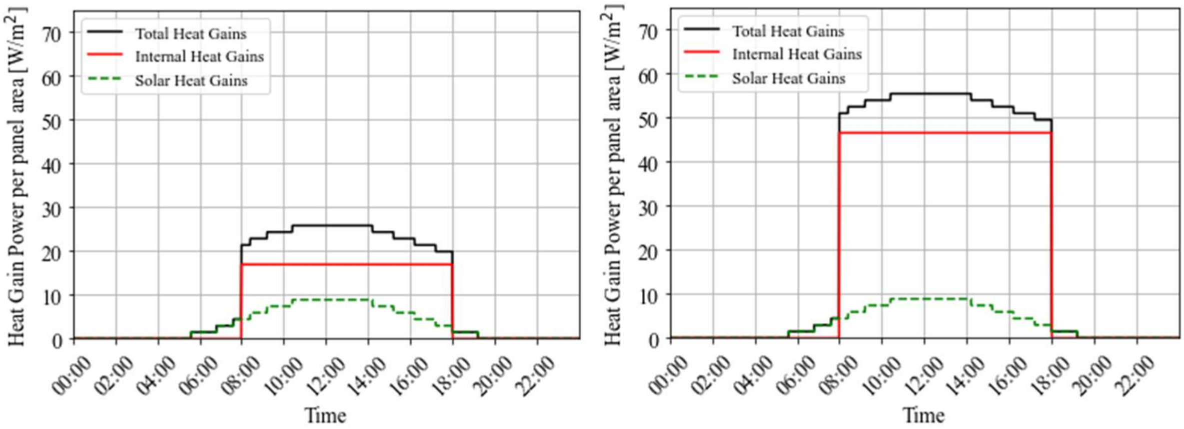

Figure 4: Heat gain profiles for IHG1 and IHG2.

2.4 Instrumentation

Monitoring the whole system required sensors in the climatic chamber, the water circuit and the ventilation system. PT1000 were used to measure the operative temperature as well as surface temperatures of ceiling panels, the floor temperature, wall temperatures inside the test chamber and the external wall temperature. Heat Flux sensors measured the heat exchanged between the room and the MEP. The water flowrates and temperatures (for the two main sub parts of the water circuit) were respectively measured using an ultrasonic flowmeter and a PT500 temperature sensor. Finally, the ventilation temperatures and velocities were measured using anemometers.

These measurements were used to compute the ventilation flowrate (using the duct area) and the internal energy gain/removal in the chamber of both of the thermal systems and of the heat losses. Table 2 summarizes the main characteristics of the sensor used in this study.

Table 2: Summary of relevant sensor characteristics.

Measured Variable	Sensor Type	Range	Accuracy / Rel. error
Temperature	PT1000	[-50 ; 500] °C	± 0.15 °C
Water Temperature	PT500	[2 ; 180] °C	± 0.3 °C
Water Flowrate	Ultrasonic Flow Sensor	[0 ; 0.6] m^3/h	± 0.14%
Heat Flux	Heat Flux Sensor	[-150 ; 150] kW/m^2	± 3%
Air Temperature	Anemometer	[-10 ; 50] °C	± 0.2 °C
Air velocity	Anemometer	[0.05 ; 5] m/s	± 0.02 m/s ± 1.5%

3 EXPERIMENTS

The experiments conducted in this study are shown in Table 3. Each experimental scenario was run and monitored for 4 days minimum achieve a steady-periodic state. Occupancy was defined from 8:00 to 18:00. This was the time range when the internal heat gains were activated. During the first experimental scenarios, ventilation was not activated. The water circulation supply temperature and flowrate did not change between the different scenarios. These were kept constant at 18 °C and 220 kg/h, respectively.

First, the reference scenario (REF) was conducted with the IHG1 configuration (with two occupants). The water circulation strategy was the CTRL1 strategy. It consisted in using only off-occupancy water circulation according to a non-occupancy (N-OCC) operative temperature setpoint. Water circulated until the room operative temperature reached 1 °C below that setpoint (for the REF scenario, water circulated until the room operative temperature reached 21 °C, ensuring that all the PCM inside the MEPs is frozen). The 1 °C difference avoids frequent system start/stop. The 6OCC scenario kept the same parameters except for the internal heat gains where the IHG2 configuration (6 occupants) was used instead.

