BENEFITS OF LATENT THERMAL ENERGY STORAGE IN THE RETROFIT OF CANADIAN HIGH-RISE RESIDENTIAL BUILDINGS

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ABSTRACT

High-rise buildings hold the highest share of the existing residential stock in major Canadian cities. However, their poor performance is often characterized by indoor discomfort conditions and high energy consumptions. Decreasing the energy demand of high-rise residential buildings is therefore critical. Over the last few years, thermal energy storage has often been proposed to stabilize indoor temperatures and improve the thermal environment, which influences the energy demand of buildings. This study investigates the benefits of latent thermal energy storage systems obtained by incorporation of phase change materials (PCM) into walls and ceilings of apartment units. A composite system, 2 cm thick, composed of two PCM products with melting temperatures of 21.7 ºC and 25 ºC is investigated. The effectiveness of this thin composite PCM system is studied in the climates of Toronto and Vancouver by assessing the changes in indoor temperatures and energy demands. A parametric analysis is performed using simulations done with EnergyPlus™. The results show that the composite PCM system improves the indoor temperatures in both cities by reducing temperature fluctuations and balancing temperature peaks. Overall, the benefits of this system result in the reduction of the cooling energy demand by 6% in Toronto and 31.5% in Vancouver. Finally, the benefits of the investigated system are discussed.

INTRODUCTION

One of the greatest challenges that the world faces today is global climate change as a result of the incessant rise in greenhouse gas (GHG) emissions. Changing climatic patterns not only affect the environment, but also the human health, and many economic activities. Moreover, considering the important role of energy in our societies, the implications of climate change on energy supply and demands are critical. In this context, the built environment is accountable for nearly 40% of total GHG emissions as a result of high energy consumption (Berardi, 2017). In particular, residential buildings hold the highest share in energy use mainly attributed to space conditioning. The prediction for building energy use indicates a 179% rise in space heating and cooling demands by 2050 with respect to 2010 energy consumption rates in buildings (Berardi, 2017).

Fast growing population, social changes and new lifestyles are leading to increased urbanization processes, which have a direct link with energy demands and related GHG emissions. Considering the pattern of urbanization and housing typology, more and more people live in multi-unit residential buildings in large cities, even in countries such as Canada where the availability of lands is not a critical issue. In fact, high-rise apartments make up the largest share of residential stock in major Canadian cities such as Toronto and Vancouver (NRCan, 2016). Given the high number of high-rise apartments and their fast-growing market in Canada, it is essential to apply energy efficiency measures in this building typology (RDH, 2012; Touchie et al., 2014). However, considering the low rate of replacing this existing stock with new buildings, energy

retrofit is an imperative solution to mitigate the environmental impacts of the existing residential towers.

The majority of high-rise apartments in Canada were built in an era of cheap energy when energy efficiency was not an important design criterion. The wasteful energy performance of high-rise apartments is attributed to multiple factors such as poor insulation, inefficient mechanical systems, air leakage and poor performing windows. However, even in new high-rise apartments often built with fully glazed facades, the negative impacts of the large window to wall ratios (WWR) reduce the benefits of the better building enclosures. Thermal discomfort, often due to indoor temperature fluctuations, is hence a major issue in both new and old apartments. Meanwhile, several studies on high-rise apartments in Canada concluded that the highest percentage of energy demand in these buildings is due space conditioning (RDH, 2012; Alsaadani et al., 2016). Consequently, new solutions to reduce the energy demand of Canadian buildings are timely important (Nikoofard et al., 2015).

In this study, the thermal energy storage is proposed as a retrofit measure to regulate indoor temperatures and mitigate daily temperature swings in apartments in order to reduce the need for mechanical systems. Based on the results of recent researches (Nikoofard et al., 2015), the incorporation of latent thermal energy storage systems using phase change materials (PCMs) is investigated. In particular, this study investigates innovative thermal energy storage systems obtained by combining multiple PCMs with different melting temperatures.

LITERATURE REVIEW

The energy consumption patterns of existing Canadian high-rise apartments have been investigated in several studies. RDH (2012) and Alsaadani et al. (2016) have shown that the age of the buildings and the thermal resistance of the enclosure and glazing areas are the main factors influencing the energy demand of high-rise residential buildings. In particular, WWR was shown to have a linear correlation with the energy use intensity (EUI) in high-rise apartments (RDH, 2012; Touchie et al., 2014).

By reviewing the literature, it is inferred that for retrofit projects, the building sector has typically focused on improving the thermal resistance or reducing the air leakages in the enclosure. However, the thermal mass of a building is another feature that influence the energy consumption since it affects and regulates the indoor temperatures. Thermal energy storage (TES) in the indoor environment is hence key to reach a temperature stabilization. TES targets energy use savings by limiting the energy demand or transferring of loads in time, a strategy often known as peak shifting (Taylor and Miner, 2014, Bourne and Novoselac, 2015). TES was traditionally applied to buildings in form of sensible heat storage through the incorporation of massive materials, and has been typical to contrast overheating in mild or warm climates (Cabeza et al. 2011). In contrast to sensible TES systems, the use of PCMs as a form of Latent TES has gained some popularity as an optimal choice for retrofit applications (Sharma et al., 2009; Ascione et al., 2014). This is due to the higher heat storage capacity in small volumes of PCMs and to their applicability as unobtrusive measures (Soares et al., 2013). PCMs undergo a state change and store heat in narrow temperature ranges; this behavior makes them suitable for temperature regulations. The phase change is an isothermal process as PCMs melt at a specific temperature, or in a small temperature range, while their enthalpy changes. Optimally, during the day the PCMs store excess energy from the indoor spaces as they melt, and at night with lower temperatures, they solidify and release the heat back to the indoor space.

Despite the wide range of PCM applications in light-weight frame buildings (Soares et al., 2017), several studies such as Fraser (2009) or Rodriguez-Ubinas et al. (2013) have investigated the addition of PCMs to masonry and high mass buildings too, and have emphasized the positive benefits that supplementing PCMs

may provide to the existing thermal mass. Integrating PCM as an additional TES to the thermal capacity of concrete structures in high-rise apartments can thus provide benefits in regulating the indoor temperatures.

