BUILDING-INTEGRATED PCM-TES FOR PEAK LOAD REDUCTION

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ABSTRACT

The objective of this paper is to study, through simulation, the impact of an active Phase-Change Material based Thermal Energy Storage (PCM-TES) system on the peak heating demand during a winter morning start-up for a low thermal mass office. The PCM-TES intended for building integration consists of PCM panels with active air circulation between the panels. Air is drawn through multiple channels to charge and discharge the PCM enabling the system to be used for both heating and cooling purposes – conditioned air, room air or outdoor air for night cooling can be utilized. Model-based control strategies are employed for better latent heat utilization and improved system integration. Results showing the reduction of the peak electric demand are presented for varying amounts of PCM and for different HVAC activation times.

INTRODUCTION

In Québec, non-industrial buildings account for 51% of the electrical consumption (NRCan-OEE, 2013). Winters are characterized by large electrical peak demands due to the need for space heating, which is often electric in residential and small to medium commercial buildings. During the morning start-up, the room temperature must be raised from its night setback to a comfortable level, resulting in a large amount of heating power. There are significant opportunities to reduce and shift this space heating peak demand by using an active Phase-Change Material based Thermal Energy Storage (PCM-TES) system. The system consists of PCM panels with active air circulation between the panels. Air is drawn through multiple channels to charge and discharge the PCM enabling the system to be used for both heating and cooling purposes. Here, only its heating performance is considered. The system would be charged throughout the day and would be used early next morning to supplement the building's HVAC system output and reduce the peak electricity demand.

The objective of this paper is to study the impact of the PCM-TES systems on the heating peak during the morning start-up in winter for an office with light thermal mass level (mainly gypsum board walls; thin concrete and/or carpeted floors) by simulating: (1) the best time to start discharging the system, and (2) the reduction of the peak given the amount of PCM added.

This paper is based on the previous work by Dermardiros (Dermardiros, 2015; Dermardiros *et al.*, 2015; Dermardiros and Athienitis, 2015). These studies conclude that a one-dimensional thermal model of the PCM-TES using a single temperature-varying capacitance per panel is accurate since the panels used are relatively thin and the heat transfer dynamics are slow. Equations describing specific heat and conductivity of the latent material as a function of its temperature were given. It was found that the fan losses in the PCM-TES were negligible compared to the energy released/stored in the system; the panels used were smooth and the air flow path was short. Finally, it was demonstrated that it is more effective to add PCM-TES systems in a parallel configuration rather than in series, *i.e.* by adding systems in series, the air exiting one system enters the other; the air being warmer will exchange less heat when passing through the second PCM-TES due to a smaller temperature difference. The new work presented here builds on the modelling methods used previously and aims to study the operation of the system in an office.

METHODOLOGY

The paper is divided into 3 sections where: (1) the office with both its EnergyPlus and simplified 1st-order models are described and developed, (2) the PCM-TES model and how it is integrated into the simplified office model

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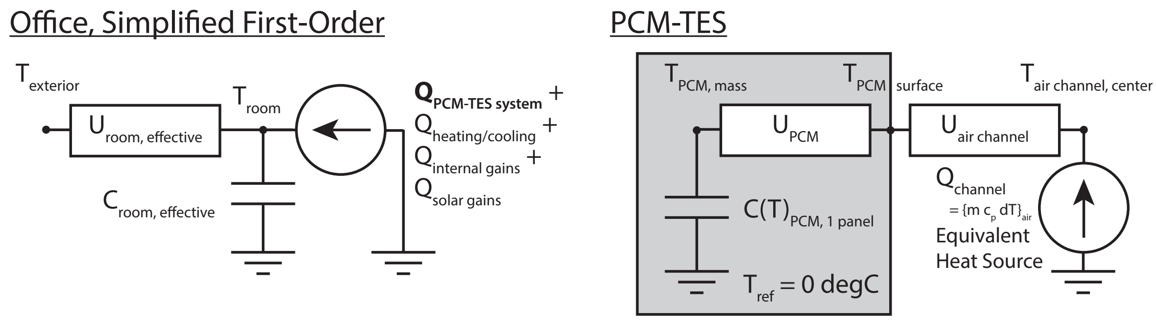

