Application of PCM to shift and shave peak demand: Parametric studies

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ABSTRACT

Application of PCM to shift and shave peak demand:

Parametric studies

Ali Karim Lee

Space conditioning is a main contributor to energy usage in buildings. In Quebec, electric baseboard heaters are the predominant household space-heating systems, in the other words, electrical energy is the main source of energy used for space heating. Thus in such a cold climate like Quebec, residential peak heating demand is a significant contributor to high and critical electricity grid peak periods. Reducing peak heating demand by shifting a portion of peak heating demand to off-peak period is thus of high interest. On the supply side, this strategy requires less generated power, and on the demand side it helps downsize heating systems. One possible approach to shifting peak heating demand to off-peak time is to store thermal energy during off-peak periods and release the stored energy during peak periods. To adopt this approach, set-point temperature of heating systems can be lowered during the peak period, while a release of stored energy maintains the indoor temperature within the desired comfort zone. This capability could be implemented using the concept of latent heat, offered by phase-change-material (PCM)–impregnated building wallboard, such as PCM-gypsum wallboard. In this thesis, a PCM module within TRNSYS software is first validated with experimental data, available in literature, for a simple case of one cubicle. The code is then applied to a typical one-story residential building, also modeled in

TRNSYS. Later, several parametric studies are carried out to investigate the influence of PCM's thermal properties and convective heat transfer coefficient on the rate of PCM's thermal discharge and its resulting improvement in indoor air condition. The simulation results reveal that it is possible to maintain a trade-off between shifting the peak heating demand and preserving thermal comfort by applying PCMs with proper characteristics. It was observed that improving thermal conductivity of PCM has a negligible impact on heat discharge during peak time. Simulations also show that the PCM melting temperature range should be chosen closest to the assigned set-point temperature. It has been shown that increasing the thickness of the PCM layer more than a certain value, 0.013 m, has no effect on thermal storage or, therefore, on PCM thermal discharge. Investigation of interior convective heat transfer on PCM discharge reveals that for a specific climate and PCM wallboard, there is a threshold for effective performance of PCM. For a building located in Montreal, it was shown that with a typical PCM-gypsum wallboard, the interior heat transfer coefficient has to be at least 6.6 W/m^2K to sustain the desired thermal comfort. Finally, thermal behavior of the building integrated with PCM wallboards was assessed in three different climates and by applying two different PCM-gypsum wallboards. It was found that PCM wallboard selection and set-point temperature control strategy must be considered according to the outdoor weather conditions.

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	**Stands for**
BLDG	Building
PCM	Phase Change Material
TES	Thermal Energy Storage
TRNSYS	Transient Systems Simulation Program
ACH	Air Change per Hour
IAT	Indoor Air Temperature

LIST OF SYMBOLS

Symbol	Description
C_p	Specific Heat Capacity (KJ Kg^{-1} K^{-1})
h	Convective Heat Transfer Coefficient (W m^{-2} K^{-1})
L	Latent Heat (KJ Kg^{-1})
λ	Thermal Conductivity (W m^{-1} K^{-1})
T_m	Melting Temperature (ºC)
ρ	Density (Kg m^{-3})
t	Time (hr)
T	Zone/Setpoint Temperature (ºC)

CHAPTER 1: INTRODUCTION

1.1 Background

Presently, the increasing rate of energy consumption has raised major concerns over energy resources availability. Such an increasing rate also has potentially harmful effects on the environment. Building applications comprise a considerable portion of overall energy consumption, especially in areas such as Canada where extreme climates are the norm.

According to the Natural Resources Canada (2010), about 29% of the total secondary energy use and 25% of greenhouse gas emissions are attributed to residential and commercial buildings. A major portion of building energy demands originates from heating and air-conditioning requirements. Specifically, about 65% of the total energy usage in non-industrial buildings is due to space heating and air conditioning (Natural Resources Canada, 2010).

Electrical power is the main form of energy utilized for space heating in residential and commercial buildings in Quebec (Kummert et al., 2011). The consumption rate of electrical power for space heating varies notably during the day due to the demand profiles determined by social and economic behavior of consumers (Applying Energy Storage in Building of the Future, 2013).