The first step for integrating Latent TES in buildings is the selection of an appropriate PCM system. The most important PCM characteristic is the melting temperature (T_{mp}); this is typically selected according to the expected indoor temperature range. In mechanically conditioned buildings, melting temperature of the PCM is hence matched to the operating set point temperatures of the HVAC system (Fiorito, 2014; Fleischer, 2015). Childs and Stovall (2012), Ascione et al. (2014), and Vautherot et al. (2015) focused on the importance of the climate and of the set point temperatures over the PCM effectiveness. The results showed a distinct behavior of PCMs in various climates for different seasons, and implied to case-specific nature of PCMs used for indoor Latent TES. For this reason, recent studies have evaluated the performance of PCM applications in Canadian buildings both in building envelopes ~~and~~ or in HVAC systems (Nikoofard et al., 2015, Bigaila and Athienitis, 2017). However, more research on PCMs in Canadian climate is necessary to show their applicability in this context, especially targeting retrofit applications in high-rise buildings. In addition to climate, the importance of solar gain is mentioned by Roriguez-Ubinas et al. (2013) and Kensiarin and Mahkamov (2016) as a critical factor for PCM performance, specifically discussing the WWR for affecting the amount of incoming solar gains inside the buildings.

Studies done by Diaconu and Crucero (2010), Passupathy and Velraj (2008) and Heim and Wieprzkowicz (2016) state that integrating a PCM with one melting point is not sufficient for annual TES. Thus, the concept of hybrid PCM systems with multiple melting points has been proposed to cover the entire year by using systems that have different melting points applicable to both the heating and cooling seasons.

To quantify the performance of PCM integration in buildings, different methods have been adopted. So far, Multiphysics modelling of building components and whole building simulations are the most prominent methods for PCM optimization and for assessing their performance. Table 1 shows a summary of the main studies that have adopted a software simulation for assessing PCMs in buildings.

Table 1: Literature of some of the main numerical studies on PCM applications in buildings.

Study	**PCM Type and Application** / **PCM Melting Temperature (T_{mp})**	**Building Type** / **Location**	**Software** / **Testing Period**	**Parameters of Study**	**Results**
Virgone et al. (2009)	Energain™ PCM in walls + ceiling	Office Building	SIM. CoDyBa	Pre and post retrofit PCM thickness	Applying PCMs with lower thicknesses in large surface areas performs better.
	T_{mp}: 21.7 ºC	Lyon 45.7 ºN	Summer		
Childs & Stovall (2012)	Paraffin in wall insulation	Test Room	Sim. HEATING 8	Climate Location of PCM Amount of PCM Wall orientation Temperature range and set point correlation	Installing PCMs on south and west walls showed to be more cost effective. Lower savings in cooling energy were observed when PCMs were applied to highly insulated walls. High effectiveness of PCMs in peak load shifting was shown.
	T_{mp}: 25 - 27 ºC	Phoenix 33.4 ºN Baltimore 39.2 ºN	Annual		
Fiorito (2014)	Rubitherm in walls	Office Room	Sim. EnergyPlus™ (Design Builder)	Lightweight and well insulated structures Location of PCM Position in	PCMs placed in interior side of the walls are more effective. PCM and insulation thickness showed direct impact of PCMs on discomfort hour reduction.

	T_{mp}:18-43 °C	Sydney 33.52 °N	One year	enclosure Thickness of PCM Melting range	
Ascione et al. (2014)	Commercial gypsum wallboard	Office Building	EnergyPlus™	T_{mp} Climate PCM location PCM thickness Natural and mechanical ventilation	The greatest energy saving was observed with the highest thickness of 3 cm for the PCM. Highest cooling energy saving of 7% was achieved in Ankara with a T_{mp}= 29 °C for the PCM.
	T_{mp}: 26 °C	Ankara 39.9°N Athens 37.9°N Marseille 43°N Naples 40.8°N Seville 37.4°N	Cooling Season		
Pisello et al. (2015)	Theoretical - PCM in roof membrane	Test room	SIM. EnergyPlus™	Two different types of roof membrane Insulation availability on the roof	The effectiveness of PCMs added to roof membrane is higher in reducing energy when no roof insulation is applied.
	T_{mp}:26 °C	Perugia 43.1 °N	Summer and Winter		

Simulation modeling is a suitable method to analyze the performance of PCMs and their impacts on energy use and indoor temperatures on a whole building scale. Furthermore, investigating several variables through parametric analysis becomes only possible using simulation models, which allow to perform comparative analysis of the factors affecting the PCM performance in buildings, as shown in Table 1 (Kosny, 2015).

EnergyPlus™ is a common simulation software for assessing PCMs (Evola et al., 2013; Ascione et al., 2014; Pisello et al., 2015; Vautherot et. al., 2015). EnergyPlus™ models PCMs using a conduction finite difference algorithm (ConFD) which discretizes the building components into multiple sensors. The ConFD algorithm is an implicit model which can be performed by either Crank-Nicholson or fully-implicit algorithms to numerically solve the heat transfer problems while the material changes phase. The algorithm uses an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase change energy accurately. The reliability of EnergyPlus™ in PCM modelling has been validated in multiple studies which showed good agreement between experimental and simulation tests (Tabares-Velasco et al., 2012).

METHODOLOGY

Since the objective of this study is to provide annual Latent TES in high-rise buildings, a composite PCM system is studied to introduce two temperatures in one zone in order to control different set point temperatures of the air-conditioning system. To investigate the practicality of PCM applications in buildings nowadays, it was also decided to focus on PCM products currently available in the market. Two products, Energain™ and BioPCM™ were finally selected to form the composite PCM system. The melting range of Energain™ PCM makes it suitable for the heating season as its melting temperature corresponds to indoor temperatures common in winter (Table 2). Reversely, BioPCM™ is intended for the cooling season since it is produced with two melting points of 23 °C and 25 °C, more suitable for summer conditions. To select the most appropriate melting point for the BioPCM™ in the composite PCM system, an optimization study was performed. The studied configuration of the composite PCM system investigated in this paper is shown in Fig 1. The BioPCM™ panel is located on the first layer behind the drywall finish and the Energain™ layer is located behind it; the reason for this layout is the higher thermal conductivity of the BioPCM™ which allows higher heat transfer from the room to the Energain™ layer.

Table 2: Thermo-physical properties of the selected PCM products.

PCM product	Thickness (cm)	Melting Temperature Range (°C)	Latent Heat Capacity (KJ/Kg)	Specific Heat (KJ/Kg·°C)	Conductivity (W/m·K)
Energain™ PCM (Gilbert and Koster, 2010)	0.5	18- 21.7	70	2.5	0.18 - Solid 0.14 – Liquid
BioPCM™ (Phase change energy solutions, 2016)	1.5	21 - 25	200	2.1	0.2

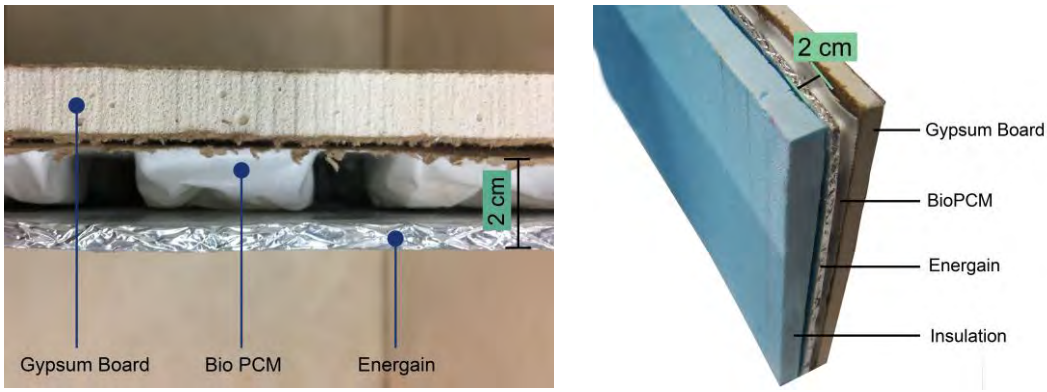

Figure 1: Composite thin PCM system investigated in this paper.

