Energy Efficient Room Temperature Control Through the use of Phase Change Materials: Identification of potential for optimization based on an *ESP-r* model and simulation

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***Abstract*—In this study it is of interest to determine how the presence of phase change materials (PCMs) in an office environment influences the room temperature, after being in operation for ten years, and to analyse under which conditions they can operate more efficiently. To accomplish this, a model in the simulation software *ESP-r* was set up, adjusted to measured data during a calibration process, and then validated. Afterwards, the model was implemented by varying parameters of interest and simulating hypothetical scenarios. At the end, the model was successfully calibrated for a period of time of three months; nevertheless, its robustness was compromised when being validated against a different set of measurements not used during the calibration. From the implementation it was concluded that the shading control must be operated every day in order to maintain the room temperature within the melting range of the PCM between 23 and 26 °C. Also, the increase of the air exchange rate during the evening proved to be beneficial, instead of relying on natural ventilation only. In general, the presence of PCMs was determined to be advantageous. Furthermore, from the built model it was not possible to determine to which extent the PCMs have deteriorated after ten years, since the measured data contained too many influencing factors. Finally, details from the model setup using *ESP-r* are provided, and the observed model limitations and uncertainties are further discussed.**

Keywords*—Phase change materials (PCMs), Building simulation, Modelling, ESP-r, Thermal mass, Model calibration and validation

I. INTRODUCTION

In the European Union, the building sector accounts for 40% of the final energy consumption [1], from which 50% correspond to the amount used for heating and cooling applications. Throughout the years, the global average temperature has increased, as well as the thermal comfort expectations among the general population. This will lead to an increase in the cooling and heating demand, as established by the European Commission, who establishes that by the year 2030 in Europe the number of air conditioning units and refrigeration systems is expected to double [2]. For instance, in the area of heating and cooling in buildings, there has been a shift in interest towards more sustainable and energy-efficient solutions, being the use of thermal energy storage (TES) systems one of them. Multiple TES systems exist and have been successfully employed throughout the years; however, in the presented study a focus is given to the use of phase-change materials (PCMs) as a TES method.

For instance, the objective of this study is to examine the influence that PCMs have in the indoor climate of an office environment, after ten years under operation. To carry this out, a model of the office containing PCMs in its internal walls was built using the building simulation software *ESP-r*. A second office, which does not contain any PCMs was also modelled in order to use it as a reference. Both offices are located in a building in the city of Freiburg im Breisgau, Germany. In addition, it is also of interest to determine under which operational settings the PCMs would operate in a more efficient manner, in order to bring a greater benefit to the indoor climate. Furthermore, it was intended with this study to present a more detailed explanation of the model setup, calibration and validation processes within the *ESP-r* simulation environment, in order to contribute towards the documentation available.

II. GENERAL BACKGROUND

A. The Sonnenschiff building

The offices to be modelled are located in a building under the name of the Sonnenschiff, specifically located in the district of Vauban in the city of Freiburg im Breisgau, Germany. The Sonneschiff was built considering low consumption measures, and it accounts with a highly efficient ventilation system, a well-isolated façade and windows, a shading control to cover the windows when the sun irradiation is high, as well as with a night cooling method in order to avoid overheating of the room temperature during the warmer months by means of natural ventilation [3]. Both offices have a ventilation panel at the façade which could be left tilted or opened at night in order to take advantage of the lower temperatures during the evening, and allow the rooms to cool down. A security wall is located in front of these ventilation panels to prevent breaking or entering while the offices remain unoccupied.

As previously stated, two offices are to be modelled. The first one is located on the first floor of the Sonnenschiff and it contains micro-encapsulated paraffin wax PCMs in its internal walls, which were installed ten years ago. The second office is located on the second floor directly above the first one, and it does not contain any PCMs. Further on, the offices on the first and second floor will be referred to as Office 1 and Office 2, respectively.

B. *Measurement campaign*

The Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) performed a measuring campaign in the Sonnenschiff with the purpose of acquiring relevant room-climate parameters and in this way, be able to build the models in *ESP-r*. This campaign took place from May 23rd until October 10th of the year 2018. Sensors were installed in Office 1 and Office 2. The recorded data includes: inside and outside temperatures, outside relative humidity, illuminance incident on the middle and lower sections of the outside-facing windows, motion in the offices, as well as the closing and opening of windows, the ventilation panels and doors.

C. *Phase change materials (PCMs)*

PCMs are a TES method which absorb and release heat at a constant temperature while going through a phase change process. Referring to Figure 1, as the temperature in a room starts to increase, the PCM, originally in solid state, starts to absorb heat in the sensible form while its temperature increases. Then, once the room temperature reaches the melting point of the PCM, it starts to absorb latent heat at a constant temperature until completing the phase change process from solid to liquid. When considering the reverse process, the PCM starts to solidify by releasing the previously absorbed heat, once the temperature of the surroundings goes down [4].