Figure 1: (Left) simplified first-order model and (right) PCM-TES model. During the training stage, the heating/cooling, internal gains and solar gains in the simplified office come from the EnergyPlus simulation results. During the analysis stage, the heating/cooling supplements the heat discharged from the PCM-TES.

is explained, and (3) simulation procedure, results and conclusion are discussed.

OFFICE DESCRIPTION AND MODELS

The office is modelled and simulated using the EnergyPlus (Crawley *et al.*, 2001) building performance simulation software. Subsequently, the outputs are used to train a simplified 1st-order model based on the implicit finite difference method. The simplified model is used in combination with the PCM-TES model. Simplified models are preferred to aid the speed of convergence of the optimization algorithm. The tuning of parameters can also be achieved using trend logs from the building automation system. The latter would allow the engineer to design and size a PCM-TES tailored for that specific office as a retrofit measure.

EnergyPlus Model

A shoebox model was designed in SketchUp with OpenStudio (Guglielmetti *et al.*, 2011) and exported into EnergyPlus. The room is a south-facing perimeter office among self-similar offices located in Montreal, QC [ASHRAE Climate Zone 6 (NRC, 2011)]. A window-to-wall ratio of 40% is used. The window is double-glazed, argon filled with a low-e (ε = 0.05) coating on surface 3. The office is 3 m wide by 4 m deep by 3.2 m high. Gypsum walls of 18 mm thickness and a 50 mm light-weight concrete floor make up the interior construction. Pre-constructed RSI-2.5 panels are used for the exterior enclosure in compliance with ASHRAE Standard 189.1 (ASHRAE, 2009).

The interior schedules are based on ASHRAE Standard 189.1. Occupants start coming in at 6:00 AM and are all present by 8:00 AM. Occupants leave work starting 5:00 PM. Lighting, electrical equipment and infiltration schedules are input following the Standard. A 10 $W \cdot m^{-2}$ power density was assumed for lighting, 5.4 $W \cdot m^{-2}$ for the equipment and a 0.2 ACH infiltration rate. The heating setpoints are 21°C when occupied (6:00 AM to 7:00 PM during weekdays) and 16°C when unoccupied (nights, weekends and holidays). The cooling setpoints are 24°C when occupied and 28°C when unoccupied. An idealized HVAC system is used. Gunay *et al.* (2014) report that a 5-minute timestep is adequate to estimate the parameters of 1st-order and 2nd-order control models and this timestep was used in the study.

Simplified Model

The EnergyPlus simulation results corresponding to the coldest week in Montreal – based on the TMY2 weather file (EPW, 2016) – are used to train a simplified 1st-order model with one capacitor and one resistor shown in Figure 1 Left. The internal gains are aggregated into one term. Higher order models were not trained since they may lead to unstable parameter estimates (Maasoumy *et al.*, 2014), such as negative resistance values. To remedy the issue, more observation points would be required, *e.g.* the average enclosure surface temperature would be added and attached to one point in the model, then, the operative temperature on another. The heat balance equation following the implicit finite difference method can be written as follows:

$$U_{room}\left(T_{exterior}^{t+1} - T_{room}^{t+1}\right) - \frac{C_{room}}{\Delta t}\mathrm{T}_{\mathrm{room}}^{\mathrm{t+1}} + \sum \dot{Q}_{gains}^{t} = -\frac{C_{room}}{\Delta t}\mathrm{T}_{\mathrm{room}}^{\mathrm{t}} \quad (1)$$

In order to estimate the room effective resistor/capacitor pair, the Nelder-Mead (1965) optimization algorithm implemented in SciPy (Jones *et al.*, 2014) was used. The two values minimizing the squared error of the difference between the EnergyPlus room operative temperature and the model's room air node temperature are evaluated. The resulting values and a comparative plot are shown in Figure 2 and Table 1.