To quantify the performance of the composite PCM system, annual simulations using EnergyPlus™ were performed. Two apartment units were modeled, one base case unit as a benchmark with no PCM application and the second unit with PCM integrated walls and ceiling. Three WWRs of 40%, 60%, and 80%, were selected for each of the modeled units. In this study, only middle apartment units, with adiabatic conditions above and below and a single large glazed façade were considered, as illustrated in Fig. 2. The modeled units were created using the conventional construction characteristics; the typical structure of high-rise apartments in Toronto and Vancouver is reinforced concrete using flat slab systems. The total resistance of the opaque exterior wall is 3.6 $m^2 \cdot K/W$. The windows are double glazing windows with an overall U-value of 2.7 $W/m^2 \cdot K$. The three main walls of the units were modeled with party walls comprised of steel studs with double gypsum boards on each side. No interior partitions were added in the modeled units. The incorporation of PCMs was investigated in the three main interior walls and on the ceiling of the unit. Heat transfer was only considered from the exterior wall, since all other surfaces were set to adiabatic.

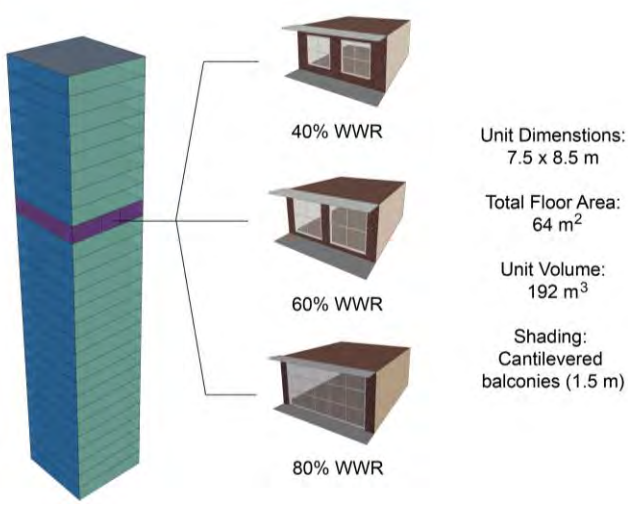

Figure 2: Representation of the three modeled units with different WWRs.

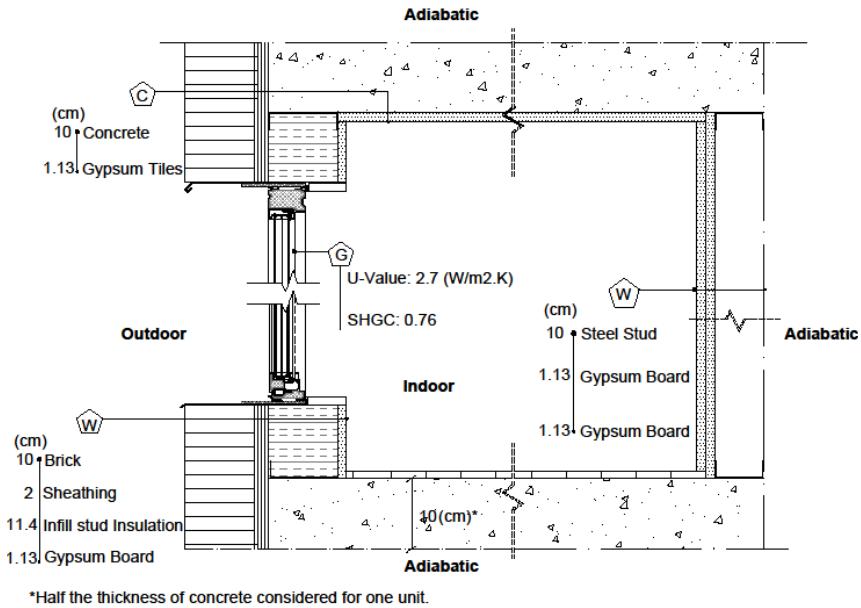

Figure 3: Schematic drawing of the enclosure in the base case model.

The mechanical system used in the model was a traditional fan coil system for both heating and cooling modes. A unitary COP was selected in order to have results independent from the mechanical system efficiency. The heating system worked from Jan 1st to May 20th and from September 20th to December 31st. Cooling operated from May 20th until September 20th. The number of occupants considered in the unit was three, and the occupancy schedule considered an unoccupied period from 9 am to 5 pm each weekday with the highest activity in the early morning and evening. The set points for heating and cooling modes are presented in Table 3; as evident, the indoor set points oscillated above and below the composite PCM's functional melting temperature to ensure the cyclical activation of the composite PCM.

The simulation study was conducted for one full year to consider the different climatic conditions experienced in the two major Canadian cities, Toronto and Vancouver. Based on ASHRAE climate zone classification, Toronto is in zone 6 while Vancouver is in zone 5: the city of Toronto has cold winters and hot summers, while Vancouver has a temperate climate with mild summers.

A prominent method extensively studied in the literature is night cooling to accelerate the solidification process of PCMs. Night cooling is either facilitated by natural ventilation or mechanical ventilation. In the simulation model, natural ventilation was not considered, as including natural ventilation in high-rise buildings is not common in the context of analysis. Furthermore, natural ventilation is an occupant driven factor which is not a reliable method due to the unpredictable nature of occupant behavior. Mechanical ventilation with a flow rate of 1 ACH allowed for the provision of night cooling in this study.

Table 3: Occupant profile and HVAC set points used in the simulations.