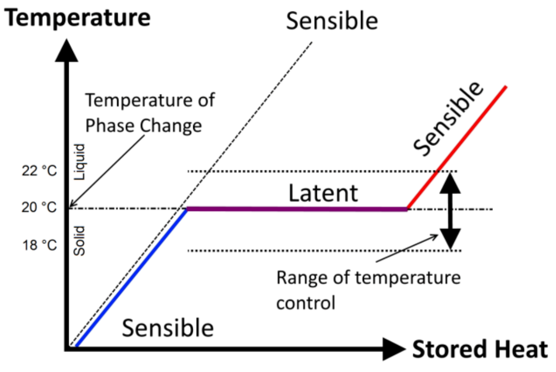

Fig. 1: Working principle of PCMs [4]

Furthermore, PCMs can be divided in the following categories: organic, inorganic, and eutectic and mixtures. Organic PCMs are non-corrosive and can undergo repeated melting and cooling cycles without showing a significant decrease in its latent heat capacity. Organic PCMs can be further subdivided into paraffin wax, fatty acids, sugar alcohols, and non-paraffin. From these, paraffin wax is the most commonly used in building applications, due to its non-corrosiveness and beneficial chemical stability. In the case of the Sonnenschiff building, micro-encapsulated paraffin wax PCMs were installed, which are chemically stable, can be easily microencapsulated, and count with a high latent heat capacity, which can vary between 150 to 270 kJ/kg. The latent heat capacity of paraffin wax PCMs depends on their chemical composition and purity [5].

D. *ESP-r*

As previously stated, *ESP-r* is the building simulation software used in this study to build the model of the offices in question. This software was developed by the Energy Systems Research Unit in the University of Strathclyde in Scotland. *ESP-r* examines a control volume defined as a geometry, and performs a transient analysis of both energy and mass flows. The program allows the integration of different building components, such as electrical ones, HVAC systems (heating, ventilation, and air conditioning), as well as renewable energy systems [6]. Furthermore, the integration of PCMs in the construction elements of a model is also possible by defining their thermal properties, and specifying their location within the construction layers. Once integrated, *ESP-r* considers the changes hapenning within the construction layer containing the PCM, as time progresses and the room temperature varies.

III. METHODOLOGY

A. *Model setup*

The model for both Office 1 and Office 2 was set up in *ESP-r* once the relevant data from the measurement campaign and other sources was gathered and properly adjusted.

Before carrying out a simulation, the input data defined in *ESP-r* includes but is not limited to: complete geometry of both offices (shown in Figure 2), weather data for the city of Freiburg im Breisgau, construction and material details, boundary conditions, air flow schedules, among others. The air flow schedules are divided into infiltration and ventilation. Infiltration corresponds to the amount of air coming from the ambient through the façade, and it represents the air-tightness of the building. When a window exposed to the ambient air is opened or tilted (e.g. when modelling the effect of the night cooling), the infiltration value is increased for a defined period of time. On the other hand, ventilation corresponds to the amount of air coming from an active ventilation system at a fixed temperature and/or from a room nearby. In the case of the Sonnenschiff, since no active ventilation system is being operated, the only ventilation source corresponds to the hallway outside the offices.

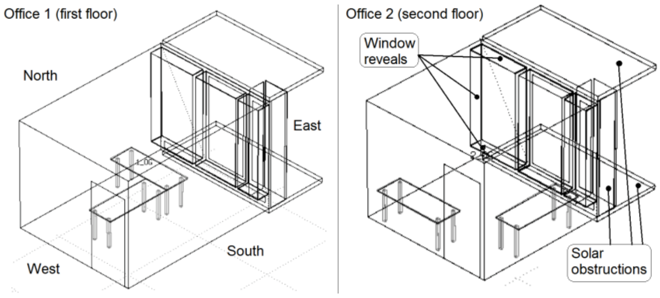

Fig. 2: Final version of the geometry generated in *ESP-r* for Office 1 (left) and Office 2 (right)

Finally, PCMs were also inserted in the model by defining their location within the construction, as well as their thermal properties, including: melting and solidification temperatures, thermal conductivity, as well as their specific and latent heat storage capacity.

1) *Integrating PCMs in ESP-r*

ESP-r has various PCM models representing different mathematical methods and approaches, which simulate the changes occurring in the thermo-physical properties of the PCM while undergoing a phase change process. In this study, a focus is given only to the apparent heat capacity method explained by Equation (1) below. Here C_{app} corresponds to the apparent heat capacity, C_p the specific capacity of the PCM, $L_p(T)$ its latent heat capacity as a function of temperature, and T_{melt} and T_{solid} its melting and solidification temperatures, respectively. The latent heat capacity is represented as a linear function of temperature, as shown in Equation (2), where the slope of the line is given by coefficient a, and the y-intercept by the coefficient b.

$$C_{app} = C_p + \frac{L_p(T)}{T_{melt} - T_{solid}} \quad (1)$$

$$L_p(T) = aT + b \quad (2)$$

When defining the value of the latent heat capacity $L_p(T)$, two cases can be considered:

- *Case 1:* Latent heat storage remains constant over the melting range ($a = 0, b \neq 0$)
- *Case 2:* Latent heat storage changes as a function of temperature over the melting range ($a \neq 0, b = 0$)

Besides the definition of the latent heat storage by means of either of the above mentioned cases, the melting and solidification temperatures of the PCM must also be entered (23 and 26 °C, respectively), as well as its specific heat storage capacity (1650.1 J/kg.K) and thermal conductivity (0.2 W/m.K), as previously stated.