The varying consumption rate creates peak periods and off-peak periods during the day. The uneven consumption profile forces power generation companies to maintain ongoing investments in equipment in order to keep up with ever-increasing peak loads. According to Hydro-Quebec (2011), the cost to supply electricity during peak hours in heating season is $10/kW, which in 2015 will increase to $40/kW. In addition to the economic considerations, this overcapacity requirement in power generation equipment has negative environmental implications as well. Developing an energy storage system could help solve the problem (Khudhair and Farid, 2004). For instance, the thermal mass of a building as well as its ability to store thermal energy, can contribute to improve energy performance in the building. A traditional way to store thermal energy in buildings is accomplished by means of sensible heat storage. Under this practice, large masses of concrete, brick or thick plaster walls increase a building's thermal mass.

The majority of modern residential and commercial buildings in the United States and Canada are constructed by lightweight materials and thinner wallboards intended to reduce transportation cost and construction time. Using lightweight construction materials decreases energy-storing capacities and, more importantly, causes low building thermal mass. In cold climates, compared to other energy demands heating is dominant. In general, to avoid high heating demand, conventional wall assembly for cold climates first needs to include insulation, light wood and frame construction. In addition, the thermostat set-point temperature can be lowered, especially in unoccupied rooms. While the heating demand is reduced, release of the stored energy within building's thermal mass can keep the indoor air temperature not to drop fast. However for the buildings constructed by lightweight construction materials, the amount of stored energy released by the material thermal mass is insufficient to maintain the temperature at the comfortable level. To overcome this problem the phase-change-material (PCM) wallboards with high thermal storage capacity can be an approach to improve buildings thermal mass.

1.2 Latent Thermal Energy Storage

Applying the latent heat of materials (the heat consumed or released to cause the phase change) provides storing and releasing an extensive amount of energy witch is a promising method to improve energy performance for lightweight modern buildings. The latent thermal energy storage offers a significant storage level in comparison to other traditional approaches.

One possible technique to apply latent thermal energy storage within modern buildings is the integration of phase change materials with conventional construction materials, rendering a new commercial building materials known as PCM-impregnated wallboards. PCM can increase the effective thermal storage capacity of a building. Specifically, PCMs are designed to undergo phase changes, either from liquid to solid or vice versa, near a typical room-temperature setting. Due to the extensive amount of energy involved in phase changes, PCMs are able to store or release large quantities of heat per unit of mass. Considering the large surface area and volume that wallboards provide within a building, the high latent heat storage capacity of PCM wallboards presents a great opportunity to store and release thermal energy. Another advantage of adding PCM-impregnated wallboards is that there will be no need for a container for the thermal storage materials.

The superiority of PCM as an energy storage medium over conventional building materials can be illustrated by the following simple comparison: To increase the temperature of 1kg of conventional brick by 1^{o}C would require 0.84 kJ of energy. To change the phase of 1 kg of commercial salt hydrate PCM brick type storage would require 160 kJ. This superior capability makes PCMs attractive choices for incorporation into the construction of a new type of wallboards. Through the concept of latent heat, PCM-impregnated walls would be able to store larger quantities of energy within the same mass and/or volume compared to conventional wallboards. In other words, PCM wallboards are more volume-efficient, compared to regular thermal mass. Table 1 provides more specific data comparing the capacities to store energy for the same mass or volume of conventional and PCM-impregnated building materials.

Table 1 - Comparison of sensible heat storage versus latent heat storage

Properties/Materials	**Conventional Wallboard**		**PCM Wallboard**	
Wallboard	Regular Gypsum Board	Brick	Gypsum Board loaded with 20% Emerest 2326 (T_m, 17-21 °C)[1]	PCM-Brick (T_m, 22 °C)[2]
Density (Kg/m^3)	720	1980	900	1520
Specific Heat(KJ/KgK)	1.08	0.84	1.34	1.9
Latent Heat (KJ/Kg)	-	-	28.8	160
Latent Heat (KJ/m^3)	-	-	25920	243200
Required Mass for 1MJ Heat Storage (kg)	231.5[a]	1190.5[b]	34.7	6.25
Required Volume for 1MJ Heat Storage (m^3)	0.32[a]	0.60[b]	0.04	0.004
	[a] ΔT=4 °C	[b] ΔT=1 °C		

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[1] Scalat et al. (1996).

[2] FlatICE (2013).

1.3 Main Advantages Offered by PCM-Impregnated Wallboards

- Peak Shifting of Electrical Demand:

  By storing thermal energy during off-peak periods, PCM-impregnated wallboards could actually function as thermal energy means. At the beginning of peak time, releasing the energy stored during off-peak time, power generation companies can delay the delivery of the load to the buildings.