	Schedule	Heating Set Point	Cooling Set Point
0 am - 7 am & 6 pm - 12 pm	main	22 °C	24 °C
7 am – 6 pm	setback (during unoccupied periods)	18 °C	25 °C

PCM Data Inputs

The temperature-enthalpy function is required by the ConFD algorithm as enthalpy is updated at each time step to develop a variable specific heat capacity (Pedersen, 2007). The data inputs were derived from Differential Scanning Calorimetry (DSC) test results. While this is a well-established technique, Delcroix et al. (2015) showed differences between properties obtained from different experimental conditions for PCM, such as higher increase rates in the hysteresis and shift of the phase change temperature range towards colder temperatures. The method used to define PCM enthalpy–temperature curves was selected taking into account the particularly slow rate of temperature change in a building. Figure 4 shows the DSC curves of the selected products as they were incorporated in to the model. It should be noted that EnergyPlus™ does not model PCM hysteresis or sub-cooling behaviors, so a unique temperature/enthalpy relationship was considered. The calculation time-step was set to one minute to ensure accurate assessment of the composite PCM behavior.

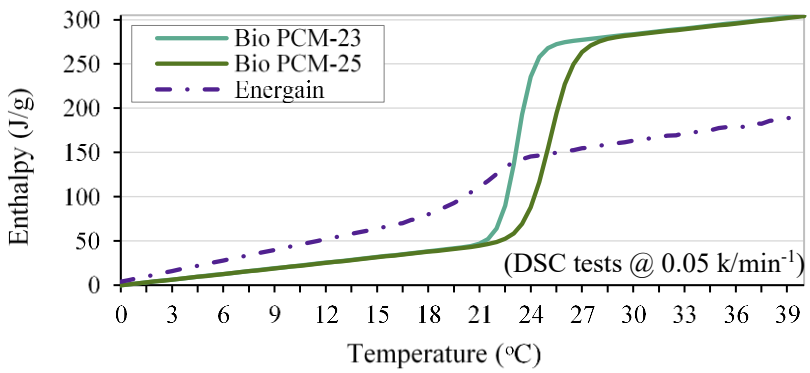

Figure 4: Temperature-enthalpy curves for the PCM products investigated in this paper

Parameters of Analysis

The simulation study is composed by two sections: the preliminary analysis to select the appropriate melting point for the BioPCM™ layer and to finalize the design of the composite PCM system, and then, the main study to assess the impact of the composite PCM system on a whole building scale. For ease of comparison, the unit with no PCM is referred to as the "Baseline unit" and the unit with PCM-enhanced walls and ceiling is called the "PCM-integrated unit". Both indoor temperature and energy use variations are studied as these two factors are interrelated. The governing variables in the simulation study are WWR and climate to find a correlation between PCM performance and changes in solar gains and temperature (Table 4).

Table 4: Parameters and methodology for the simulation study.

Test	Tested Variables	Constant Variables	Description
Preliminary Study	Melting temperature of BioPCM™ WWR 40%, 60%, and 80%	Orientation Set points	Summer test was conducted to select the most appropriate melting point of BioPCM
Study #1	WWR 40%, 60%, and 80%	Orientation Set points	Different WWRs are tested in south facing units to correlate WWR and PCM effectiveness.
Study #2	Façade Orientation	WWR Set points	Units facing four cardinal directions are tested
Study #3	Heating and cooling set point temperatures from 20 °C to -26 °C	WWR Orientation	Different ranges for heating and cooling set points are tested

The performance of the composite PCM system and its impacts are quantified using the following indicators:

1) Indoor thermal environment; the impact of PCMs on the thermal environment is investigated by assessing the changes in the indoor operative and radiant temperatures, and by assessing changes in daily high and low temperature peaks and fluctuations;

2) Energy consumption; the pattern of energy use is analyzed in regards to TES cycles of the composite PCM system. The rate of cooling and heating energy demand and savings are also assessed.

RESULTS

Preliminary Study

The preliminary study provides an understanding of how the BioPCM™ layer would regulate indoor temperatures in summer and would impact the cooling energy demand. A comparative study between the melting points of 23 ºC and 25 ºC for the BioPCM™ is presented. The simulation results for the city of Toronto shown in Fig. 5a demonstrate a better overall performance in reducing cooling energy demand for the BioPCM™ with the melting point at 25 ºC. In the same figure, the percentage reduction in average daily indoor operative temperature (T_{OP}) swings is also reported. This value represents average daily T_{OP} fluctuations in units which is averaged on a monthly basis.

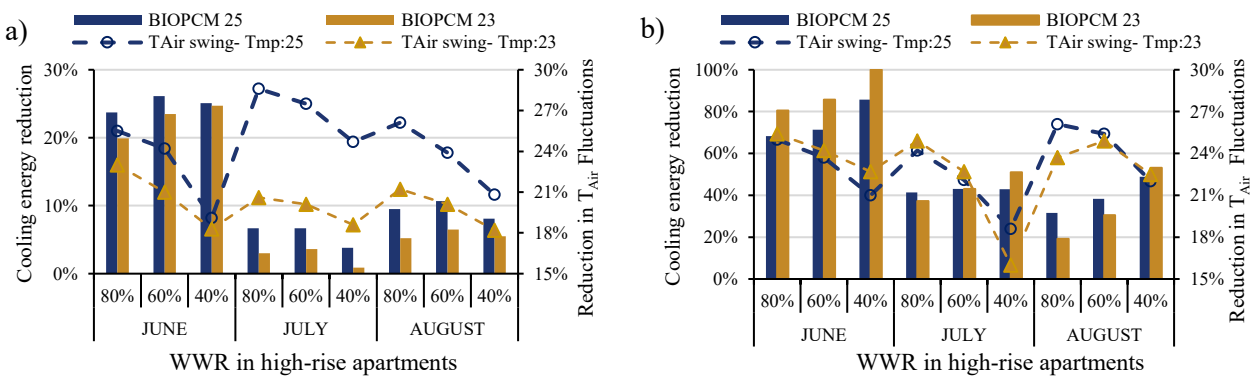

Figure 5: Correlation of cooling energy use and air temperature swing changes in Toronto (a) and Vancouver (b)

In contrast to Toronto units, the benefits of BioPCM™-25 in Vancouver in terms of reduction of the cooling energy demand are not always higher than those obtainable with the BioPCM™-23. Figure 5b shows that BioPCM™-23 performs better in Vancouver units in regulating temperature swings and reducing energy consumption in June and in the 40% WWR unit. Due to milder weather conditions in the city of Vancouver, the number of hours in which indoor air temperatures exceed 26 ºC is not high during the summer; in fact, in units with 40% WWR, temperatures are below 26 ºC in the Baseline unit and the PCM integrated unit. Finally, a better performance of the BioPCM™-25 is observed in reducing high peak temperatures in the month of August for units with 60% and 80% WWR in both cities. The trend of change for Vancouver and Toronto shown in Fig. 5 demonstrates a higher effectiveness of BioPCM™ with melting point of 23 ºC in the month of June. However, in an annual simulation run, using BioPCM™-25 results in more energy use saving compared to BioPCM™-23.