B. *Calibration*

The objective of the calibration process was to adjust the Office 1 and Office 2 models so that the simulation results would fit a set of measured data during the months of July, August and September of the year 2018. This was done by varying a selected set of parameters and performing manual iterations in *ESP-r*, until reaching an acceptable value of the objective function, which was established to be the coefficient of determination, also known as the R^2 coefficient. This value provides a statistical measure of how well a set of observed data is being represented by the model, and it ranges from 0 to 1. The higher the value, the better fit is provided by the model [7]. An acceptable R^2 value depends on the area of study, and the desired accuracy of the model. For instance, it is common to see that an acceptable value varies from study to study; however, in this case, an R^2 coefficient of 0.60 was considered to fall within the acceptable range. The root mean square error (RMSE) was also calculated as an additional indicator of the quality of the model and its results; nevertheless it was not meant to be optimized along with the R^2 coefficient.

For simplification purposes and to reduce the uncertainty level, the infiltration value was kept fixed at 0.5 ACH (air changes per hour), as well as the ventilation at 1.5 ACH at a temperature of 24 °C. Also, neither casual gains nor shading control were defined.

The calibration process took place separately for both offices. First, when calibrating Office 2 (without PCMs) the objective was to alter the construction layers, since the exact details were unknown, until reaching an R^2 coefficient of at least 0.60. After multiple iterations and modifications in the construction layers, an R^2 of 0.75 was obtained. A summary of the calibration results for Office 2 is provided in Table I.

Following, the final construction obtained from the calibration of Office 2 was then implemented in the Office 1 model (with PCMs) before carrying out its adjustment process. When calibrating Office 1, the main objective was to first determine the correct way in which the latent heat storage of the PCM is defined in *ESP-r* by implementing either Case 1 or Case 2. Again, when using Case 1, the latent heat storage is taken to be constant over the melting range, and with Case 2 it varies as a function of temperature. Then, the latent heat storage capacity is altered for each iteration by using only one of the aforementioned cases. A summary of the calibration results for Office 1 is shown in Table II, from which it can be observed that the R^2 did not present a significant variation among all cases; therefore, the RMSE was employed as an additional indicator of the model quality. From these statistical results, it was determined that the *ESP-r* model of Office 1 provides a better fit when implementing Case 2 with a PCM containing 100% of its latent heat storage capacity.

In general, it was concluded that statistically the simulation results showed a good fit, and both Office 1 and Office 2 models were considered to be successfully calibrated for the months of July, August and September of the year 2018. Furthermore, the resultant temperature profile from the calibration is shown for the month of August only in Figures 3 and 4, corresponding to Office 1 and Office 2, respectively.

TABLE I. SUMMARY OF CALIBRATION RESULTS FOR OFFICE 2. TIME FRAME CALIBRATED: JULY 1 – SEPTEMBER 30, 2018

Office 2 - Calibration results		
Case	**R^2**	**RMSE [°C]**
No PCMs	0.75	1.14

TABLE II. SUMMARY OF CALIBRATION RESULTS FOR OFFICE 1. TIME FRAME CALIBRATED: JULY 1 – SEPTEMBER 30, 2018

Office 1 - Calibration results					
Case	**Coefficient a [J/kg.K^2]**	**Coefficient b [J/kg.K]**	**Latent heat capacity**	**R^2**	**RMSE [°C]**
1	0	10898.4	100%	0.80	0.93
2	3214.4	0	100%	0.80	0.87
2	1607.2	0	50%	0.80	0.90
No PCMs	0	0	0%	0.79	0.97

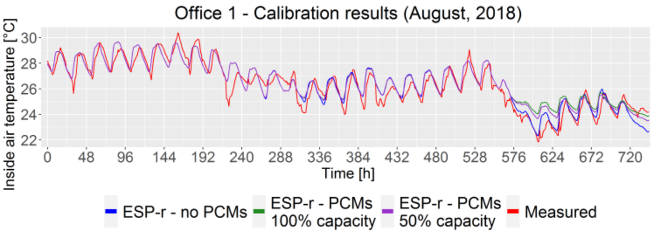

Fig. 3: Calibration results from the Office 1 model for the month of August, 2018

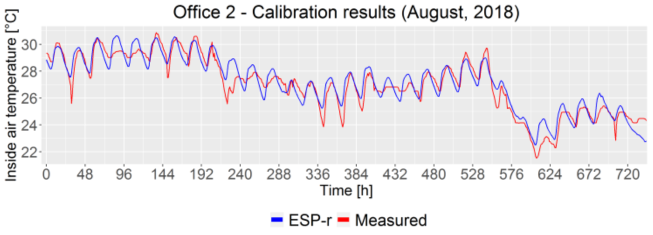

Fig. 4: Calibration results from the Office 2 model for the month of August, 2018