The next scenario (25SP) was the same as the 6OCC except for the addition of an occupancy water circulation with an occupancy (OCC) operative temperature setpoint at 25 °C (corresponding to the temperature at which all the PCM is melted). When the room operative reached that setpoint, water circulated until it returned to 1 °C below it. The 23SP scenario was designed to investigate the effect of setting the occupancy setpoint at 23 °C.

Finally, the effect of ventilation was investigated as it is required to satisfy air quality requirements. 25SPV had the same parameters as the 25SP scenario except for the addition of ventilation. For that scenario, the air supply temperature was of 20 °C and the supply air flowrate was 210 m^3/h. Then, an attempt of tighter control was tried during the TIGHT scenario in which the effect of ventilation was decreased by increasing the supply air temperature to 22 °C and by reducing the air flowrate to 152 m^3/h. Another modification introduced in the TIGHT scenario is to set the day and non-occupancy setpoints at 23 °C in order to keep the room operative temperature as close to constant as possible.

The chosen values for the ventilation flowrates were determined according to different criteria in EN16798-1 (2019). For the 25SPV scenario, it was based on perceived air quality and for the TIGHT scenario, on limit CO2 concentration. The aim was to have a Category II air quality (moderate occupant expectation).

Table 3 shows an overview of the main parameters of the different scenarios with the main difference between them in bold.

Table 3: Overview of main parameters of all scenarios.

Scenario	IHG	$T_{a,s}$ [°C]	$\dot{m}_a$ [m^3/h]	CTRL	OCC SP [°C]	N-OCC SP [°C]
REF	IHG1	N / A	N / A	CTRL1	N / A	22
6OCC	**IHG2**	N / A	N / A	CTRL1	N / A	22
25SP	IHG2	N / A	N / A	**CTRL2**	25	22
23SP	IHG2	N / A	N / A	CTRL2	**23**	22
25SPV	IHG2	**20**	**210**	CTRL2	25	22
TIGHT	IHG2	**22**	**152**	CTRL2	**23**	**23**

4 RESULTS

The scenarios presented in the previous subsection were compared mainly in terms of indoor thermal environment (operative temperature), room heat extraction and water circulation intensity. This section provides the main results of these investigations.

4.1 Indoor Thermal Environment

Figure 5 shows the evolution of operative temperatures for all scenarios during the day and displays using boxplots the distribution of operative temperature during occupancy for all scenarios. The general trend is a low temperature variation before 8:00. When occupancy starts, the temperature rises until 18:00 where the internal heat gains are deactivated. The water circulation then starts to bring the temperature down to a value depending on the non-occupancy setpoint.