It is suggested from the results that the BioPCM™-23 is more compatible with lower threshold of indoor temperatures in units with higher glazing ratios which in the case of summer occurs in June. The same compatibility is observed in 40% WWR units in summer. The substantial reduction of total cooling energy

demand, in addition to decrease in overheating in summer in both cities by using BioPCM™ with the higher melting temperature, prompted the selection of the BioPCM™ with the melting temperature of 25 ºC. The final configuration of the composite PCM systems applied to walls and ceiling surfaces is shown in Fig. 6.

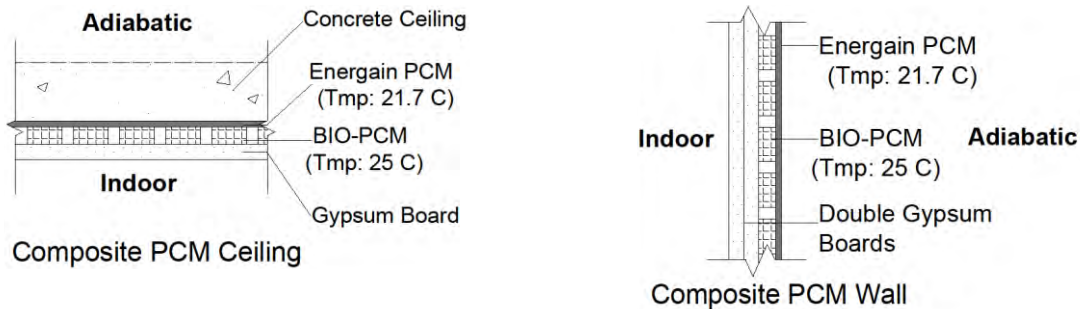

Figure 6: Final composite PCM configuration

Study #1: Effect of WWR on PCM Performance

The orientation of the units is kept to the south while different WWRs are tested. The outcomes of this test are assessed first on an annual, and then on a monthly level. The rate of change in energy consumption, i.e. the energy savings by integrating the PCM system in retrofitting the unit, is investigated. As reported in Table 5, the impact of the composite PCM system is significant in reducing the cooling EUI in apartment units in both Toronto and Vancouver, while comparing the rate of saving for the heating load, higher savings occur by using the composite PCM system in apartment units in Vancouver.

Table 5: Annual energy use reduction

	Cooling ΔE_{Saving} (%)		**Heating ΔE_{Saving} (%)**	
	Toronto	**Vancouver**	**Toronto**	**Vancouver**
80% WWR	14.7%	38.1%	1.1%	3.7%
60% WWR	16%	46.8%	0.5%	2%
40% WWR	14.3%	56.1%	-0.2%	0.3%

It should be noted that the overall heating and cooling energy loads in the Baseline units are also lower in Vancouver due to milder weather conditions. A total reduction of 4.4% in annual EUI could be achieved in apartment units with 80% WWR in Vancouver, whereas in Toronto, the reduction in annual EUI is 2.6%. The trend observed in energy saving shows higher heating energy saving in 80% WWR units and higher cooling energy saving in 40% WWR units by using the composite PCM system.

The potential for the composite PCM system in decreasing cooling loads is high, while its effectiveness in the heating season is negligible. Monthly average cooling energy demand in Toronto and Vancouver units is presented in Fig. 7. The maximum energy loads in the cooling season occur in the month of August in Vancouver, and in July in Toronto. By analyzing the graphs in Fig.7 regarding different WWRs, a similar pattern of energy use reduction of 9% is observed in the PCM integrated units in Toronto. However, in the last week of May and first two weeks of September, the impact of PCM in reducing cooling load is minimal. A different behavior results in Vancouver as the energy consumption saving in the PCM integrated unit is considerably different from the Baseline unit in all the three WWR scenarios. The cooling demand is drastically reduced in September by using the composite PCM system for units with 60% and 80% WWR.

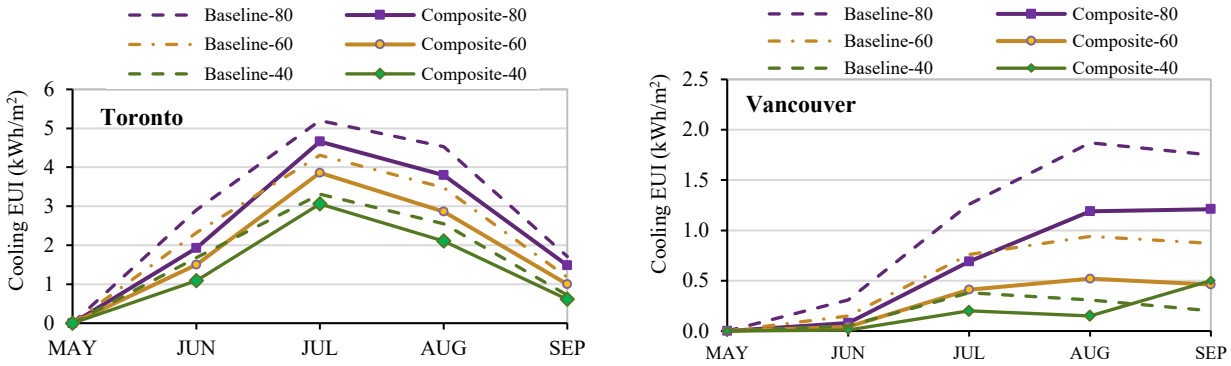

Figure 7: Monthly cooling energy use intensity (EUI) in Toronto and Vancouver for units with different WWRs

The impact of the composite PCM system in reducing daily temperature fluctuations is shown in Fig.8 for one month in each season. The graphs demonstrate how daily operative temperature (T_{OP}) swings are reduced in the PCM integrated unit. An average daily T_{OP} swing in a Toronto Baseline unit with 80% WWR in October shows that the wide range of temperature fluctuation is reduced from 4.6 ºC to 3.2 ºC with the application of the composite PCM system. As WWRs get smaller, the range of daily temperature swings reduces in Baseline units; for instance, in October, in Vancouver, the average daily temperature swing is 2.8 ºC for 40% WWR units and 4.8 ºC for the 80% WWR units. Correspondingly, the effectiveness of PCMs in reducing temperature fluctuations is higher in units with higher WWRs.