C. Validation

Once Office 1 and Office 2 were successfully calibrated, the validation process followed in order to determine how the models adjust when being validated against a different set of data not used during the calibration process. Since both models were adjusted for the months of July, August and September, the validation period was defined to start on the 12th of June until the 30th, 2018. The entire month was not employed given that there were gaps in the measurements. From the statistical results summarized in Table III, it was observed that the model is sensitive when being compared to data from a month not used during the calibration. Consequently, it was decided to use a week in July for the implementation of the model, given that the model presented a better fit for this month. Here, it is important to highlight the fact that the extrapolation of the simulation results is compromised, based on the results of the validation. Some limitations in the way the data is entered in *ESP-r* and the level of detail provided by the software, does compromise the quality of the results and the robustness of the model.

TABLE III. SUMMARY OF VALIDATION RESULTS FOR BOTH OFFICES. TIME FRAME VALIDATED: JUNE 12 - 30, 2018

	Validation results			
	Office 1			***Office 2***
	No PCMs	PCMs with 50% capacity	PCMs with 100% capacity	No PCMs
R^2	0.52	0.50	0.51	0.53
RMSE	0.80 °C	0.68 °C	0.74 °C	1.31 °C

D. Model implementation

Following the calibration and validation processes, various hypothetical scenarios were established in order to compare the temperature profiles in Office 1 and Office 2 when changing the operational conditions of the night cooling and the shading control. Furthermore, even though in reality only Office 1 contains PCMs, they were also integrated in Office 2 in *ESP-r* in order to see how they would operate in this environment, and to determine the effect they could have in the room temperature.

Each scenario allows the analysis and isolation of the effect caused by changes in the shading control and the night cooling operation. The latter is modelled in *ESP-r* by altering the infiltration value (i.e. the amount of air coming from the outside environment), which represents the opening and closing of windows. For all the considered scenarios, no casual gains were defined and the ventilation value remained fixed at 1.5 ACH at a temperature of 24 °C. The period of interest was taken to be the week from July 9th until the 15th of 2018, since the average measured temperature inside the rooms falls within the melting range of the PCM, defined to be between 23 and 26 °C.

1) Changes in shading control: Two scenarios were established which represent two different shading control configurations. First, the “Real” case was defined as a time-dependent control operating from 7:00 until 16:00, independent from the irradiance measured at the façade. Then, the “Optimal” case was also defined as a time-dependent control, but this time operating from 7:00 until 20:00. PCMs were added only to Office 1, and the infiltration values remained fixed at all times in both models to isolate only the effect caused by changes in the shading control operating schedule.

2) Changes in infiltration: To analyse the response caused by changes in the night cooling operation, different hypothetical configurations were defined. First, the base scenario under the name of “Real” (Table IV) represents regular operating conditions. Here, the ventilation panel is left opened the entire evening until the beginning of the working hours between 9:00 and 18:00 from Monday through Friday. Then, in the Optimal 1 scenario (Table V), the time at which the night cooling operates was changed. In this case, the ventilation panel is opened later in the evening, when the ambient temperature is lower, and closed again early in the morning at 7:00 before the temperature starts to increase more. Following, in the case of Optimal 2 (Table VI), the operation time stays the same as the one from the Real case, but the air change rate was increased from 2 to 4 ACH during the evening. Finally, in Optimal 3 (Table VI) the change happened only during working hours, which would represent the opening and closing of windows at more convenient times based on the outside temperature, meaning that the occupants in the office would open the windows only when the ambient temperature is less than the temperature inside the office.

TABLE IV. REAL (BASE) INFILTRATION SCHEDULE

Real	
Time [hours]	***Infiltration [ACH]***
00:00 – 9:00	2
9:00 – 18:00	1
18:00 – 23:00	2

TABLE V. FIRST OPTIMAL INFILTRATION SCHEDULE

Optimal 1	
Time [hours]	***Infiltration [ACH]***
00:00 – 7:00	2
7:00 – 21:00	1
21:00 – 23:00	2

TABLE VI. SECOND OPTIMAL INFILTRATION SCHEDULE

Optimal 2	
Time [hours]	***Infiltration [ACH]***
00:00 – 9:00	4
9:00 – 18:00	1
18:00 – 23:00	4

TABLE VII. THIRD OPTIMAL INFILTRATION SCHEDULE

Optimal 3	
Time [hours]	***Infiltration [ACH]***
00:00 – 9:00	2
9:00 – 18:00	Based on outside temperature
18:00 – 23:00	2

IV. RESULTS AND DISCUSSION

A. *Effects of changes in infiltration (night-cooling operation)*

From the obtained results when simulating the Optimal 1 case, it was determined that a shift in the operating hours of the ventilation panel does not provide a significant improvement in the room temperature, even though the panel is opened later in the evening at 21:00 instead of 18:00, and it remains opened until 7:00 instead of 9:00. Ideally, this would prevent an airstream at a higher temperature from entering the room; however, no significant effect was observed in the simulation results. Similarly, the temperature drop provided by the Optimal 3 configuration is almost negligible. Again, this scenario represents the opening and closing of the office windows at more convenient times when the outside temperature is lower than the temperature in the offices.