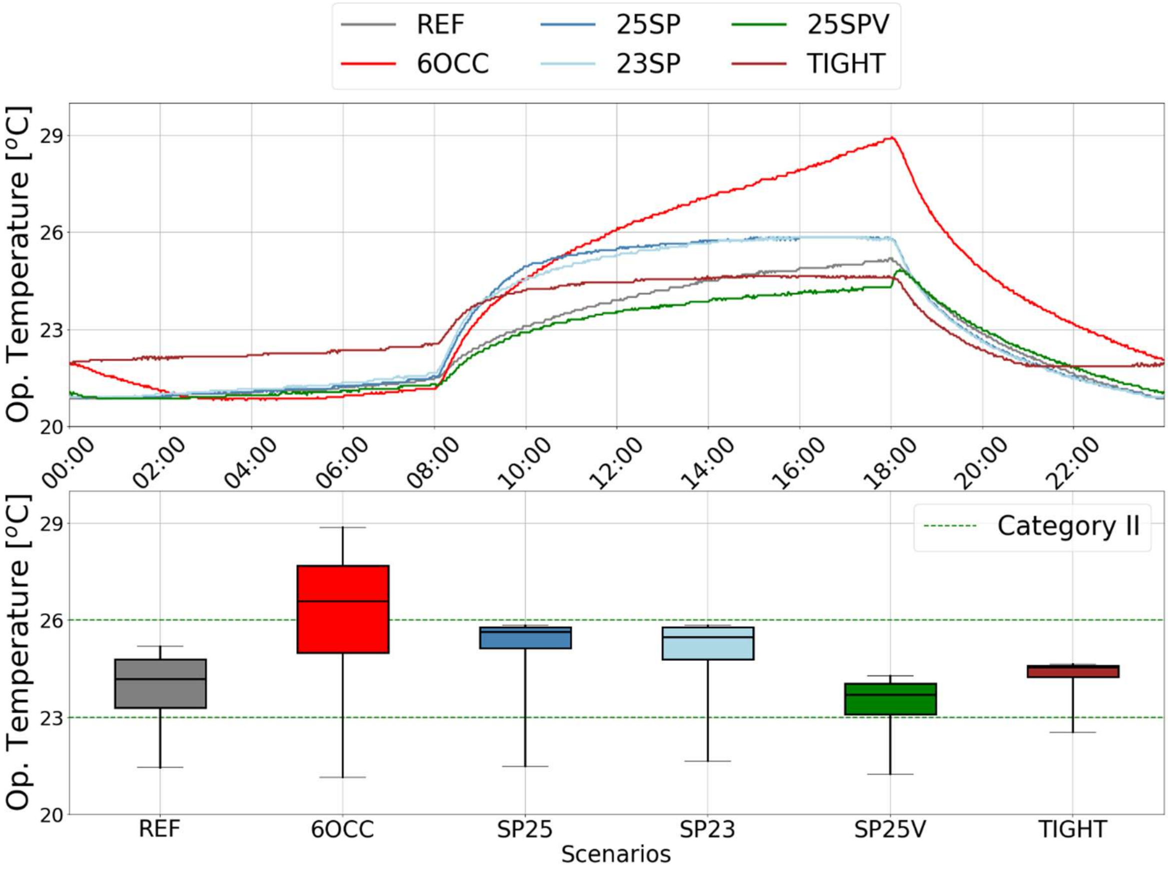

Figure 5: Evolution of operative temperatures throughout the day and boxplot of operative temperatures during occupancy.

First, it can be observed in Figure 5 that the operative temperature for the 6OCC scenario rises much higher than the others. It reaches up to 29 °C (which is 3 °C above the upper limit of Category II in EN16798-1 (2019)). It is also the only scenario for which the mean operative temperature is outside the thermal comfort Category II. This shows that only non-occupancy water circulation was not enough to cool down an overcrowded room on its own.

Secondly, the operative temperatures of 25SP and 23SP did not exceed 26 °C. This shows that the addition of occupancy water circulation allowed to effectively limit the temperature increase during occupancy. However, varying the occupancy setpoint for the water circulation did not induce significant improvement in the evolution of the operative temperature. An explanation could be that such an operation pushed the system to its limits in terms of room heat extraction as the system was cooling down the room while re-freezing the energy-dense PCM.

Finally, the results of 25SPV and TIGHT scenarios showed that the addition of ventilation can have a significant impact on the operative temperature evolution. On the one hand, at the end of occupancy in the 25SPV scenario, an increase of operative temperature can be observed. This is because during the day, ventilation cooled the room and the operative temperature never reached the occupancy setpoint of 25 °C. The panels were thus warmer than the room. The operative temperature rose during the time it took for the water circulation to start cooling the PCM in the panels. On the other hand, the results of the TIGHT scenario showed that the occupancy water circulation and the ventilation were working together during occupancy. This prevented the temperatures to increase higher than 24.7 °C while selecting a higher non-occupancy setpoint ensured a slightly higher temperature at the start of the occupancy. These allowed the operative temperature to stay in Category II for a larger proportion of the occupancy time.

4.2 Cooling Performance Comparison

Figure 6 shows the heat extracted by the water circuit and the ventilation, the heat losses and the total heat gains for all scenarios. The heat extracted by the ventilation and the water circuit have been computed from the air and water flowrates and from their temperatures. One thing that can be noted is the difference between the total heat gains and the total heat extracted. This can be explained by sensor imprecision and by the fact that steady-periodic state was not perfectly reached. Figure 6 also confirms the effect of room overcrowd with non-occupancy water circulation on the indoor thermal environment. During the 6OCC scenario, passive use of the MEPs did not allow enough heat removal, leading to higher heat losses and an accumulation of heat in the room, causing the temperatures to rise. Another observation is the fact that ventilation had a similar heat removal compared to the MEP set in the 25SPV scenario. The changes introduced in the TIGHT scenario reduced the ventilation heat removal.

