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Modelling PCM-Enhanced Building Components in Residential Buildings: A Case Study

Mohd Hedayatullah Mobeen[1], Miroslava Kavgic[1], Ali Al-Janabi[1]

[1] Department of Civil Engineering, University of Manitoba, Winnipeg, Canada

Abstract: *In countries with extreme weather conditions such as Canada, thermal storage plays an important role in energy conservation and in providing adequate thermal comfort. Phase Change Materials (PCMs) have the potential to store and release large quantities of heat per unit of mass through a phase change process from liquid to solid and back near typical room temperatures. Successful and cost-effective application of PCMs in buildings depends on many factors including working temperature range, material thickness, location within the space, and location within the building component. This paper presents the application of PCM-enhanced building components to reduce space heating and cooling energy consumption while maintaining comfortable indoor conditions in a single-family house located in Winnipeg, Manitoba. Detailed whole building energy model is developed in EnergyPlus and is validated against real measurements. Different possible error types in simulation are also discussed in this paper.*

Keywords: *EnergyPlus, PCMs, Thermal Storage, Residential, Whole-building Energy Modeling*

INTRODUCTION

Envelope thermal performance requirements are becoming more stringent, and the most common compliance approach is to add more insulation. In many cases, this may not be practical due to space constraints and greater use of glazing façade systems. An alternative approach is to increase building envelope's thermal storage capacity by incorporating Phase Change Materials. PCMs can store and release large amounts of energy through the phase change process without substantial change in temperature. Depending on the PCM type, it can store about 3-4 times more heat per volume than sensible heat in solids and liquids at an approximate temperature of 20 °C as reported by Mehling & Cabeza (2008). The idea is that PCMs absorbs part of a building's heat load during the day as they melt and releases absorbed heat during the colder night by returning to their solid state. In the summer, the released heat would be removed using natural or mechanical ventilation, while in the winter it would reduce the heating requirements (Kosny, 2015).

The first documented use of a PCM was by Massachusetts Institute of Technology researcher Dr. Maria Telkes in 1948 in a five-room 135m² house located in Dover, Massachusetts, USA. In her passive solar house, metal drums filled with Glauber's salt (Na2SO4.IOH2O) were used as a part of a passive solar heating system (Kosny, 2015). Since then, researchers investigated the application of PCMs for different purposes and the most common include: reduction of space cooling and heating energy consumption; thermal peak load shaving and shifting; and improvement of indoor thermal comfort. The use of PCMs in buildings is becoming more appealing with the arrival of a variety of ready-made PCM-enhanced building products on the market, including insulations, gypsum boards, panel products, concrete blends, ready-made plaster blends, windows and window attachment products.

Researchers in the US and Europe reported that use of PCM-enhanced foam insulation (Kosny et al, 2007 and Kosny et al, 2010) and celluloses insulation (Kosny (2008), Fang (2009), & Kosny et al (2012)) in wood-framed walls can reduce peak-hour cooling loads by 30-40 %, whereas heating loads during mixed seasons and winter can be reduced by about 16 % as reported by Kosny, J. (2008). Tardieu et al. (2011) investigated the application of PCM-enhanced gypsum boards in wood-framed structures in New Zealand. The researcher reported that the use of PCM-enhanced products can reduce the daily indoor space temperature fluctuation by up to 4 °C during summer. Muruganantham et al. (2010) tested several wooden-framed walls, floor and attic systems containing biobased PCM packaged in arrays of plastic foil containers under field conditions in Tempe, AZ, USA. The researchers reported cooling energy savings between 12 and 30 % while heating energy savings ranged from 9 to 29 %. Weinlaeder et al. (2011) monitored interior vertical slats filled with PCM for more than 2 years. Their results show that the temperature of the interior surface of the PCM-filled slats did not go beyond the PCM melting temperature of 28 °C, whereas conventional systems frequently reached 40 °C. The capabilities of saving peak hour loads and shifting peak hour time by incorporating PCMs into building components have successfully been reported by Kosny et al. (2014) and Childs and Stovall (2012). Kosny

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et al (2014) reported that PCM-enhanced insulation assemblies reduced peak hour loads by 25-35% and a 5 hour peak load time shift during the day time was reported with 255 mm thick insulation layer with centrally located 90% concentrated PCM.

Successful and cost-effective application of PCMs in buildings depends on careful selection of many factors including working temperature range, material thickness, location within the space, and location within the building component. There is still much work to be done related to the use of PCM-enhanced materials in buildings (Kosny, 2015). In particular, there is a lack of research on the use of PCMs as latent heat storage systems in buildings located in cold climates. Furthermore, the International Energy Agency reported that while many computer simulations of PCMs have inherent sources of inaccuracies, possible sources of inaccuracies and errors are rarely discussed and acknowledged in the current research studies.

This paper employs the whole-building energy simulation approach to investigate the integration of PCMs in building components and PCM's potential to reduce cooling and heating loads while maintaining and potentially improving thermal comfort. In addition, it discusses the limitations of the study as well as possible sources of inaccuracies and errors. EnergyPlus, used to run the simulation, is an energy simulation software developed by The US Department of Energy (Input-Output Reference, EnergyPlus™, 2016). EnergyPlus is a "new generation" simulation engine that incorporates ASHRAE's preferred heat balance method based on actual thermodynamic equations and allows to model application of PCMs in buildings (Kosny et al, 2007).