Contrary to the effects observed with the Optimal 1 and Optimal 3 scenarios, the Optimal 2 setup does provide a benefit to the room temperature with a maximum temperature drop of 2 K and 1.4 K in Office 1 and Office 2, respectively, taking the real scenario as a reference. A summary of the obtained results for the Optimal 2 configuration is provided in Table VIII. From these results the importance of increasing the amount of air coming from the outside into the building at night can be observed. The Optimal 2 configuration would assist the PCM in Office 1 in going back to its solid state during the evening, and enhance its cooling effect during the day. Similarly, based on the results, this configuration proves to be beneficial for Office 2 (without PCMs); however, the temperature reduction in Office 1 (with PCMs) is more noticeable.

TABLE VIII. SUMMARY OF RESULTS SHOWING THE TEMPERATURE REDUCTIONS PROVIDED BY THE OPTIMAL 2 CONFIGURATION WITH RESPECT TO THE REAL ONE. WORKING HOURS: MONDAY – FRIDAY, 9:00 – 18:00

Summary of results: Optimal 2 vs. Real configurations		
	Office 1 (with PCMs)	***Office 2 (without PCMs)***
Maximum temperature drop [K]	2.05	1.36
Maximum temperature drop during working hours [K]	0.98	0.88
Average temperature drop [K]	0.56	0.57

B. *Effects of changes in the shading control*

From the obtained results, it was observed that the scenario representing the real case provided almost the same effect in the room temperature as the optimal one. This can be explained by the fact that the real shading control was defined to operate from 7:00 until 16:00, and at this time the sun is no longer directly facing the façade. This leads to a lower solar irradiance being received at the window, which does not cause a significant deviation from the optimal case operating from 7:00 until 20:00. For instance, to illustrate a more unfavorable scenario and to better identify the effect caused by the window blinds, the case without any shading control was also included in the model, which represents the windows remaining uncovered during the entire day. A summary of the results is provided in Table IX, showing the temperature increase caused by the lack of a shading control.

TABLE IX. SUMMARY OF RESULTS SHOWING THE TEMPERATURE INCREASE CAUSED BY A LACK OF SHADING CONTROL. WORKING HOURS: MONDAY – FRIDAY, 9:00 – 18:00

Summary of results: Optimal shading vs. no shading		
	Office 1 (with PCMs)	***Office 2 (without PCMs)***
Maximum temperature increase [K]	1.23	1.78
Maximum temperature increase during working hours [K]	1.21	1.78
Average temperature increase [K]	1.09	1.38

C. *Influence of PCMs in Office 2*

Since Office 2 does not contain any PCMs in reality, it was of interest to implement the established hypothetical scenarios when PCMs are integrated, with the purpose of discerning the influence these could have in Office 2 under different operating conditions. Again, when isolating the effects caused by changes in the night cooling operation, it was concluded that the greatest benefit to the room temperature is brought by an increase in the air change rate during the evening (Optimal 2). Regarding the shading control, its effect was better observed when comparing the optimal scenario with the case without any shading. For instance, these were the configurations taken into account when modelling Office 2 with PCMs. The obtained temperature profiles are provided in Figures 5 and 6, when varying the night cooling operation and the shading control, respectively.

When looking at the effect that PCMs have in Office 2 under different infiltration configurations, shown in Figure 5, it was found that even under optimal infiltration conditions, the use of PCMs provides an additional maximum temperature drop of 1.0 K (labelled in Figure 5) when considering all the hours during the day from the 9th until the 15th of July. This temperature difference is obtained when comparing the Optimal 2 setup with and without PCMs (i.e. the green dashed and solid lines in Figure 5, respectively). Also, a maximum decrease of 0.6 K during working hours from Monday through Friday, from 9:00 until 18:00, was obtained, as well as an average temperature reduction of 0.5 K.

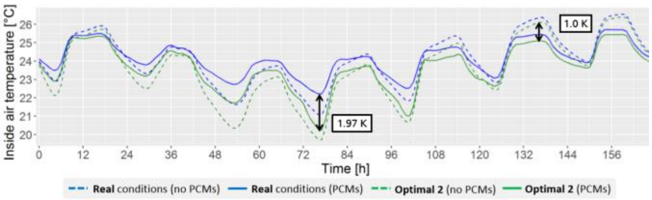

Fig. 5: Temperature profile obtained from *ESP-r* for the different infiltration configurations, with and without PCMs, in Office 2. Time frame considered: July 9 – 15, 2018

Furthermore, when comparing the Real and Optimal 2 setups, both with PCMs (i.e. the solid blue and solid green lines in Figure 5, respectively), it was concluded that the use of a higher air change rate leads to lower temperatures in the evening, which can further assist the PCM in releasing the heat absorbed during the day and in returning to its solid state. More specifically, the use of the Optimal 2 configuration with PCMs provides a maximum temperature drop in the evening of 1.97 K (labelled in Figure 5), with respect to the Real case also containing with PCMs. Also, during working hours a maximum reduction of 0.8 K was obtained, as well as an average temperature drop of 0.5 K during the week in question.