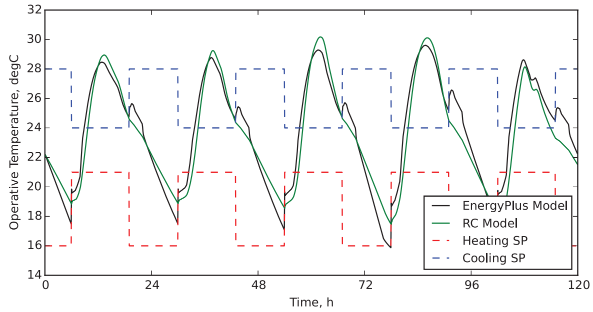

Figure 2: EnergyPlus and first-order model room temperatures.

Table 1: 1st-order model parameter estimates.

R, $K \cdot W^{-1}$	2.754
C, $J \cdot K^{-1}$	$2.021 \cdot 10^6$

PCM-TES

More than 30 years of research and development have been realized on phase-change materials integrated into construction materials and building systems (Kuznik *et al.*, 2011). Systems have been simulated and experimentally analyzed utilizing PCMs in either isolated, zone-coupled or surface-coupled configurations (Kosny, 2015; Osterman *et al.*, 2012; Sharma *et al.*, 2009). Among them, multi-panel PCM-TES systems designed like a heat-exchanger offer a scalable and controllable solution for active thermal energy storage (Charvát *et al.*, 2014; Dolado *et al.*, 2012).

An active panel system can be installed in the building enclosure, ceiling or floor space, close to the thermal zone it serves. It can be zone-coupled where the PCM-TES exchanges heat with the zone indirectly through ventilation; or, it can be surface-coupled where a PCM surface is left exposed and exchanges heat directly with the zone (see Figure 3). The latter would, for example, improve the ability of the system to absorb solar radiation, but would degrade the controllability of the system due to passive heat exchanges. The PCM-TES serves as a retrofit or new construction measure. It acts as dispatchable storage: a solution to augment the thermal inertia of a building with minimal structural weight. By using air as the heat transfer fluid, the system can be directly integrated to the HVAC system – without the need for heat-exchangers – and can also take advantage of night-time free-cooling. It can be used for both heating and cooling purposes. Here, a zone-coupled system is analysed focusing strictly on heating.

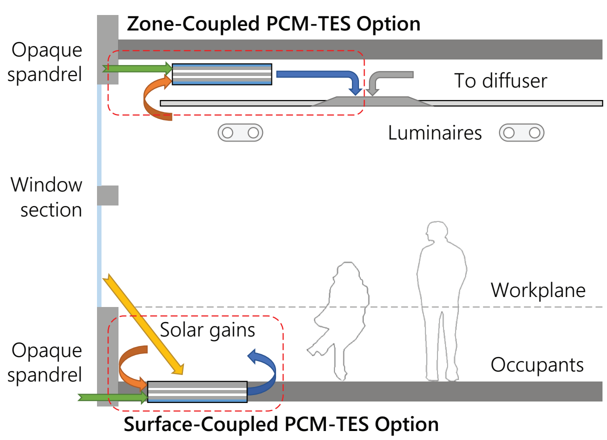

Figure 3: PCM-TES configurations: zone-coupled and surface-coupled.