BUILDING DESCRIPTION AND WEATHER

The selected residential building is located in Winnipeg, Manitoba, Canada. The building is a split level wood framed single-family house. The orientation of the building is 25° to the west of true north. The house was built in the 1970s and has 105 m² (1,130 sq.ft.) total living area composed of 3 bedrooms, 2 bathrooms, a living room with open kitchen, a conditioned basement, and a utility room. The house has a conventional attic and insulated crawl space foundation. The wall assembly is made of 2 by 4 in studs spaced at 16 in apart and insulated with the fiberglass batt insulation. The external walls on north and south have windows, whereas, the external walls on the east and west do not have any glazing. All the windows except one are triple-pane argon filled windows with wood framing. The window on the south-facing wall of the utility room is a single pane. The above ground window-wall ratio for north facing walls is 15 % and south facing walls is 20 %. The building heating, ventilation, and air conditioning (HVAC) system is a forced air system that uses natural gas for heating and electricity for cooling. However, natural ventilation was used for cooling during the summer season. The efficiency of the gas furnace is 80%. Natural gas is also the heating source for the domestic hot water. Winnipeg falls under climate zone 7 according to the zoning criteria designated by American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), ASHRAE (2013). Winnipeg experiences all four seasons with extreme variation in temperature between summer and winter that can range between +40 °C and -40 °C, respectively. The average high/low temperature is 26 °C in July, -22 °C January according to Environment and Natural Resources Canada (Environment Canada, 2017).

ENERGYPLUS MODEL AND VALIDATION

The first step of creating an energy model is to divide the building into thermal zones. The objective of this step is to define as few zones as possible without compromising the accuracy of the model's prediction. A zone is defined as an air volume at a uniform temperature plus all the heat transfer and heat storage surfaces bounding or inside of that air volume. (EnergyPlus™, Getting Started, 2016). Energy plus defines a zone as a thermal and not a geometric entity. According to EnergyPlus documentation, the number of zones in a general simulation usually should be equal to the number of systems serving the building (EnergyPlus™, Getting Started, 2016). This would imply that the model for the residential building used should have only one zone as it is served by a single system. However, single zone model of the house would result in inaccurate energy predictions as the house comprises of different rooms having different orientation, glazing area, occupancy behavior, and thus different heat gains. Furthermore, O'Brien, W., et al (2011) showed that models with too few thermal zones can under-predict energy usage by over-predicting the rate of air mixing caused when rooms are grouped together as a single zone. Figure 1 shows the zoning approach we employed. The building was divided into 9 thermal zones based on orientation, occupancy behavior, and glazing area. The two attic space were modeled separately as thermal zone 8 and thermal zone 9 (see Figure 1).

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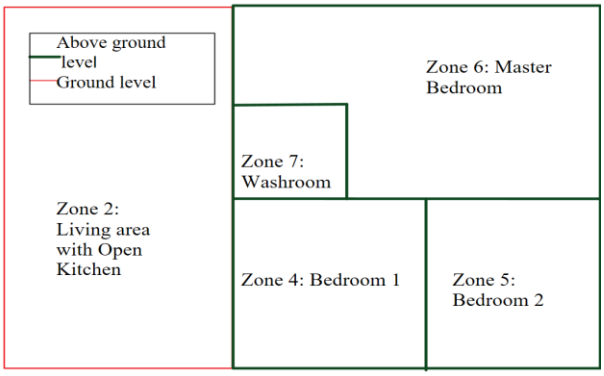
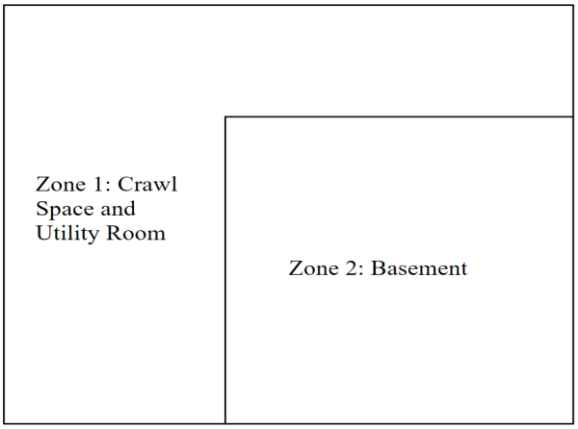


(a)



(b)

Figure 1: (a) Thermal Zones on and above ground level and (b) Thermal zones below ground level

Since EnergyPlus does not have a built-in interface the geometry of the model was constructed using Open Studio plugin in SketchUp (SketchUp, 2016). Figure 2 shows the 3D SketchUp model of the modeled house.