- Increasing Thermal Comfort:

  Aside from energy consumption, PCM wallboards could also contribute toward improving thermal comfort level. Specifically, in addition to the indoor air temperature, thermal comfort is also affected by the interior wallboard surface temperature. PCM-impregnated wallboards could increase human comfort by decreasing the frequency of swings in room air temperature and maintaining a steadier room temperature for a longer period of time. This would also keep the interior surface temperatures within a constant range during phase change, thus decrease the temperature difference between an interior surface and the human body.

- Compatibility with Conventional Building Materials:

  Most PCMs can be easily incorporated with traditional wood and steel framing technologies (Kosny et al., 2006). Furthermore, in addition to their use in new buildings, PCM-impregnated wallboards could easily be used in existing buildings in major renovation and retrofit projects (Kosny et al., 2006).

- Reduction in Heating Consumption:

  Overheating is a major issue in many modern buildings, deteriorating thermal comfort, specifically passive solar buildings, due to the use of lightweight construction materials with low heat-storage capacity. A main reason for overheating is the energy that enters rooms by way of solar radiation on sunny days. PCM-impregnated wallboards could effectively absorb this energy, preventing overheating of the living space and, more importantly, discharging the stored energy when it is needed.

1.4 Design Aspects and Considerations in PCM Wallboard Applications

With respect to managing heating demand, another important aspect of PCM is its melting temperature. An optimized setting for PCM melting temperature depends on various factors, such as application type (heating or cooling), temperature set-point of heating and cooling, and climatic conditions (location of the building).

Application of PCM wallboard thermal storage may decrease the heat flux via interaction with outdoor temperature variation; therefore, diurnal temperature variation of the exterior affects the PCM wallboard thermal performance. Outdoor weather conditions should be considered in investigating the effectiveness of PCM wallboard systems. As the aim of this thesis is to utilize PCM as a thermal energy storage, PCM should be applied in the interior layer of wall assembly.

To reduce transportation costs, wallboards are usually manufactured on a regional basis. To determine optimized solutions for PCM wallboard specifications, including thermal properties and specifically melting temperature, it is imperative to have access to a well-defined and easy-to-use methodology that accounts for all relevant parameters to produce appropriate solutions for a building in any given location.

1.5 Thesis Scope

Regarding the potential application of PCM wallboards to reduce peak heating demand in a thermally active environment, this thesis has the following objectives:

The main objective of this thesis is to investigate the viability of reducing peak heating demand through thermal energy storage during off-peak time, using PCM-gypsum wallboards and discharge of the stored heat during peak time. This thesis also studies the influence of PCM's thermal properties and convective heat transfer coefficient on the rate of thermal discharge, and its resulting improvement in indoor air condition. Also the impact of PCM application on the globe temperature including the air temperature and the mean radiant temperature was studied. Finally, the feasibility of using such an approach to reduce peak heating demand is evaluated in three different climates and by using two PCM-gypsum wallboards.

CHAPTER 2: LITERATURE REVIEW

2.1 Phase-Change-Material (PCM): General Concepts

Application of Phase Change Material (PCM) as a means to store thermal energy is becoming of more attention due to its potential interesting benefits for energy conservation purposes in buildings. Accordingly, this section outlines the most important terminology and insights regarding the application of PCM in buildings.

PCMs are substances with high latent heat. They are capable of absorb or release a considerable amount of energy while undergoing the change from one phase to another (e.g., from solid to liquid or liquid to gas). In building applications, only a phase change from solid to liquid or vice versa is of concern. Other phase change processes are not practical for building applications. For instance, there is a large volume change during the liquid-to-gas phase change process, which would make PCM containment more challenging.

Phase change materials used in building wall applications can be categorized in two main groups, organic or inorganic materials. Kuznik et al. (2011b) listed the organic and inorganic PCMs available, along with their thermal properties. A comprehensive review of the available materials and ideal candidates for building applications is also mentioned in the literature (Farid et al., 2004; Zalba et al., 2003). For instance, paraffin, which is organic, and salt hydrates, which are inorganic, are the most commonly used PCMs in building envelope applications. Some of the advantages and disadvantages of organic and inorganic PCMs are tabulated in Table 2, (Soares et al., 2013).