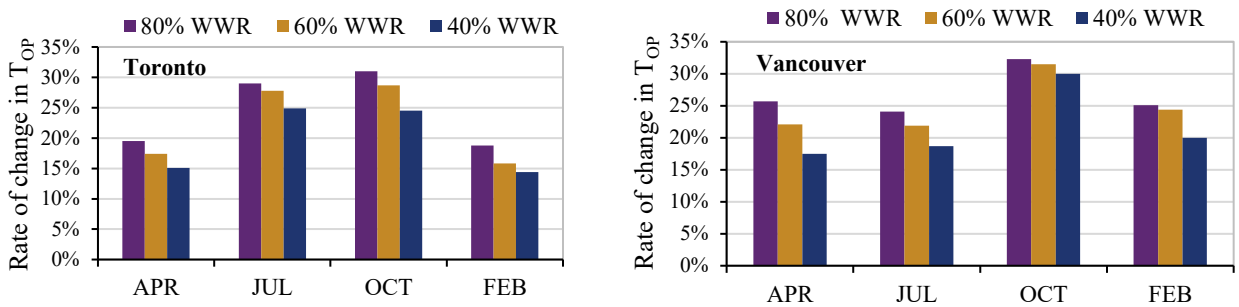

Figure 8: Rate of change in daily operative temperature swings in the PCM integrated unit in some representative months

By comparing the solar gain values in the units in October and July, thanks to the effective shading design and South orientation, a higher daily solar gain is observed in October, and therefore, the number of hours with T_{OP} above 26 ºC in October is also higher. The overheating in the units was assessed by observing operative temperatures exceeding 26 ºC during the day. Additionally, low peak temperature variations were analyzed by calculating the rate of change in operative temperatures falling below 21 ºC. Considering the lowest operative peak temperature of 21 ºC, the month of October shows better results with the integration of the composite PCM system. Specifically, in Vancouver units with 80% WWR that experience higher heat loss, the number of hours in which the operative temperature falls below 21 ºC is reduced to 71 hours from 151 hours in the Baseline unit.

Overall, the results of peak temperature variation by adopting the composite PCM system shows a higher benefit in reducing high peak temperatures. Therefore, mitigation of daily temperature swings can be attributed to the decrease of high peak temperatures rather than to low peak temperature variations by using the PCM system. Finally, the results in Fig.6 and 7 confirm that units integrating the two-melting point PCM systems have a higher energy load reduction and better indoor temperature regulation when they had higher

WWR in both cities, especially in the shoulder seasons.

Study #2: Effect of orientation on PCM performance

To study the impact of orientation on the effectiveness of PCMs, 80% WWR units were simulated; oriented in the four cardinal directions. The south facing unit was considered as the reference orientation. Considering annual energy consumption in the Baseline unit with no PCMs, a significant rise was observed in units facing the other three orientations in both cities. Cooling energy consumption is considerably higher in the west and east facing Baseline units in Toronto and Vancouver units due the ineffective shading system. In Vancouver units facing west, the cooling EUI is increased to 7.9 kWh/m^2 in the month of July, which is 84% higher than the south cooling load of 1.2 kWh/m^2 in the Baseline unit, again due to more effective shading devices. However, in the heating months, north facing units have the highest energy load as expected due to lack of direct solar gains, consequently heating energy savings is only 1% in fall months by using PCMs.

The impact of the composite PCM system in units facing different orientations is considerably lower in reducing annual energy consumption compared to the south facing units. For instance, the annual energy saving in the west facing units is 0.7% in the PCM integrated unit in Toronto, and 10.5% saving in cooling energy in the east facing units which is 22% lower than the saving in the south units. Monthly energy results show a decrease in PCMs' impact in reducing cooling energy as the units are rotated from south to west.

As shown in section 4.2, the impact of the composite PCM system is quite significant in the month of October and July, thus some representative days in these months are analyzed to compare the effect of solar gain and peak solar periods on cooling and heating energy loads. Figure 9 shows the hourly rate of energy changes compared to hourly solar gain variations on July 3rd and October 5th.

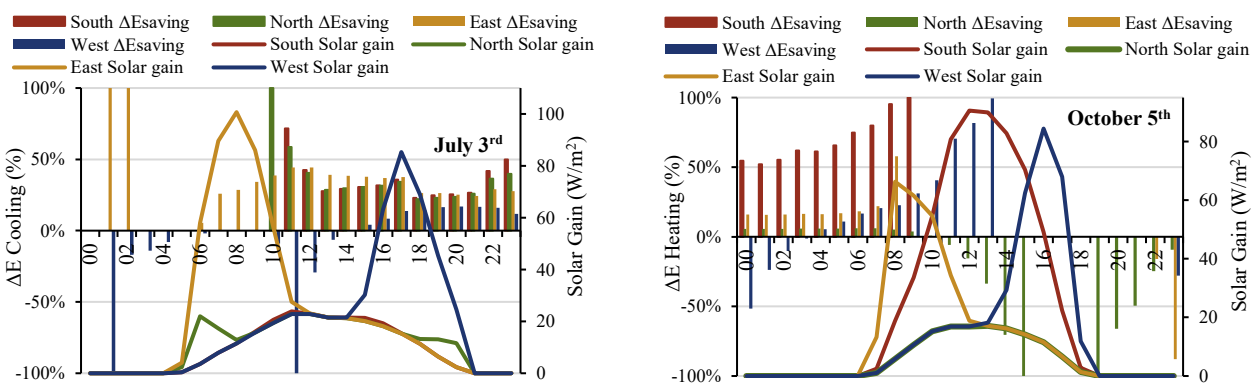

Figure 9: Rate of energy saving and solar gains in PCM integrating units in Toronto in two days in July and October

Average savings of 35% in cooling load resulted in the east facing units as solar gain reaches its peak in the early morning hours from 6 am to 10 am to 100 W/m^2. As the solar radiation gets into the room from 7 am, the same time that cooling system turns into the setback temperature, the surface temperature of PCM integrated walls and ceiling are more moderated due to the TES in correspondence to the melting, and during the following 10 hours, they only change by 0.4 ºC. The significant stabilization of the radiant temperature, in turn, affects the air temperature in the unit indicating a lower cooling energy demand. Overall, low energy saving in west facing units was analyzed by observing wall and ceiling surface temperature variations. Unfortunately, the still high surface temperatures at night prevented the full solidification of the PCM integrated surfaces as they were above the melting threshold of the BioPCM^{TM} layer in the PCM system.

In October, no change in heating energy loads is recorded in south and east facing Baseline units, as sufficient solar gain eliminates the need for heating. In the west facing unit, however, during early morning hours after midnight, stable temperatures in the PCM integrated unit lower heating demands. Specifically, the surface temperatures are kept constant at 23.5 ºC for 13 hours which allows for partial solidification of the composite PCM system. In the south, east and west facing orientations, PCM solidification at night period allows for reduction of heating energy as the stored heat in the composite PCM system compensates for the heat loss from the room at night. However, in the north facing unit on October 5th, hourly energy changes in the PCM integrated units are negative, which is a result of more heating demand since the PCM system stores energy, taking part of the energy produced by the heating system. By observing hourly solar gains and surface temperature variations, peak temperatures in the units are one hour apart from peak solar gain values entering the unit in all orientations, except in west facing units. In west facing units, peak solar gain and peak surface temperatures are recorded at the same time for most days. Nevertheless, this correlation is not accurate as the surface temperatures is not dependent on solar heat gains alone.