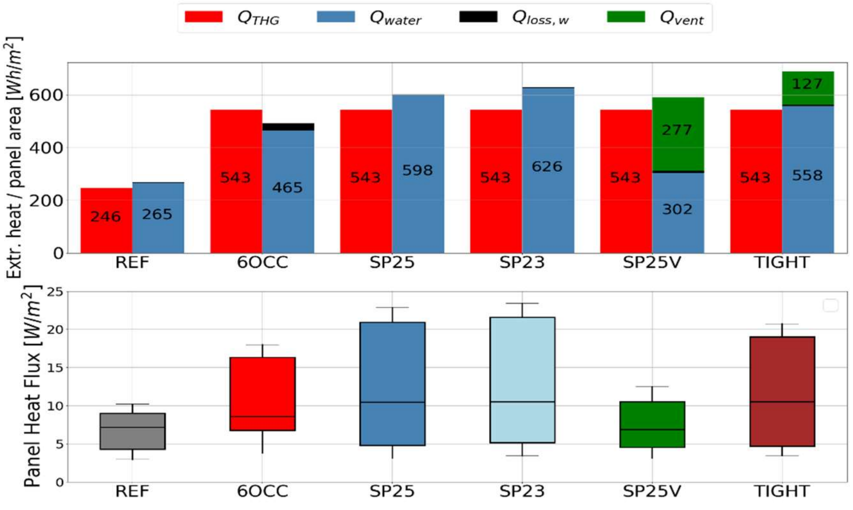

Figure 6: Extracted heat per panel area and comparison of panel each flux for all scenarios during a whole day.

Figure 6 also compares the panel heat flux values between the different scenarios. It shows that occupancy water circulation increases the panel potential for heat extraction from 18 W/m² (6OCC) to 22.8 W/m² (SP25) which translates into a 27% gain in maximum heat flux. Also, changing the occupancy setpoint from 25 °C to 23 °C only showed a slight increase of 2.6% in maximum heat flux (from 22.8 W/m² to 23.4 W/m²). Finally, depending on the ventilation parameters, it is still possible to reach a bigger heat flux through the panels with occupancy water circulation even if the MEP system is coupled with a ventilation (from 18 W/m² to 20.7 W/m² which translates into a gain of 15%).

4.3 Water Circulation Intensity

Figure 7 shows the quantity of circulated water (separated in terms of occupancy and non-occupancy). It shows that the amount of circulated water is significantly higher when the occupancy water circulation is used. This means that the additional thermal comfort comes with the cost of higher water circulation. Also, in day-active configuration, the system trades its load-shifting ability to increase its adaptability. The ratio of water circulation during occupancy and non-occupancy also shows whether the MEPs act as an active or as a passive system. In the REF, 6OCC and 25SPV scenarios, the system would be closer to a system such as TABS in terms of operation. In the 25SP, 23SP and TIGHT scenarios, the system operates similar to a radiant ceiling panel.

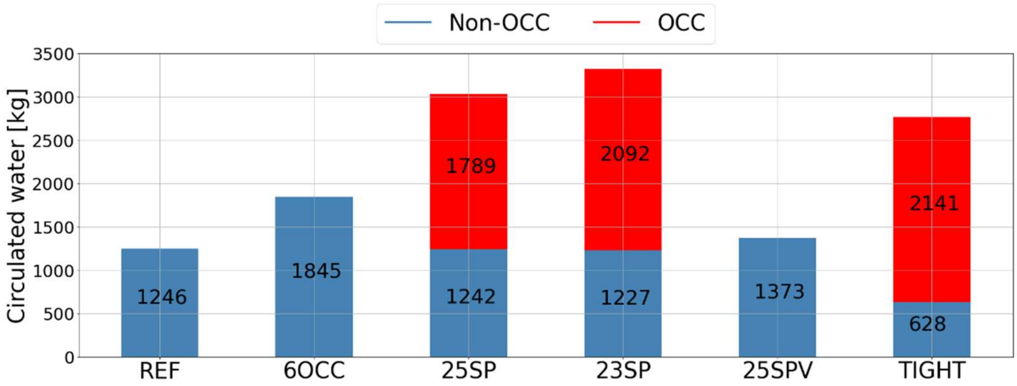

Figure 7: Quantity of circulated water inside and outside occupancy for all scenarios.