Table 2 - Advantages and disadvantages of organic and inorganic PCMs

Materials	**Advantages**	**Disadvantages**
Organic PCMs	- High latent heat capacity (45.3-244 kJ/kg)[3], - Compatible with conventional building materials, - Not much supercooling.	- Low thermal conductivity, - Low volumetric latent heat, - Flammable.
Inorganic PCMs	- High volumetric latent heat, - High thermal conductivity, - Non-flammable, - Available at low cost.	- High volume change, - Supercooling.

An ideal PCM candidate for use in building applications should meet a number of criteria, including high latent heat and thermal conductivity, high specific heat capacity, small volume change, non-corrosiveness, non-toxicity, and exhibition of little or no super cooling. Small volume change reduces requirements for mechanical stability of the PCM's container (Mehling et al., 2007). In building applications, only PCMs that have a phase transition close to human comfort temperature, near 20°C, can be used (Rao et al., 2012).

Several forms of bulk-encapsulated PCM packages to be used in active or passive solar applications are available on the market (Pasupathy et al., 2008a). The problem with these PCM packages is insufficient surface area for heat transfer. For example, in passive solar applications, the stored heat by solar heat gain requires more heat transfer surface area to later release the heat by convective heat transfer. Walls, ceilings, and floors of the buildings offer large surface area for the convective heat transfer (Neeper, 2000), so integrating PCMs within these surfaces is of interest.

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[3] Kuznik et al. (2011b).

The different ways to integrate PCMs into building walls can be categorized as direct incorporation, impregnation, and encapsulation (Kuznik et al., 2011b). PCMs can be incorporated directly into conventional building construction materials by adding liquid or powdered PCM to the construction materials, such as gypsum or concrete, during production, or through immersion, where porous manufactured construction materials are immersed in melted PCM so that the PCM is absorbed and fills in the pores (Khudhair and Farid, 2004). Leakage may be an issue during both processes, direct incorporation and immersion (Hawes et al., 1990). Hawes et al. (1993) mentioned that the melting and freezing temperatures of PCMs incorporated into construction materials may vary slightly from the temperatures gained from differential scanning calorimetry for regular PCMs, so that the phase change temperature for the compound must be considered for the simulations. Another method of incorporating PCMs that helps avoid the leakage problem is to encapsulate PCM in a container, adding it to the conventional construction materials. There are two ways of encapsulating PCMs. The first is macro-encapsulation, in which the PCM is enclosed in large-volume containers, such as tubes, spheres, and panels (Zhou et al., 2012). These containers function as heat exchangers. The problem with macro-encapsulation is that at the time of regaining the stored heat from the melted PCM, solidification around the edges prevents heat transfer; the poor conductivity of the PCM also inhibits heat transfer (Khudhair and Farid, 2004). Another method is enclosing PCM in microscopic polymer capsules. The microcapsules form a powder which is later added to the recipe of building construction material such as concrete or plaster during their manufacture. When applying the microencapsulation method, the small size of the capsule prevents the formation of solid crust and the deterioration of the heat transfer (Kuznik et al., 2011b). Hawlader et al. (2003) carried out experiments on microencapsulated paraffin and found that paraffin kept its geometrical profile and heat storage capacity after 1,000 cycles. Microencapsulation by impregnating the concrete with PCM is very effective, but it has been reported by some researchers that it might deteriorate concrete's mechanical properties such as compressive strength and porosity and density of concrete. For the compressive strength two mechanisms can be considered which decreases compressive strength, firstly the significant difference between the microcapsule's strength and other materials consisting concrete such as cement paste. Secondly the leakage of PCM from the microcapsule and mixing with other concrete's constituents. Furthermore porosity of a PCM-concrete was mentioned to decrease due to structural changing of concrete packing density. Also the density of a PCM-concrete was mentioned to be less than the concrete due to relatively lower specific gravity of PCM compared to other concrete constituents. . Ling et al. (2013) studied the feasibility of using PCM in concrete. Their findings show that the PCM content and the means of PCM incorporation into concrete affect the compressive strength of the PCM concrete considerably. Cabeza et al. (2007) designed and constructed two identical cubicles, one made of concrete impregnated with microencapsulated PCM, called Mopcon concrete, and one with conventional concrete, to investigate the possibility of energy conservation without affecting the strength of the concrete. Cabeza et al. (2007) found that the Mopcon concrete reached a compressive strength of over 25 MPa and tensile splitting strength of over 6 MPa (after 28 days), which is appropriate for some structural applications. A new technique of incorporating PCMs into building envelopes is shape-stabilized PCMs, in which a liquid form of PCM, like paraffin, is dispersed in another phase of a supporting material such as high-density polyethylene (HDPE) to comprise a stable compound material (Zhou et al., 2008). Since the operating temperature is below the melting temperature of the supporting material, the compound maintains its shape even if the PCM changes phase.