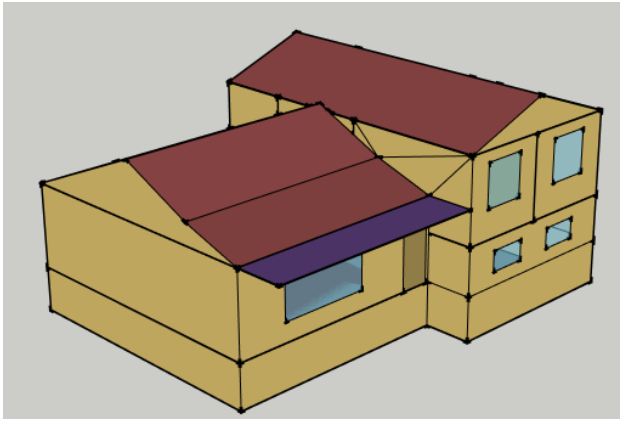


Figure 2: *SketchUp model of the house*

Materials and construction were defined in EnergyPlus. Most of the material physical properties (conductivity, density, specific heat, roughness, etc.) were taken from the EnergyPlus datasets and ASHRAE handbook fundamentals ASHRAE (2005). Construction in EnergyPlus is defined as an array of multiple layers from outside to the inside. The effective U-Value for studs and cavity insulation was calculated as per ASHRAE 90.1 (2004). Therefore, the studs are taken to be 25% of the total area of a wood-framed wall, while the cavity insulation is taken to be 75% of the total area. Table 1 shows the conductivity and thickness of wood stud and fibre batt insulation.

Table 1: Physical Properties of wall cavity materials

Material	***Conductivity* (k) [W m^{-1} K^{-1}]**	***Thickness* (t) [L]**
Wood Stud	0.125	0.1025
Insulation	0.05	0.1025

Effective U-value is calculated as the weighted average (1).

$$Ueff = 0.25 * \left(\frac{k(wood)}{t(wood)}\right) + 0.75 * \left(\frac{k(insulation)}{t(insulation)}\right) \quad (2)$$

$$Ueff = 0.25 * \left(\frac{0.125}{0.1025}\right) + 0.75 * \left(\frac{0.05}{0.1025}\right) \quad (3)$$

$$Ueff = 0.671\ Wm^{-2}K^{-1} \quad (4)$$

Real occupancy, lighting and electrical equipment schedule were obtained from the occupants. As shown in Figure 3, the most often occupied zones are zone 3 (living room with open kitchen) and zone 6 (master bedroom, south facing), whereas, other zones, except for zone 2 (basement), are unoccupied at all times. The lighting schedule is closely related to the occupancy behavior. Zone 2 (basement) has very limited and irregular occupancy. Thus, the fraction for occupancy of basement was assumed to be 0.01 (i.e. 10%).

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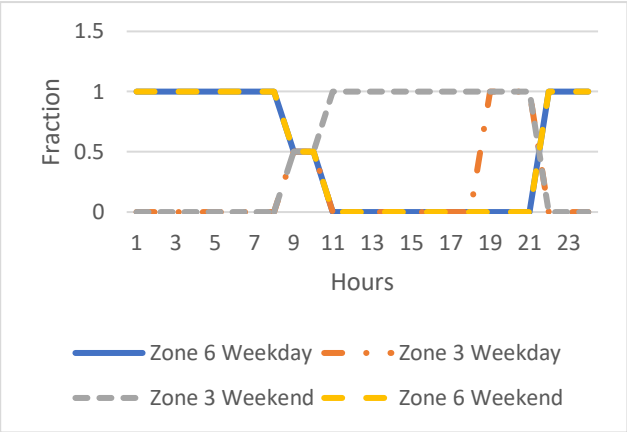


Figure 3: Occupancy Schedule

HVAC template was used to define the HVAC system of the house. The template group allows for the specification of simple zone thermostats and HVAC systems with automatically generated node names. As defined by Input-Output Reference, EnergyPlus (2016), one zone should be selected as control zone. It is the zone which controls the heating and cooling operation and is the zone where the thermostat is located. Since, the thermostat is located in the living room of the house which is represented by zone 3 in the model, zone 3 is defined as the control zone in the model (Input-Output Reference, EnergyPlus, 2016). Table 2 shows the heating setpoint schedule that is used in the model.

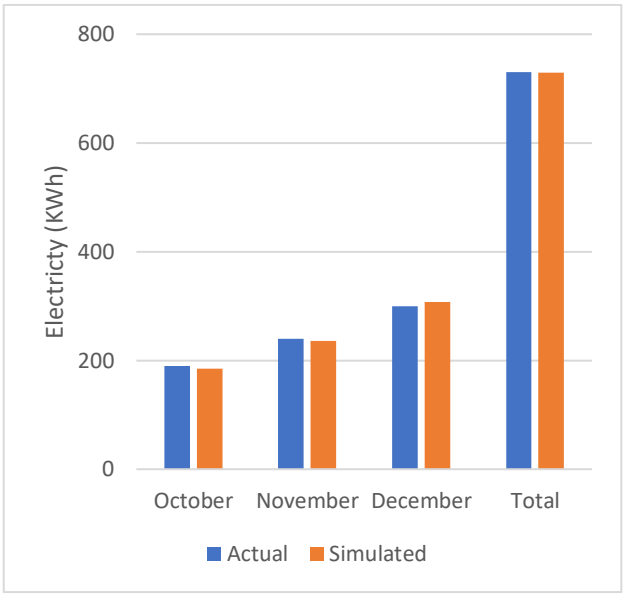
Table 2: Heating setpoint schedule

Time ***(24 hours)***	***Temperature*** ***(°C/°F)***
00:00-08:00	16.11/61
08:00-09:00	20.56/69
09:00-18:00	16.11/61
18:00-24:00	21.11/70