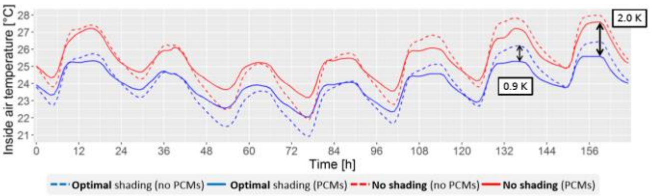

Fig. 6: Temperature profile obtained from *ESP-r* for the different shading control configurations with and without PCMs

Continuing with the results obtained in Figure 6 when considering the effect that PCMs have in Office 2 under different shading conditions, it was found that even though the shades could be operated more efficiently without having any installed PCMs, the presence of PCMs under optimal shading conditions provides an additional maximum temperature drop of 0.9 K (labelled in Figure 6), a maximum decrease of 0.6 K during working hours, and a reduction of 0.40 K in average. Also, the use of latent heat storage contributes towards the attenuation of temperature fluctuations inside the room. Finally, it was concluded that the use of shading control was crucial to enhance the performance of the PCMs. When comparing the results from the scenarios containing PCMs (i.e. the solid blue and solid red lines in Figure 6), it was determined that the use of the optimal shading control from 7:00 until 20:00, provides an average temperature reduction of 1.3 K, a maximum decrease of 2 K (shown in Figure 6), and a maximum temperature drop of 1.9 K during working hours. This additional decrease in temperature provided by the shading control would prevent the PCM from reaching a saturated state during the day. Finally, in Figure 6 it was also observed how the use of the optimal shading settings assists in keeping the room temperature within the melting range of the PCM, defined to be between 23 and 26 °C.

1) Cooling degree hours (CDH)

To further analyse the influence that PCMs would have in Office 2, the cooling degree hours (CDH) were calculated employing the simulation results for the scenarios established in Table X. Here the Real and Optimal 2 infiltration scenarios correspond to the same ones described previously in Tables IV and VI, respectively, which were used to illustrate the differences in the night cooling operation. Similarly, the shading control was defined to operate between 7:00 and 16:00 independently of the irradiation at the façade. Here the time frame considered includes the months of July, August and September, 2018. The CDH correspond to the number of hours in which the temperature inside the room goes above a defined maximum comfort value, established to be equal to 25.5 °C, based on the norm DIN EN 15251 [8]. The CDH would then represent the number of hours during which a cooling system would be needed, in order to bring the temperature below the defined maximum comfort temperature. Decreasing the CDH implies that the cooling demand of a building is reduced; for instance, a broader overview of the effect caused by the PCMs can be examined for a longer period of time, instead of focusing entirely on the temperature differences during a week only. This approach would show a macro effect, whereas the temperature differences previously calculated correspond to a more detailed and specific approach.

TABLE X. SUMMARY OF RESULTS SHOWING THE TEMPERATURE INCREASE CAUSED BY A LACK OF SHADING CONTROL. WORKING HOURS: MONDAY – FRIDAY, 9:00 – 18:00

Case	**Parameter of interest**	**Infiltration**	**Shading**	**PCMs**	**CDH [°C hours]**
1a	Infiltration	Real	None	✔	820
1b	Infiltration	Real	None	✘	912
1c	Infiltration	Optimal 2	None	✔	630
1d	Infiltration	Optimal 2	None	✘	771
2a	Shading	Real	None	✔	820
2b	Shading	Real	None	✘	912
2c	Shading	Real	Yes	✔	324
2d	Shading	Real	Yes	✘	449
3a	Infiltration and shading	Optimal 2	Yes	✔	258
3b	Infiltration and shading	Optimal 2	Yes	✘	385

The differences in CDH, with and without PCMs, for different infiltration and shading control conditions are provided in Figures 7 and 8, respectively. From both diagrams it can be observed that the presence of PCMs reduces the cooling demand of the office due to a smaller number of CDH. When considering the infiltration cases in Figure 7, under the Real conditions, the PCM provides a decrease in CDH of 10% whereas with the optimal case, a decrease of 18.3% is obtained. On the other hand, following Figure 8 to observe the influence of the shading control, if the windows remain completely uncovered a reduction of 10% would be achieved, whereas when operating the window blinds with the established schedule, a decrease of 27.8% can be attained. Finally, in Table X the last cases labelled as Case 3a and 3b represent the maximum benefit which can be provided by the Optimal 2 setup along with the shading control, with and without PCMs. Even under optimal conditions of both the night cooling (represented by the infiltration value) and the shading control, the use of PCMs provides a decrease in CDH of 33%.