The PCM-TES modelling in this section is based on experimental and numerical work by Dermardiros (Dermardiros, 2015; Dermardiros *et al.*, 2015; Dermardiros and Athienitis, 2015). Shape-stabilized DuPont Energain panels that are 1 m by 1.2 m by 5.2 mm thickness, weighing 5.4 kg, and consisting of a paraffin wax (60%wt) suspended in an ethylene-based polymer is used (Kuznik *et al.*, 2008). The active PCM-TES system is modeled by a thermal network shown in Figure 1 Right and described by Equation Set 2. Unlike conventional building materials, both the thermal capacitance and conductance of the PCM varies greatly around its phase transition temperature. The capacitance is modelled using the heat capacity method which consists of varying the PCM specific heat as a function of its temperature (Al-Saadi and Zhai, 2013) (see Figure 4). The conductance varies by ±12% around its mean $0.20\ W \cdot m^{-2} \cdot K^{-1}$. Using simply the average has a negligible effect on the overall energy balance. Each panel can store around 0.18 kWh within the temperature range used in this study.

Within the PCM-TES air channel, heat is exchanged between the air stream and the PCM through convection – represented by a convective heat transfer coefficient of

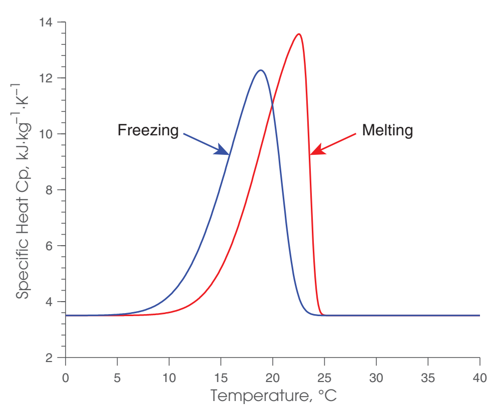

Figure 4: Specific heat as a function of PCM temperature. In this study, only the freezing curve is considered.

$$U_{PCM}\left(T^{t+1}_{PCM,\,surface}-T^{t+1}_{PCM,\,mass}\right)-\frac{C_{PCM}\,(T)^{t}_{i}}{\Delta t}\mathrm{T}^{t+1}_{PCM}=-\frac{C_{PCM}\,(T)^{t}_{i}}{\Delta t}\mathrm{T}^{t}_{PCM} \tag{2a}$$

$$U_{PCM}\left(T^{t+1}_{PCM,\,mass}-T^{t+1}_{PCM,\,surface}\right)+U_{air\ channel,\,convection}\left(T^{t+1}_{air\ channel}-T^{t+1}_{PCM,\,surface}\right)=0 \tag{2b}$$

$$U_{air\ channel,\,convection}\left(T^{t+1}_{PCM,\,surface}-T^{t+1}_{air\ channel}\right)+\dot{Q}^{t}_{equiv.\ source}=0 \tag{2c}$$

$$T_{air,outlet}=T_{air,\,inlet}\cdot\exp\left(\frac{-h_{conv}\cdot A_{PCM}}{\dot{m}_{air}\cdot C_{p,air}}\right)+T_{PCM,\,surface}\cdot\left[1-\exp\left(\frac{-h_{conv}\cdot A_{PCM}}{\dot{m}_{air}\cdot C_{p,air}}\right)\right] \tag{3a}$$

$$\dot{Q}^{t}_{equiv.\,source}=\dot{m}_{air}\cdot C_{p,\,air}\cdot(T^{t}_{air,\,outlet}-T^{t}_{air,\,inlet}) \tag{3b}$$

18 $W\cdot m^{-2}\cdot K^{-1}$ (Dermardiros and Athienitis, 2015). Air flows through the 30 mm channel at 50 $kg\cdot h^{-1}$ (11.8 $L\cdot s^{-1}$) times the number of PCM panels. The air stream heating is modelled by an equivalent heat source (see Equation Set 3). The boundary behind the PCM is assumed to be adiabatic and heat transfer is one-dimensional along the width of the PCM.

SIMULATION PROCEDURE

The models of the office and the PCM-TES are combined. When the PCM-TES is enabled, room air is drawn into the system and it discharges the stored heat into the office air node. Perfect air mixing is assumed. Throughout the day, the PCM-TES is assumed to be charged using waste heat from internal gains, *e.g.* solar gains, electrical loads, occupancy, either from the actual zone or from the building core zones. Since the system would be installed in the ceiling space, it can also utilize heat from recessed lighting. At the beginning of the simulation, the PCM-TES is charged to 28°C. For the system to be effective, the energy quality used to charge should be near the energy quality being discharged, *i.e.* electrical heat should seldom be used to charge the system. When the air going through the TES system no longer gains heat, the airflow is toggled off.