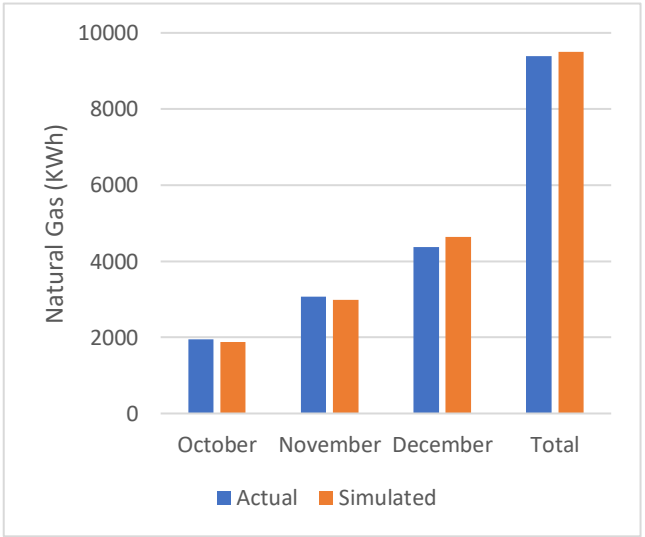
Typical meteorological year that contains historical weather data obtained from the Winnipeg International Airport was used to simulate the developed house model in EnergyPlus.

Validation of EnergyPlus model against real energy consumption data

Due to the limited data for model validation, the EnergyPlus simulation was carried for the period October, 2017 to December, 2017. Electricity predictions are compared against both hourly data provided by TED Pro Home (https://www.ted5000.ca/) and monthly data provided by Manitoba Hydro. Gas predictions on the other hand are only compared against monthly data provided by Manitoba Hydro. Figure 4 (a) shows simulated electricity consumption against actual energy consumption, whereas Figure 4 (b) shows the comparison between the predicted gas consumption and real energy use. It can be observed as a very good agreement between the simulated and measured energy consumptions for both energy carriers.



(a) Electricity consumption comparison of simulation and real data



(b) Natural gas consumption comparison of simulation and real data

Figure 4: *Comparison of simulated energy consumption and actual energy consumption*

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Furthermore, Table 3 gives the summary of percentage differences between the simulated energy consumptions and real energy consumptions. We can see that total discrepancy is only 0.14% for the electricity and 1.08% for the gas. Regarding the monthly consumptions, the largest discrepancy between model predictions and measured data is for the gas consumption (5. 82%) in December and the smallest is for electricity (1.67%) in November.

Table 3: Percentage difference between simulated energy and actual energy consumption

Period	***Natural-Gas Consumption difference (%)***	***Electricity Consumption difference (%)***
October	-3.34	-2.63
November	-2.83	-1.67
December	5.82	2.67
Total	**1.08**	**-0.14%**

In order to further investigate the difference between real and simulated energy consumption, we also calculated Coefficient for the Variation of the Root Mean Square Error (CVRSME), which is defined by the Eqns (5)-(6)

$$CVRSME = \frac{\sqrt{\sum_{i=1}^{i=N}((yr-ys)^2)/N}}{Ys} \quad (5)$$

$$Ys = \frac{\sum_1^N yr}{N} \quad (6)$$

where yr is the real data, ys is the simulated data and N is the sample size. CVRSME for the months provided is 2.4% for electricity consumption and 5.1% for natural gas consumption, which is less than the 15% for monthly predictions set by ASHRAE Guideline 14 (ASHRAE, 2002).

SIMULATION DESCRIPTION, RESULT, AND ANALYSIS

EnergyPlus models the PCM using the enthalpy-temperature method and Conduction Finite Difference Algorithm. Sixteen pairs of enthalpy and temperature are required to be defined in EnergyPlus. PCM 23 was selected as its phase change temperature falls under the thermal comfort range. The physical properties and enthalpy curve for the PCM 23 were provided by the commercial vendor. Table 4 shows the physical properties of the PCM 23. Since the price of the PCM is relatively high, we performed a sensitivity analysis which showed that the optimal thickness for PCM 23 for our case study is 1cm. Therefore, a concentrated PCM layer of thickness 1 cm was applied on the ceiling, west, east and south facing walls.