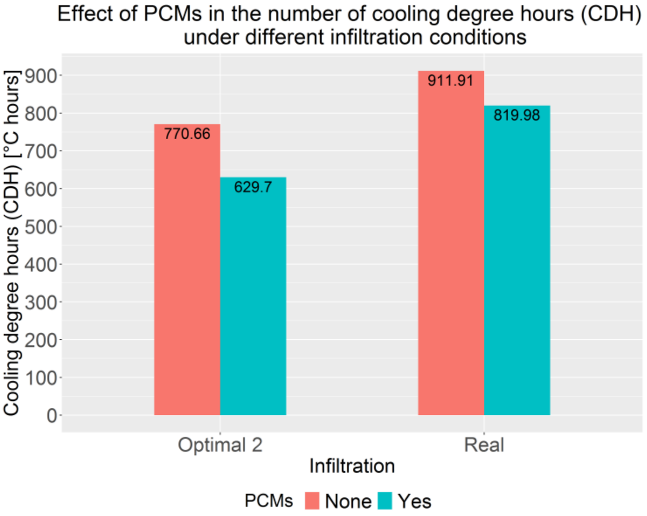

Fig. 7: Difference on the cooling degree hours (CDH) under different night cooling conditions. Time frame considered: July, August and September, 2018.

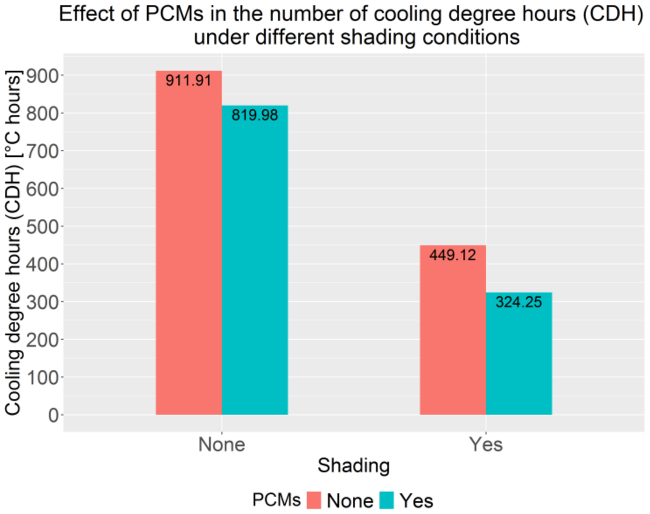

Fig. 8: Difference on the cooling degree hours (CDH) caused by use of the shading control operating everyday from 7:00 until 16:00. Time frame considered: July, August and September, 2018.

V. CONCLUSIONS

A. *Operation recommendations*

Based on the results obtained in the implementation of the model and the CDH calculations, the following recommendations could be made in regard to the night cooling operation and the control of the window shades, in order to increase thermal comfort in the office environments, and enhance the effect of the PCMs:

1) *Night cooling operation:*

a) The operation of the ventilation system in the Sonnenschiff is advised. This system counts with a cross-flow heat exchanger and a high efficient motor [3]. During the mesurement campaign this system was not under operation; nevertheless, its operation at night during the warmer months is recommended, in order to assist the PCM in releasing the absorbed heat and going back to its solid state. Results shown during the model implementation and the CDH calculations, did prove that the increase of the air change rate during the evening would enhance the performance of the PCM, which in turn would be reflected in lower room temperature levels even during working hours.

b) In the scenario labelled as Optimal 2, the ACH was doubled from 2 to 4 ACH. Nevertheless, in practice the air change rate could be further increased if desired by the occupants in the offices. In the Sonnenschiff, the ventilation system can be controlled by alternating between three switching stages, which provide three different air velocities. Even though a highly efficient motor is installed [3], its consumption must also be taken into account. Therefore, the selected air velocity must be optimized with the objective of maximizing temperature drop and thermal comfort, while maintaining low electricity expenditures and operational costs.

2) *Shading control operation:*

a) It is of great importance to operate the window blinds during the day in order to prevent the PCM from reaching a saturated state. Results show how the use of the shading control helps in reducing the room temperature during working hours, and in maintaining the room temperature within the melting range of the PCM between 23 and 26 °C. This allows the PCM in maintaining its cyclic behaviour from solid to liquid state and vice versa.

b) If a time-dependent control is employed, it was concluded that its activation at 7:00 was reasonable. During the summer, the façade is already exposed to the sun as early as 6:00; nevertheless, results from the simulation indicated that the activation of the shades at 6:00 instead of 7:00 did not present any additional benefit to the room temperature. The simulation results in these two cases were almost identical. Also, the shading control could stay activated until either 15:00 or 16:00 without compromising the room temperature. Keeping the window shades down after 16:00 did not show a significant drop in the room temperature. This was observed when comparing a shading control operaitng from 7:00 until 16:00, with another one from 7:00 until 20:00.

c) It is advised to set an automated shading control even during the weekends, even if the offices remain unoccupied.