5 DISCUSSION

Last subsection compared the room operative temperatures of all scenarios. From these results, they can also be compared in terms of thermal comfort. Figure 8 shows the share of the time during occupancy in the different thermal comfort categories listed in EN 16798 (2019). The main objective was to keep the room operative temperature the biggest share of the time possible within Category II.

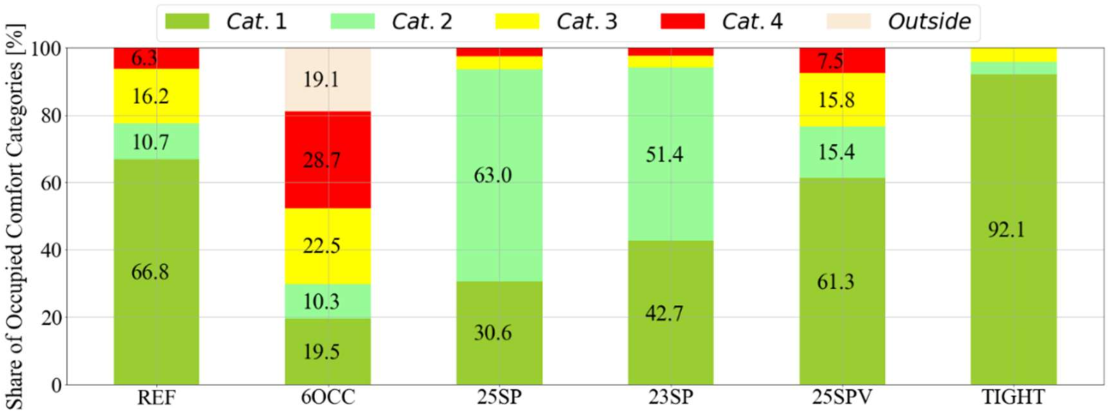

Figure 8: Comparison for all scenarios of the time share within the different thermal comfort categories in EN16798 (2019).

It shows that the high internal heat gains had a significant negative impact on thermal comfort from REF (77.5%) to 6OCC (29.8%). The latter was greatly improved beyond the levels of the REF scenario by occupancy water circulation with a 25 °C day-setpoint in 25SP (93.6%). Adjusting the day-setpoint to 23 °C did not significantly improve the thermal comfort according to the study's objective in 23SP (94.1%). The addition of ventilation with a temperature of 20 °C and a flowrate of 210 m^3/h decreased thermal comfort because of a larger share of low temperatures in 25SPV (76.7%). Finally, an adjustment of ventilation parameters to 22 °C and 152 m^3/h allowed to reach excellent thermal comfort (95.8%).

Another comparison that was made focused on the mean panel heat flux. To go further, this comparison can be done by also separating the dataset into occupancy and non-occupancy time with and without activation of water circulation as in Table 4. Focusing first on off-occupancy, it shows that heat fluxes are consistently higher when water is circulated for all scenarios. Moreover, a comparison can be made between the mean heat flux value of occupancy without water circulation of 6OCC (15.4 W/m²) and the mean heat flux values of 25SP, 23SP and TIGHT during occupancy (respectively 21, 20.8, 18.1 W/m²). The former is always lower than the others, even if the operative temperatures in the 6OCC scenario were more extreme. This indicates that circulating water in the MEPs improves their heat absorption as the heat is able to bypass the PCM through the aluminum structure. Without ventilation, this improvement is of about 36%.

Table 4: Mean panel heat fluxes for various conditions for all scenarios [W/m²].