Table 4: Physical properties of PCM 23

Properties	***PCM 23***
Peak Melting Temperature (°C)	23
Peak Solidification Temperature (°C)	21
Thermal conductivity (W/m-°C)	0.25
Density (Kg/m3)	910
Specific heat capacity (J/g-°C)	1.84

Full-year simulation was carried out with PCMs and a timestep of 2 minutes was used as timestep of less 3 minutes is recommended by Kosny (2015). To estimate the potential cooling energy savings, in the summer season a constant cooling setpoint of 24°C was selected. We chose this setpoint temperature according to the ASHRAE (ASHRAE Standard 55, 2017), "The preferred temperature range for occupants dressed in summer clothes is 22.5° to 26° C (73° to 79°F)" and 24 ° C (75.2°F) is in the middle of the suggested temperature range. Furthermore, the occupants of the house expressed that they feel the most comfortable when the indoor air temperature is 24 ° C. Figure 5 shows that with the application of PCM 23 the maximum potential cooling energy savings can be up to 50%.

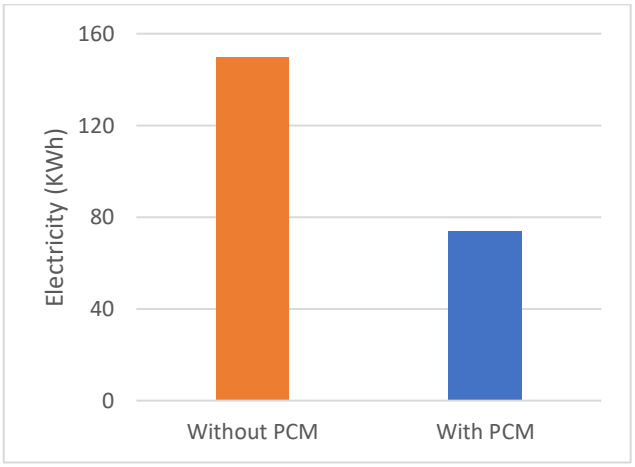

Figure 5: Annual simulated cooling energy consumption comparison

In order to maximize performance of the modeled PCM and investigate its saving potential for different setpoint temperatures during the winter season, we developed 3 scenarios taking into consideration the working temperature range of the PCM 23 (see Table 4):

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(1) Constant heating set point of 21°C, (2) Heating schedule defined in Table 2, and (3) Heating Schedule defined in Table 5.

Table 5: Heating setpoint schedule

Time ***(24 hours)***	***Temperature*** ***(°C)***
00:00-08:00	16.11/61
08:00-09:00	20.56/69
09:00-13:00	16.11/61
13:00-16:00	23/73.4
16:00-24:00	21.11/70

Figure 6 presents the percent savings during the heating for the 3 developed scenarios. It can be observed that maximum saving of about 5% are achieved for the case 3 when the heating setpoint reached up to 23°C during the daytime. This allowed PCM to melt and store energy which was later released. The total heating energy savings for case 3 are presented in Figure 7.

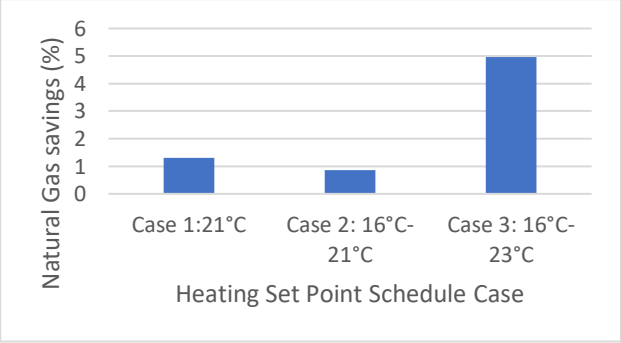

Figure 6: Percentage savings on heating energy with different heating schedules for PCM Integrated Model

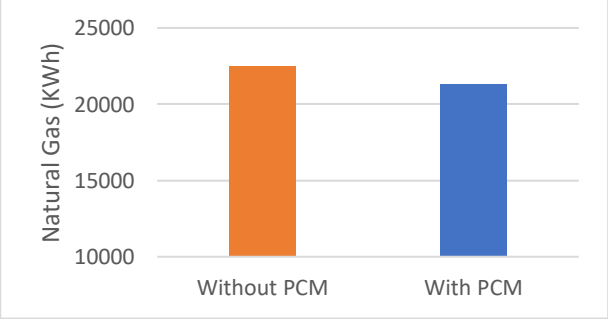

Figure 7: Annual heating energy consumption comparison (Case 3, Set point: 16°C-23°C)

Further investigation is done to observe the thermal comfort benefits of PCM 23. Since the north wall does not contain PCM, and the zone 3 (living room with open kitchen) and zone 6 (master bedroom) are occupied most of the time. Therefore, zone 3 and zone 6 will be used for further analysis.

Summer simulation (from 16th June to 20th June) was carried out without using the cooling system in order to observe the behavior of PCM when outdoor air dry-bulb temperature reached 32°C during the daytime, which is suitable for the PCM 23 to undergo the complete phase change. The mean air temperatures are compared between the model with PCM and without PCM and the results are presented in Figure 8 (a) for zone 3 and Figure 8 (b) for zone 6. It can be seen that while the maximum air temperature of zone 3 without PCM reached 25.2°C, the application of PCM reduced zone air temperature to 21.2°C, which is a reduction of 4°C. A similar trend is observed in zone 6, where maximum zone mean air temperature was 25.7°C without PCM and 21.2°C with PCM, which is a reduction of 4.5°C. Furthermore, the application of PCM also reduced variations in the indoor temperatures, thus contributing to the improvement of the overall thermal comfort.