B. *Model quality*

1) *Calibration:*

- The model generated in *ESP-r* for both Office 1 and Office 2 was successfully calibrated for the months of July, August and September. During the adjustment process, infiltration was kept fixed at 0.5 ACH, ventilation at 1.5 ACH from a 24 °C source, and neither shading control nor casual gains were defined to reduce uncertainties. After the calibration of Office 1 (with PCMs) an R^2 coefficient of 0.80 was obtained when integrating a PCM with a 100% of its latent heat capacity, and when defining its latent heat to be an increasing linear function of temperature. Regarding Office 2 (without PCMs), a final R^2 value of 0.75 was obtained.
- In general, the model showed higher temperature fluctuations during weekends and days with lower occupancy. In reality, based on the temperature measurements, these days have a more attenuated curve.

2) *Validation:*

- From the statistical results obtained during the validation process, it was observed that the model is sensitive when being compared against data from a month not used during the calibration. Again, the calibration of both models was done for the months of July, August and September, while the validation period covered nineteen days of the month of June of the same year. As a consequence, during the model implementation a week in July was analysed given that this month presented a better fit. Also, when calculating the CDH for the different scenarios to obtain a macro perspective of the effect of the PCMs, the same three months used during the model calibration were employed.

In general, from the calibration and validations results it was difficult to determine the current latent heat capacity of the PCMs integrated in the internal walls of Office 1, after being in operation for ten years. In the measured data, there are too many factors that influence the temperature inside the rooms, which prevents the isolation of the effect of the PCMs only.

C. *Model uncertainties and limitations*

The model generated for Office 1 and Office 2 in *ESP-r*, was subjected to the following uncertainties:

- The weather parameters obtained from the meteorological station at the Albert-Ludwig University in Freiburg might differ from the data which could be measured at the location of the Sonnenschiff, such as the wind velocity, wind direction and global irradiance. The different environments surrounding the Sonnenschiff and the meteorological station, the distance between both locations, as well as their relative difference in elevation, could contribute to the data uncertainty.
- The exact construction details, such as the order of the layers and their dimensions were unknown. Likewise, no information regarding the thermal properties of the materials in the Sonnenschiff was found; therefore, standard values had to be used.
- From the documentation available it was known that the melting range of the PCM goes from 23 to 26 °C, and that it was made out of micro encapsulated paraffin wax. On the other hand, the latent and specific heat storage capacities of the PCMs were obtained from the results of a differential scanning calorimetry test (DSC), facilitated by Fraunhofer ISE. Different results could be obtained from this test depending on the way it is set up, which also contributes towards the model uncertainty. The measured latent heat capacity depends on the mass of the sample, and on both cooling and heating rates [9].
- The infiltration value of 0.5 ACH was first established for closed windows based on the minimum required airtightness in order for a building to be considered as a low consumption and energy efficient construction [10]. No additional documentation was found regarding the actual airtightness of the Sonnenschiff and no experiment was carried out to determine an empirical value. In addition, when recreating a case with the ventilation panel being tilted, the infiltration of 0.5 ACH was increased to 0.7 ACH. Then, in the case the panel is opened, a higher value of 1.0 ACH was defined considering that the airstream flows through a greater area. As a consequence, these assumptions add to the model uncertainty since the values employed could be an underestimate of the actual air change renewal in the rooms.
- Regarding the ventilation value, a value of 1.5 ACH was chosen to represent the air change rate between the offices and the hallway. Similarly, no measurements were carried out and no empirical formulas were found to corroborate this value.
- The way in which the user behaviour is entered in *ESP-r* is limited. Generalizations regarding the infiltration and ventilation values, as well as the shading control had to be made when setting up the model, which could have led to discrepancies in the simulation results. For example, even though an automated shading control is activated in the Sonnenschiff during the warmer months, user intervention is always possible. This causes the shading control to vary on a daily basis, whereas in *ESP-r* the same shading control is applied for every single day in the simulation period.

D. *Future considerations*

- For future modelling and simulation tasks in the context of buildings, it is considered to be of great importance to have access to more detailed construction details, including the order of the layers with their respective dimensions.
- For the calibration process it would be beneficial to have access to measured data covering longer periods of time, during which there is very slight user intervention or none at all. This would assist in better isolating the effect of the PCMs.
- If further work is carried out within the *ESP-r* simulating environment, a different PCM model could be implemented. For this study, the simple PCM model was used, although various codes have been developed of *ESP-r* and are available on the official website [11].
- In case the ageing of the PCM is of interest in future studies, the model can be calibrated by altering not only the latent heat storage capacity, but its thermal conductivity as well, since studies have shown that this thermal property is also subjected to changes and deterioration over time [12].
- For future studies it is of interest to further quantify the effect of the PCMs. For example, the number of hours above or below a temperature of interest could be obtained. This would provide a broader overview and assist the comparison between the cases with and without PCMs.
- Switching to a different model environment such as EnergyPlus has been considered. Documentation must be revised to determine whether models including PCMs have been successfully calibrated and validated.
- Finally, besides the technical feasibility it is also important to consider the economic aspect when comparing the cases with and without PCMs. For example, the calculation of the net present value would be of great assistance by considering the investment made when purchasing, installing and operating PCMs (e.g. if a ventilation system is used to enhance the performance of the material), as well as the expected monthly monetary and energy savings. This investment appraisal method would assist in determining whether the purchase and installation of PCMs would be economically feasible.

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