The simulation timeframe is between 3:00 AM and 7:00 AM during the coldest day of the week used for calibrating the simplified model. The office temperature must be between the heating and cooling setpoints, otherwise a difference proportionate penalty is applied. Four cases for the HVAC system are simulated. The HVAC is allowed to be activated starting at {3:00, 4:00, 5:00, 5:30} AM. The PCM-TES is allowed to be activated between 3:00 AM up to the time where the HVAC is allowed to turn on. PCM-TES systems containing {6, 12, 18, 24, 48} panels have been simulated. Since the simulations are set up to minimize the peak power demand, as soon as the HVAC is allowed

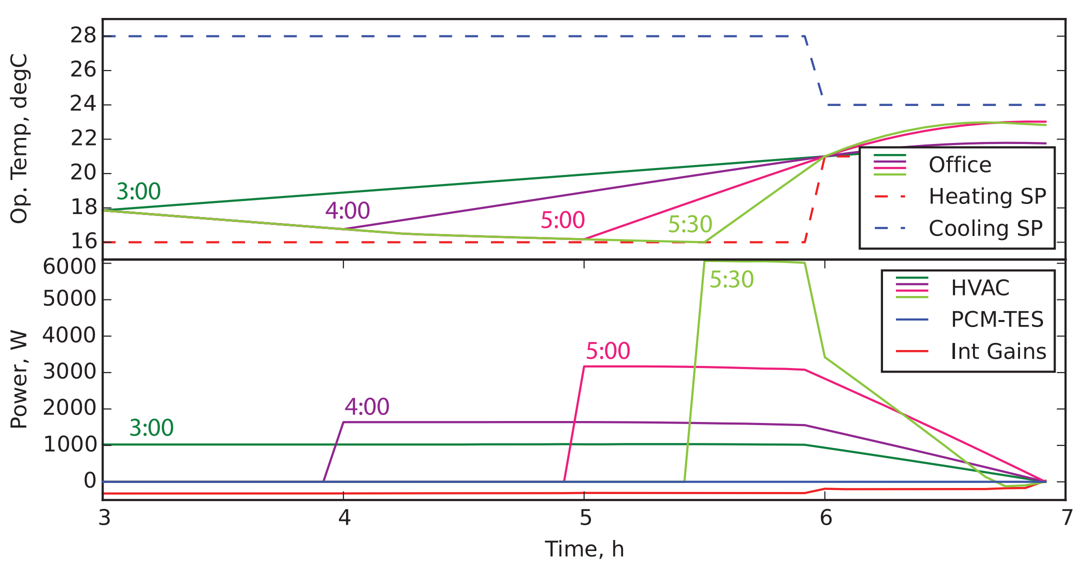

Figure 5: Office temperature and HVAC supplied heat depending on the time when HVAC is allowed to be used.

to turn on, it will; and so to better utilize the PCM-TES, the PCM needs to start discharging before the HVAC initiates. Before the HVAC or PCM-TES is activated, the room air temperature is read from the EnergyPlus results file. When either is activated, the room temperature seizes to be read and is instead calculated using the 1st-order model. The model's initial conditions come from the last read temperatures from the results file.

In order to minimize the peak heating demand, a model-based control scheme is used. During the simulation period, it is assumed that there is perfect knowledge of the future ambient temperature and internal gains. Although it is an optimistic assumption, the effects of the weather is minimal due to the enclosure's high R-value and the variance on internal gains for an unoccupied office should be low. In a future study, a statistical and robust approach will be considered to better allow for prediction and model uncertainties for full day and full year analyses.