To investigate application of PCM in the shoulder season, simulation was carried out from 22nd October to 26th October with the heating provided by the HVAC system according to the heating schedule defined in Table 2. As previously, the mean air zone temperature for zone 3 and zone 6 are compared. It can be seen in the Figure 9 that the use of PCM has reduced the overheating and smoothen the air temperature profile, as without PCM the zone mean air temperature in the zone 3 was fluctuating between 17 °C and 24.1°C, while with PCM it was between 17 °C and 21.6°C. In zone 6 the maximum zone mean air temperature is 26.3°C without, whereas, in case of PCM the corresponding zone mean air temperature is 22.4°C in zone 6, which is a difference of 3.9°C.

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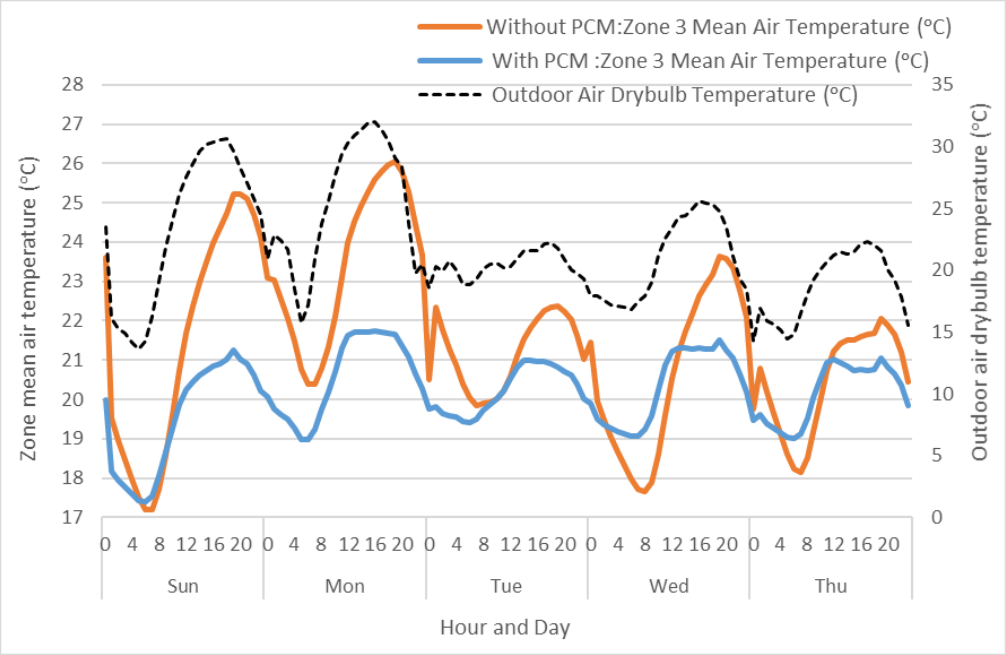
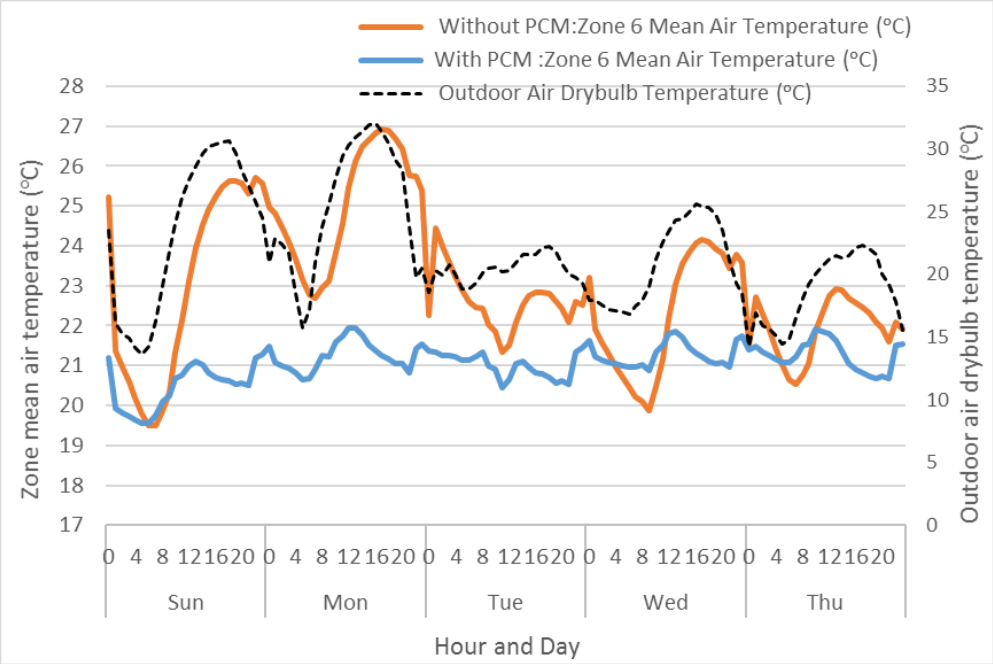