2.2 Wallboard Applications

Application of PCM in wallboards comprise the main scope of this study, although PCMs can also be incorporated into insulation layer, floors and ceilings for solar heat gain applications, or, in an active manner, be coupled with air-conditioning systems or under-floor heating systems. Various potential techniques of integrating PCMs into a building envelope are shown in Figure 1 (Zhang et al., 2007).

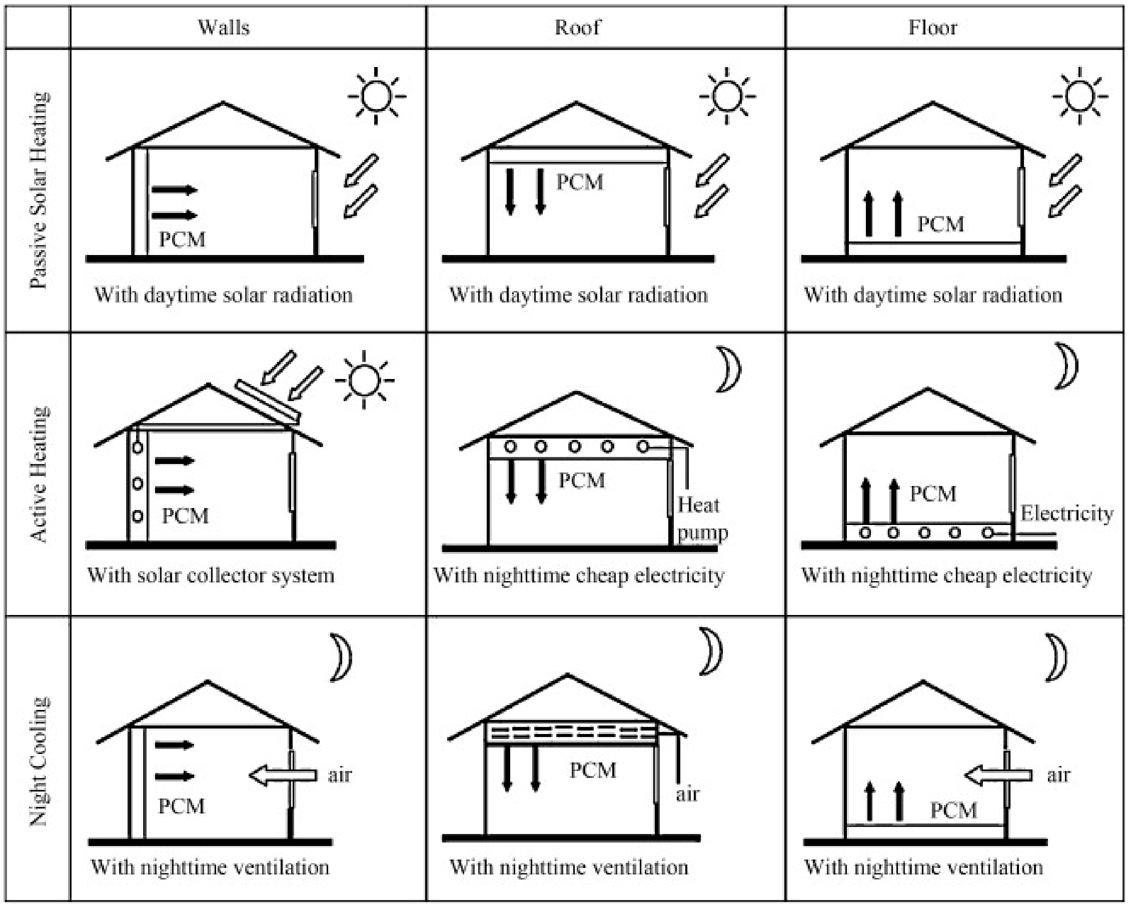

Figure 1 - Various ways of integrating PCM in building envelope, (Zhang et al., 2007).