Scenario		REF	6OCC	25SP	23SP	25SPV	TIGHT
Occupancy	Water Circulation	/	/	21	20.8	/	18.1
Occupancy	No Water Circulation	8.8	15.4	10.3	6.2	10.5	4.8
Non-Occupancy	Water Circulation	7.3	9	11.7	11.7	7	13.2
Non-Occupancy	No Water Circulation	4.1	4.9	4.6	4.9	4.3	5.1

The different scenarios were also compared in terms of water circulation use. Two interesting indicators can be computed from these results. The first one is an active use ratio (r_{act}) that can be defined as the quantity of water circulated during occupancy ($m_{w,occ}$) divided by the total quantity of circulated water ($m_{w,tot}$) as in Equation 1:

$$r_{act} = \frac{m_{w,occ}}{m_{w,tot}} \text{ [-]} \quad (1)$$

The second one is the specific panel heat extraction (q_{MEP}) can be computed as the ratio of the heat extracted by water per panel area ($Q_{extr,w}$) over the total circulated water ($m_{w,tot}$) as in Equation 2:

$$q_{MEP} = \frac{Q_{extr,w}}{m_{w,tot}} \text{ [Wh/(kg.m}^2\text{)]} \quad (2)$$

The values of these indicators for the different scenarios are listed in Table 5.

Table 5: Water circulation related indicators for all scenarios.

Scenario	REF	6OCC	25SP	23SP	25SPV	TIGHT
r_{act}	0	0	0.59	0.63	0	0.77
q_{MEP}	0.21	0.25	0.2	0.19	0.22	0.2

Results from this table shows that, for the 25SP, 23SP and TIGHT scenarios, the system performed like an active system overall as the value of r_{act} was over 0.5 in opposition to the 25SPV scenario. Also, the values of q_{MEP} show that the occupancy water circulation, even coupled with ventilation, does not impact significantly the marginal benefit created by the cost of circulating water.

6 CONCLUSION

Different scenarios were tested experimentally to determine whether PCM panels were able to be used as an active cooling system for office building when facing a high heat load (i.e. conference rooms and overcrowded rooms). It showed that without ventilation, occupancy water circulation was required when the system faced a high heat load (6 occupants with computers). It also showed that a correct choice of parameters related to water circulation (temperature setpoints for activation) and ventilation (inlet temperature and flowrate) allowed to achieve an excellent level of thermal comfort (95.8% of the time in Category II). In that context, the panels were behaving like RCPs (radiant ceiling panels) as 77% of the water was circulated during occupancy. The comfort thus came with the cost of intense water circulation during the day even if the amount of heat extracted per quantity of water did not change significantly compared to a scenario in which water circulation in the MEPs was done outside occupancy. Future work could be to fine tune the previously mentioned parameters to achieve similar thermal comfort by reducing the intensity of the water circulation (especially during the occupancy) and develop a robust control strategy. In opposite, a bad choice of these parameters could decrease thermal comfort when ventilation is added (compared to a case in which panels would operate on their own). In that context, the MEPs were behaving like TABS as no water was circulated in the panels during occupancy. These results highlighted that the setpoints and parameters related to ventilation and water circulation determined whether the system operated more like radiant panels or more like TABS. Lastly, other results showed that occupancy water circulation allowed to improve panel heat flux of 35% (from 15.4 W/m2 to about 21 W/m^2) during occupancy.

NOMENCLATURE

CTRL	Control Strategy
EXH	Exhaust
IHG	Internal Heat Gains
MEP	Macro-Encapsulated PCM Panels
N-OCC	Non-Occupancy
OCC	Occupancy
PCM	Phase Change Materials
RCP	Radiant Ceiling Panels
SP	Set point
SUP	Supply
TABS	Thermally Activated Building Systems

$m_{w,occ}$	Amount of circulated water during occupancy	(kg)
$m_{w,tot}$	Total amount of circulated water	(kg)
$Q_{extr,w}$	Amount of heat extracted by the water circuit (per panel area)	(Wh/m^2)
q_{MEP}	Specific panel heat extraction (per panel area and per kg of circulated water)	(Wh/(kg.m^2))

Subscript

a	air
act	active
extr	Extracted
s	supply
THG	Thermal Heat Gains
tot	Total
vent	ventilation
w	water

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