Study #3: Effect of HVAC Set Points on PCM Performance

Outdoor weather conditions dictate the performance of conditioning systems, which in turn affect PCM performance in conditioned buildings. In Study #3, the dynamic behavior of the composite PCM system is tested through changing heating and cooling set points to find the most suitable indoor boundary conditions to maximize the benefits of introducing PCMs during building retrofits.

For this study, south facing units with 80% WWR are tested only. As the melting range of the composite PCM system varies between 18-25 ºC, different room air set point options were selected cycling close to this range to ensure PCM activation while maintaining acceptable comfort ranges. Table 6 shows three heating and cooling set point options tested by varying both main and set back temperatures.

Table 6: Heating and cooling set points considered to assess the effectiveness and activation of the PCMs.

	Primary Scenario		**Scenario 1 (SCE1)**		**Scenario 2 (SCE2)**		**Scenario 3 (SCE3)**	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Setpoint Temperature	22 ºC	24 ºC	21 ºC	25 ºC	23 ºC	26 ºC	20 ºC	23 ºC
Setback Temperature	18 ºC	25 ºC	17 ºC	26 ºC	20 ºC	27 ºC	16 ºC	24 ºC

Monthly energy demands in both cities are illustrated in Figs. 10 and 11 for different operative temperature changes and peak temperature variations. The values shown in Table 7 indicate the rate of change in extreme temperatures. Negative values imply a reduction of extreme hours in the PCM integrated unit and positive values indicate an increase of peak temperatures in this unit.

Table 7. Peak temperature variations by using PCMs expressed by the number of hours in the PCM integrated unit.

	Toronto			**Vancouver**		
	Reduced # of hours with T_{OP}> 26 ºC	**Reduced # of hours with T_{OP} < 21 ºC**		**Reduced # of hours with T_{OP}> 26 ºC**	**Reduced # of hours with T_{OP} < 21 ºC**	
	July	October	February	July	October	February
Primary Scenario	-18	-32	-4	-2	-71	-41
SCE 1	-26	-84	+8	-39	-73	-44
SCE 2	+32	-31	-19	-88	-51	-34
SCE 3	0	-50	+32	0	-63	+19

By comparing cooling and heating energy use with indoor temperature variations in summer and winter in Toronto units, it is evident that adopting Scenario 1 leads to a higher percentage of energy saving compared

to Primary Scenario of set points. For instance, the highest cooling energy saving that occurs in June is 48.3% using Scenario 1, while using Primary set points, the percentage of savings is 33.2%. Similarly, in heating and shoulder seasons like October, the rate of energy saving in the PCM integrated unit is 3.4% higher on average when Scenario 1 set points are adopted. The rate of change in the PCM integrated unit in annual cooling EUI is 38.1% for Primary Scenario and 24.7% when Scenario 3 is adopted for the cooling set points. Furthermore, considering monthly cooling load in July, the impact of PCM in lowering cooling loads is 17% higher in the case of Primary set points, which is 24 ºC. Peak temperature variations show a complete elimination of overheating in both Baseline and PCM integrated units when the cooling set point is 23 ºC.

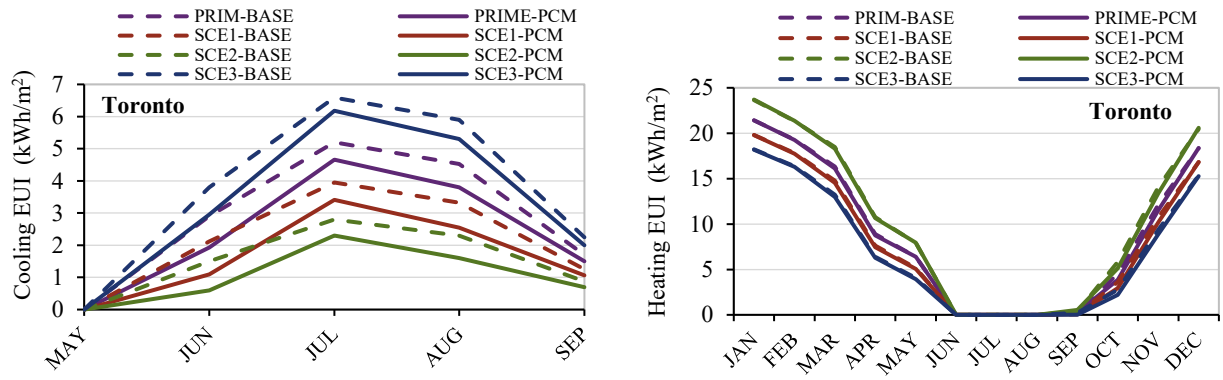

Figure 10: Monthly energy use intensity (EUI) in Toronto units with different set point temperatures

A regular pattern is observed for the heating season in Vancouver units as increasing the set point to 23 ºC leads to a higher heating load compared to the Primary Scenario which has a heating set point of 22 ºC. As expected, lowering the heating set point to 20 ºC in winter results in 21.7 kWh/m^2 lower heating EUI compared to the Primary Scenario. However, observing the low peak operative temperatures below 21 ºC, it is evident that lowering heating set point to 20 ºC in Scenario 3 entails increased low peak temperature values. The best result for reducing low peak temperatures is when the heating set point is 23 ºC in Scenario 2. However, considering the rate of change in the PCM integrated unit, the Primary Scenario with a set point of 22 ºC shows a better PCM effectiveness in changing the operative temperatures in winter.

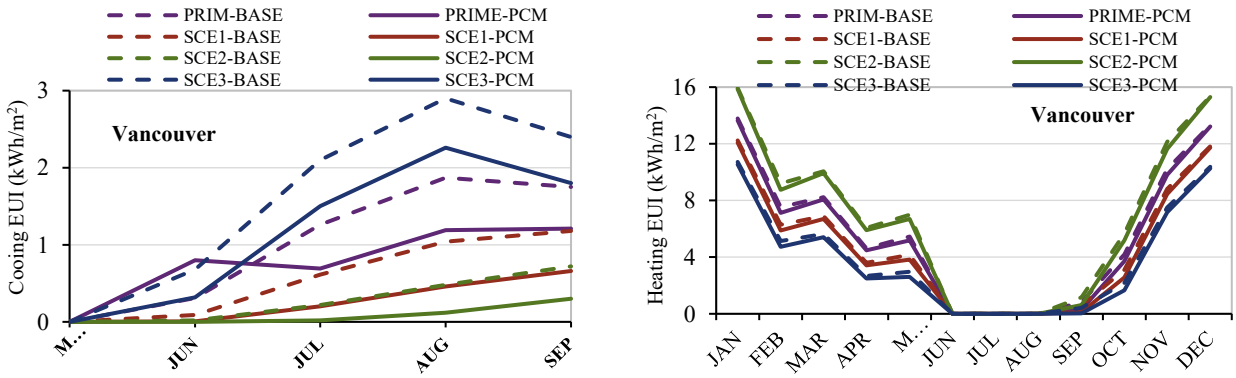

Figure 11: Monthly energy use in Vancouver units with different set point temperatures