(a)Zone 3 (Living Room) Mean Air Temperature



(b)Zone 6 (Master Bedroom) Mean Air Temperature

Figure 8: (a) Comparison of mean air temperature with and without PCM for zone 3 and (b) Comparison of mean air temperature with and without PCM for zone 6 (16th June to 20th June)

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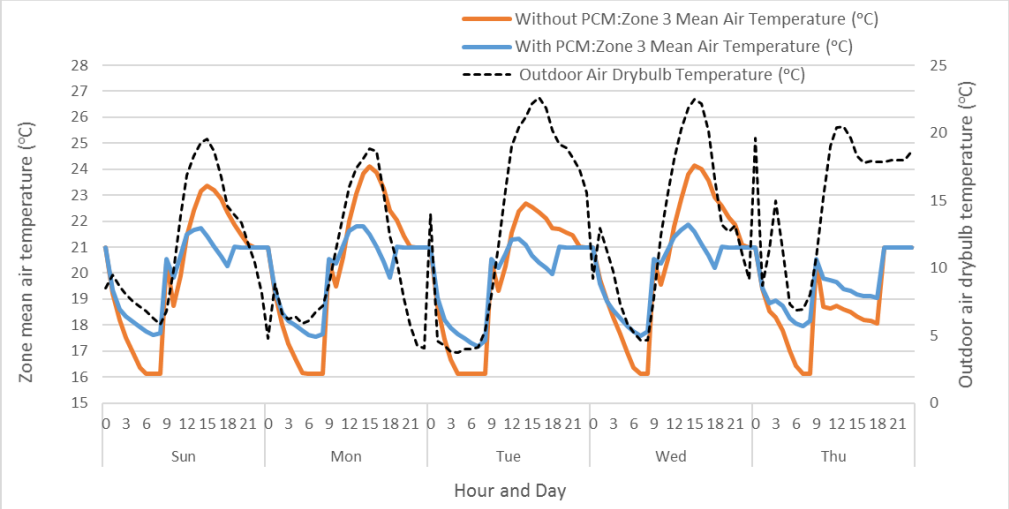
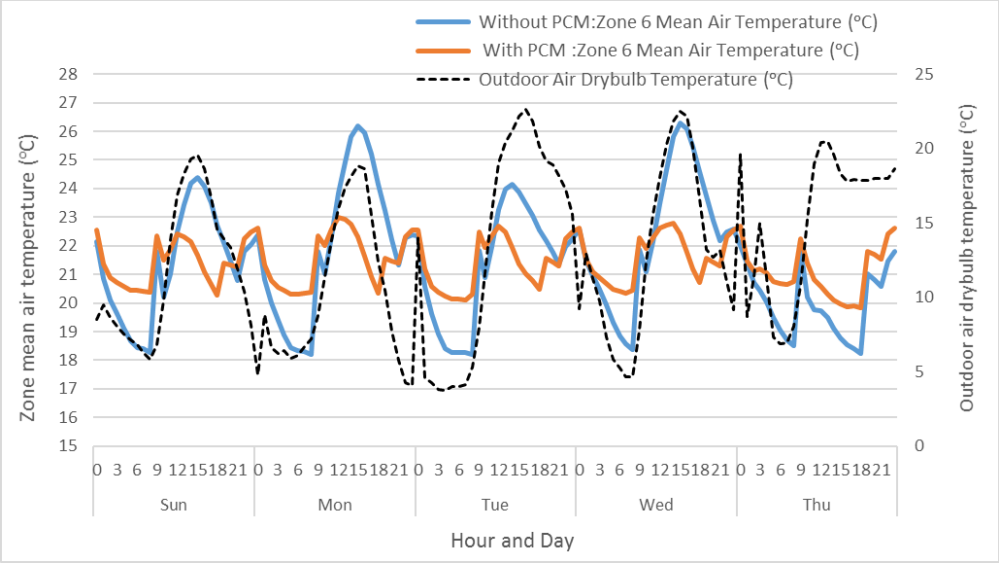


(a)Zone 3 (Living Room) Mean Air Temperature



(b)Zone 6 (Master Bedroom) Mean Air Temperature

Figure 9: (a) Comparison of mean air temperature with and without PCM for zone 3 and (b) Comparison of mean air temperature with and without PCM for zone 6 (22nd October to 26th October)

DISCUSSION

This paper shows the potential energy saving capabilities of PCMs for both heating and cooling. The potential annual heating energy saving is 5% and cooling energy saving is about 50%. The use of PCM 23 reduced the thermal oscillations within zones and shows potential use in maintaining indoor temperature for thermal comfort. The potential maximum cooling energy reduction is around 50%, whereas the maximum heating energy savings of 5% are achieved with optimization and adjustments of the setpoint temperatures. The heating energy savings was not that significant because the temperature of the surface rarely went above the phase change temperature of the PCM during the winter season. The modeling results show that PCM with phase-change temperature in the range of 20°C-23°C will not lead to a substantial heating energy savings, and therefore is not suitable for applications in single-family houses located in cold climates such as Winnipeg. Different PCMs with lower melting temperatures (PCM with phase change temperature around 15°C-18°C) should be implemented in order to achieve

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more significant heating energy savings. Furthermore, the location of PCM within the building component should also be considered as face temperature varies within the building components. The limitation and possible sources of errors are discussed below.