In order to determine the HVAC heating output sequence, the BFGS optimization algorithm (Nocedal and Wright, 2006) implemented in SciPy is used. The objective function is to minimize the squared error between the room air temperature and setpoints plus a scaled peak heating demand penalty. In order to determine the best time to start discharging the PCM-TES, all the time steps when the PCM-TES can be activated have been simulated. The PCM-TES activation time which minimizes the peak is considered the best. The results are discussed in the following section.

RESULTS AND DISCUSSION

To assess the impact of the PCM-TES systems on the peak load, cases without them must be first analysed. Figure 5 shows a clear trend: as the time between when the HVAC is allowed to be used and the morning setpoint change becomes shorter, the peak heating power required increases. In the case where this time difference approaches zero, it yields the reactive controls case; one can hypothesize the magnitude of the peak. Interestingly, if the temperature curves were to be programmed into a reactive proportional controller per time step, as a schedule, it would result in the peak reducing output from the bottom sub-chart.

Implementing the start time and number of panels of the PCM-TES systems into the objective function would have resulted in long optimization times that cannot be justified without first having well considered the prediction and modelling uncertainties. Instead, pragmatic cases were tested one by one. The objective is to, for a given time when the HVAC can be activated and for a given number of PCM panels to: (1) determine the best time to start discharging the PCM-TES, and (2) assess the reduction of the peak demand.

Before considering the results, examine the following example in Figure 6. The HVAC can be activated starting at 5:00 AM. Three cases are shown: (1) no PCM, (2) 12 PCM panels, and (3) 24 PCM panels. The curves for the cases with PCM are the results of the best PCM-TES discharging time, respectively. The best time to start discharging (2) is at 4:25 AM and (3) at 3:45 AM. By discharging the PCM earlier, the room becomes

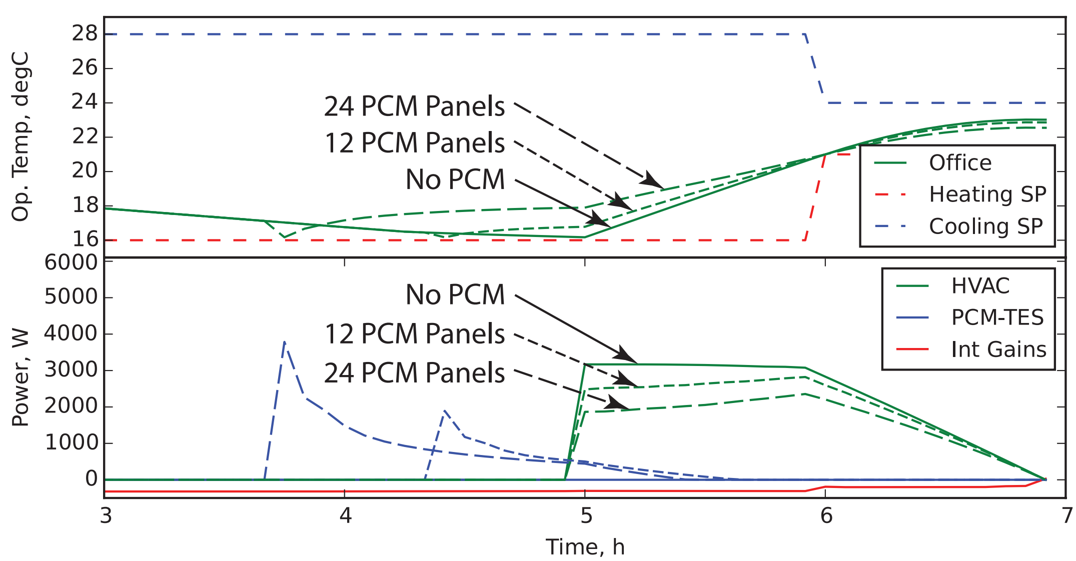

Figure 6: Office temperature, HVAC and PCM-TES supplied heat depending on three cases: (1 – solid line) when no PCM is used, (2 – short dash) a PCM-TES with 12 panels is used and (3 – long dash) a PCM-TES with 24 panels is used. The HVAC is allowed to be used starting at 5:00 AM.