As the results show, a discrepancy exists between indoor temperature regulations and energy savings. However, in both Toronto and Vancouver units, Primary Scenario and Scenario 1 show a balance in both indoor temperatures and energy changes in the PCM integrated units. Considering the different outdoor weather patterns in heating and cooling seasons in each city, the relation between the PCM performance and the selected set point is evident. The melting range of the Energain™ layer in the composite PCM system is

from 18-22 ºC which is mainly targeting the heating season. Therefore, selecting a higher set point of 22 ºC or 23 ºC ensures that this layer is melted. If the heating set point is decreased, as in Scenario 3 to 20 ºC, even though overall heating loads are much lower in the Baseline unit compared to other set point scenarios, the rate of change in the PCM integrated unit is much lower and in some instances, negative. This matter is specifically caused by the Energain™ PCM layer absorbing the heat produced by the heating system resulting in lower operative temperatures and higher heating demand to make up for the absorbed heat.

DISCUSSION

One of the main objectives of this study was finding a relation between solar gain and PCM effectiveness in Canadian high-rise residential buildings to facilitate the introduction of Latent TES in building retrofits. The results clearly point to a high influence of solar gain on PCM activation patterns and how the PCMs, in turn, affect the indoor thermal environment and energy use in apartment units. The influence of solar gain is more critical in shoulder and heating seasons. The inclusion of the composite PCM system shows better results in highly glazed units in both heating and cooling seasons due to higher PCM activation. Glazed facades entail higher vulnerability to ambient weather conditions and create a space susceptible to large solar gain and heat loss. As the best results were observed in units with 80% WWR, the effect of high heat loss becomes another important factor that must be considered. By relating the appropriate melting range to indoor conditions, the extreme fluctuations in these situations are controlled. It must be noted that as WWRs get smaller, the impact of solar gain on overall energy use and indoor temperature variation also changes, pointing to higher influence of boundary conditions on PCM performance in units with lower WWR.

By testing different orientations, it was concluded that the impact of solar gain though critical, is more periodical and has a direct relation to the time of peak temperatures. For instance, a significantly high temperature period was observed in west facing units as the sharpest solar gain was experienced. In contrast, south facing units have more stable conditions throughout the days. It is assumed that by matching conditions at solar peak periods with the HVAC set points in each orientation, different results could be obtained. For instance, considering the west facing units near sunset periods which experience high temperatures, cooling systems could run on setback temperatures to allow for passive cooling of the PCMs as they store the excess heat in the unit. In the heating season, a similar action could be performed as the heating could even be on setback for the entire night as the long thermal lag during the night and lower temperatures would facilitate a full solidification, leading to release the stored energy in the PCMs. It was suggested in Study #1 that changing glazing ratio and increasing incoming solar gain in units, positively affects PCM performance on an annual basis. By comparing the results of Study #1 and Study #2 it could be inferred that the time of peak solar radiation impacts the composite PCM's behavior differently compared to the amount of solar gains.

The second objective in this research was the connection of indoor boundary conditions with the composite PCM melting point. While many factors such as internal gains and solar gains affect indoor temperatures, a difference of 1 to 2 ºC variation between main HVAC set point and PCM melting point is more suitable in this context, therefore, a heating set point between 21-22 ºC and a cooling set point between 24-25 ºC is more compatible with the introduced PCM system. While lack of melting is a serious problem in winter, lack of solidification is an issue in the cooling season. Considering the low setback temperatures in winter and pattern of PCM effectiveness, it could be inferred that the PCMs are not melted during the day with a low setback temperatures of 18 ºC, even though solar gains are high. Therefore, increasing setback temperatures in winter could be more beneficial in activating the PCM layers, and the savings in energy at night through PCM solidification could compensate for the higher setback operation. However, in summer nights, lack of PCM

solidification affects their heat storage capacity in the next cycle. Lowering cooling set points at night and increasing mechanical ventilation flow rate are some measures that could help facilitate a full discharge for the PCM system. Clearly, such a peak shifting approach would have to consider the dynamic price of energy.

CONCLUSIONS

The focus of this research was to explore the impact of PCMs on indoor temperatures of apartment units, and how different factors could influence the performance of these materials for high-rise building retrofit. Considering the outcomes, the full potential of this system in changing surface and indoor temperatures and ultimately a decreased vulnerability of the unit to ambient weather was demonstrated. The parametric evaluation of different factors influencing the benefits of PCM integration in high-rise building retrofits showed what needs to be considered for design and optimization of PCM applications.

Using simulation modeling confirmed to be an appropriate method for a comprehensive parametric analysis, although detailed investigation of the temperature profile of the PCM layers could not be assessed through the simulation analysis. Only the surface temperature data could be calculated using the simulation models. Thus, future works should investigate the temperature and heat flow distribution through different layers of the proposed composite PCM system in relation to room temperature variations. For this scope, a detailed experimental study will be further conducted; also, given the inability of the software to calculate hysteresis and subcooling behaviors, and the uncertainty for accurate calculation of Hybrid PCM system particularly, the performance of the second PCM layer.

A notable outcome of this research is the evaluation of how market available PCM products perform in the Canadian context, as this is important to show the readiness of PCM products and their benefits as opposed to theoretical PCM scenarios. Considering two different climates, such as the more extreme climate conditions in Toronto and the milder conditions in Vancouver, showed that including PCMs is beneficial in both climates as the additional TES allows for regulating both the radiant and the indoor temperatures. The main advantage of the composite PCM system is represented by the inclusion of two different melting points in one thin system. An unobtrusive addition of 2 cm to the walls and ceiling which is suitable for retrofit projects, provided significant TES. In particular, the following main results emerged from the study:

1) The highest energy savings and decreases in daily temperature swings in the PCM integrated unit are achieved in 80% WWR units;

2) Annual energy savings are higher in the city of Vancouver, with the highest savings during the cooling season, while the savings in Toronto occurred mainly in the shoulder seasons;

3) No single linear relation was found between PCM activation and solar gain alone, as ambient climate and indoor boundary conditions are also primary influencing factors on PCM activation;

4) The impact of shading devices used in the model in controlling the incoming solar radiation proved to be an important aspect as excessive solar penetration is prevented in summer;

5) PCM systems using more products with different melting points, have a great potential for building retrofits in climates such as Canada that experience a variety of weather conditions through the year.

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