First, historical weather file from the EnergyPlus website was used to run the simulation and validate the model by comparing the simulated energy consumption against the energy bills. Comparing the temperatures from October to December of the EnergyPlus weather file with the data retrieved from Environment Canada (2017) for the year 2017 indicate some difference in the temperature as shown in Table 6.

Table 6: Weather data comparison

Dry air bulb temperature	***EnergyPlus Weather File (°C)***	***Weather data from Environment Canada (2017) (°C)***
Maximum	22.9	24.3
Minimum	-32.8	-34.7
Average	-4.3	-4.4

For validation of the model, the weather file for the run period should be used instead of the historical weather file. However, historical weather file should be used for prediction of PCM energy savings as it would give more reliable prediction for a typical year. Secondly, HVAC template was used in this simulation which may have led to some inaccuracies. A detailed HVAC system should be modeled to increase the confidence in results. Consequently, for validation of the model, the actual meteorological year should be used instead of a historical weather file. However, historical weather file should be used for prediction of PCM energy savings as it would give more reliable prediction for a typical year. Third, building components of framed structures usually do not have uniform thermal resistance across their surfaces. Thermal bridges can be observed around the framing members. Thermal bridge is the area of the building component that has a higher thermal conductivity than the surrounding materials. It results in the overall reduction of thermal resistance of the building component. Figure 10 shows the thermal bridge effect on the North East corner of the building modeled. The temperature difference is 7.1°C.

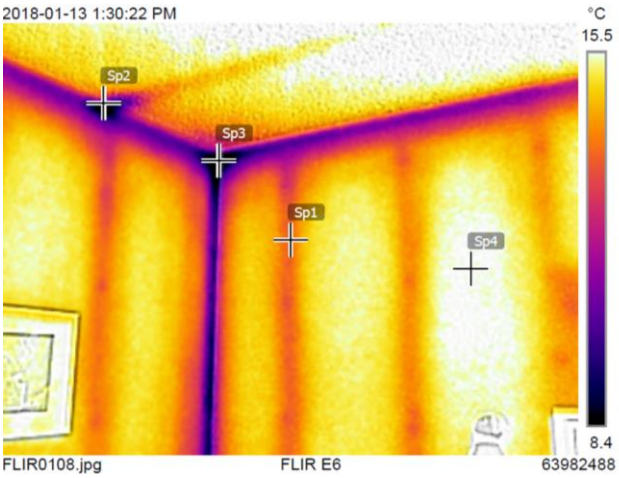

Figure 10: Thermal bridge of the Northeast corner of the living room

EnergyPlus assumes one-dimensional heat transfer, thus, a thermally equivalent wall should be developed to account for the thermal bridging effect. Equivalent wall method as defined by ASHRAE guidelines ASHRAE 90.1 (2004) was used in this simulation. Nevertheless, equivalent U-value should be calculated using available software and codes in order to better account for the thermal bridging. Furthermore, only electricity consumption predictions are compared against high resolution (e.g. hourly) measured data, whereas gas is compared against aggregated monthly consumptions. Validation of gas predictions against the high resolution measurements is required in order to have full confidence in the model predictions. In addition, since the occupants do not use air-conditioning in order to validate model during the summer, measurements of indoor air temperatures are required. Another limitation of the model is the use of standard for defining thermo-physical properties of building materials. Instead, field measurement of heat flow of the building envelope elements should be performed and used as input into the whole-building energy model. Furthermore, thermo-physical properties of the PCM 23, which is used in our simulations, are determined by Differential Scanning Calorimeter (DSC). According to Kosny (2015) this approach may result in an inaccurate model predictions as typically PCMs-enhanced materials, microencapsulated PCMs, PCM pouches, or arrays of PCM containers are applied in building envelopes instead of pure PCMs. Consequently, a heat flow meter that is capable to provide thermal properties of non-homogenous and larger samples (e.g. 30 cm by 30 cm and 10 cm thick) or a hot-box apparatus that can test full-scale (e.g. wall) building elements should be used for characterization of the PCM-enhanced building envelope components (Kosny, 2015). Last but not least, PCMs have different enthalpy curves for melting and solidification. However, EnergyPlus version

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8.7 does not have capabilities for modeling two enthalpy curves, which may result in an unrealistic predictions of the PCM performance.

CONCLUSION

The aim of the paper was to study the energy-saving potential and improvement of the thermal comfort resulting from integration of PCM in building components as well as address the limitations of our modelling approach. The initial simulations have shown that the PCMs-enhanced building components have the potential to reduce energy used for cooling and heating, and provide thermal comfort in residential buildings located in cold climates. However, more comprehensive and extensive investigation is required before the PCM material is implemented on-site. Future work will include investigation of PCMs with different melting temperatures. Further research will also include detailed modelling of the HVAC system, field measurements of indoor air temperature over the summer period, use of actual meteorological year for model validation and experimental testing of PCM-enhanced building envelopes.

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