Table 2: Ideal PCM-TES discharge starting time. The different columns represent the time when the HVAC is allowed to be used. Earliest PCM-TES starting time is 3:00 AM.

Panels	3:00	4:00	5:00	5:30
6	3:00	3:55	4:55	5:25
12	3:00	3:55	4:25	5:05
18	3:00	3:50	4:10	4:20
24	3:00	3:30	3:45	3:55
48	3:00	3:10	3:10	3:10

Table 3: Relative peak electrical heating power of the office with a PCM-TES system compared to the base scenario without. The different columns represent the time when the HVAC is allowed to be used. The first row under the header is the peak power for the office without PCM, in Watts. The electrical peak power reduction percentage can be calculated by subtracting a unit value by the percentages in this Table.

Panels	3:00	4:00	5:00	5:30
None	1035	1640	3170	6065
6	96%	96%	95%	97%
12	92%	90%	89%	88%
18	87%	85%	82%	77%
24	83%	81%	74%	69%
48	53%	52%	51%	43%

warmer so that when the HVAC is activated, there is a smaller temperature differential between the room air and the future setpoint sequence. As a general observation, the more PCM panels used, the earlier it should start being discharged. The best starting times are in Table 2.

Focusing now on the electrical peak demand, Table 3 shows the relative comparison between the office with and without PCM. As more PCM is added, the peak is reduced. However, in relative comparison, starting the HVAC system earlier has a greater impact on the peak demand than does adding a small amount of PCM.

This study was conducted on the coldest day in the Montreal weather file. For warmer days, the peak heating demand will be lessened and the effect of the PCM-TES will be reduced. More work is required to judge the diurnal and seasonal effectiveness of the PCM-TES and to assess its economic viability. From past experiences, the cost of the PCM remains relatively high in the current electricity market resulting in an unattainable return-on-investment. An affordable alternative to the PCM used in this study must be analysed. Unlike sensible TES systems, the lifespan of PCM is short, even for paraffin-based materials (Kenisarin and Mahkamov, 2007), further hindering its feasibility. Regardless of the TES system used, occupant behaviour and thermal comfort predictions must be considered in a future study.

CONCLUSION

This paper studied the impact of PCM-TES systems on the heating peak during the morning start-up for a thermally lightweight office using a model-based approach. An office was first modelled in EnergyPlus and the results were used to train a simplified 1st order resistor/capacitor model using a global optimization routine. The same methodology can be used with building trend logs to then study the retrofit potential in an existing office. The modelling of the PCM-TES and the interconnection with the office model was described. An optimization routine was used to determine the HVAC heating output sequence that minimizes the peak heating demand while maintaining the room temperature between the setpoint boundaries. By allowing the HVAC system to be used at earlier times, the peak demand is greatly reduced. The addition of PCM through the use of an active PCM-TES will further reduce the peak. However, more work is required to judge the diurnal and seasonal effectiveness of the system and to assess its economic viability. Additionally, more work is required to improve the robustness of the system under the uncertainties in predictions, *e.g* occupancy and weather, and in modelling.

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NOMENCLATURE

T_i^t, temperature of node *i*, at time step *t*, °C;

U_{ij}, conductance between nodes *i* and *j*, $W{\cdot}K^{-1}$;

R_{ij}, resistance, inverse of conductance, $K \cdot W^{-1}$;

$C(T)_i^t$, capacitance of control volume i as a function of its temperature at the current time step t and is equal to $\rho \cdot A \cdot dx \cdot C_p(T)$, the specific heat, $C_p(T)$, is assumed constant for a building material not undergoing a phase-change, $J \cdot K^{-1}$;

$\dot{Q}_i^t$, heat flow into the node, W;

Δt, time step, s; and,

$\dot{m}$, mass flow, $kg \cdot s^{-1}$

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