Previous studies have addressed the benefits of incorporating PCM into wallboards, including damping indoor temperature swings, shaving and shifting peak thermal loads ((Sharma et al., 2005), (Kuznik et al., 2009a), (Muruganantham et al., 2010), Bontemps et al., 2011b)). Muruganantham et al. (2010) investigated the possibility of improving building thermal performance by incorporating new bio-based phase change materials (derived from plant or animal base) into the building envelope. Their findings show maximum energy savings of about 30%, maximum peak load shift of about 60 minutes, and maximum cost savings of about 30%.

Kuznik et al. (2009a) imposed step temperature profiles with different slopes and sinusoidal temperature profiles to two cubicles, one with and one without PCM walls.

Their results show that the more rapid a thermal excitation, the more efficient the PCM. For the external sinusoidal temperature evolution, a 138-minute time difference between the indoor and outdoor temperature was achieved; without PCM, this was 38 minutes. The decrement factor, which is the ratio of the indoor temperature amplitude to outdoor temperature amplitude, was 0.74 with PCM walls and 0.89 without PCM walls.

Bontemps et al. (2011b) studied two adjacent test cells separated by a wall with an aluminum frame comprised of a brick-shaped glass container for PCMs. Three different phase change materials—fatty acid capric, paraffin, and salt hydrate, with melting temperatures of 21°C, 25°C, and 27.5°C, respectively—were included in the glass brick wall. The wall between the two rooms was either with PCM or without PCM. Both cells had a window on the south face to maximize solar heat gain, especially during winter. The other four walls of the cells were made up of vacuum insulated panels (VIPs). According to their experimental results, the indoor air temperature of the cells with PCM reached the maximum value with less magnitude for peak temperature and earlier than the cells without PCM, and also for the case of PCM with higher melting temperature, and the temperature attenuation seems higher. Simulation of thermal behavior of the cell by the developed model was in good agreement with experimental results. The indoor temperatures were quite a bit higher than the desired thermal comfort temperature range, implying that an air-conditioning system is essential for maintaining the indoor temperature within the comfort zone.

Ahmad et al. (2006b) carried out an experimental study by implementing a wallboard containing vacuum insulated panels (VIPs) associated with a PCM panel. They measured temperatures and heat fluxes through the walls, as well as the indoor air temperature. TRNSYS was used for modeling by applying a new module, type 101, developed by modifying a PCM wall model from a team at the Helsinki University of Technology (HUT). The new PCM module was validated with simulations and experimental measurements. The results showed that, during the summer, there is a reduction of 20ºC in indoor temperature for the room with PCM walls compared to the room without PCM walls. It was also shown that, in the winter, the thermal discharge of PCM walls keeps the indoor temperature from dropping below zero; in the case of conventional wall, the indoor temperature drops to –9ºC. Furthermore, a parametric study on the influence of thickness on temperature shows no more reduction in the indoor temperature by increasing the PCM's thickness more than 20 mm.

Xu et al. (2005b) carried out an experimental study in a room with a shape-stabilized PCM-impregnated floor. The PCM-impregnated floor absorbs solar thermal energy during the day and releases the heat at night. They further investigated the effect of various parameters such as thickness of PCM layer, melting temperature, heat of fusion, and thermal conductivity of PCM on the thermal performance of the building. They have found that the heat of fusion and the thermal conductivity of PCM should be larger than 120 kJ/kg and 0.5 W/ (mK), and the thickness of the shape-stabilized PCM plate used under the floor should not be larger than 20 mm. Pasupathy and Velraj (2008b) studied the thermal performance of an inorganic eutectic PCM-based thermal storage system for thermal management in a residential building. They concluded that for the purpose of narrowing indoor air temperature swing and to suit for all seasons, a double-layer PCM incorporated into the roof is recommended. Lin et al. (2004) used an under-floor electric heating system along with shape-stabilized PCM plates to store heat within

PCM by cheap nighttime electricity and then discharge heat during the day. By this approach it was possible to take advantage of the electricity price difference of off-peak. They studied the influence of different parameters, including thermal properties, thickness of PCM and wood floor, and thickness of the air layer, on thermal behavior of the room incorporated by the heating-thermal storage system. Their findings imply that the latent heat and thickness of PCM must be high enough to sufficiently store thermal energy. Their results also show that as long as the PCM type and the thickness of the air layer are properly chosen, the heating system can be used in various climates.

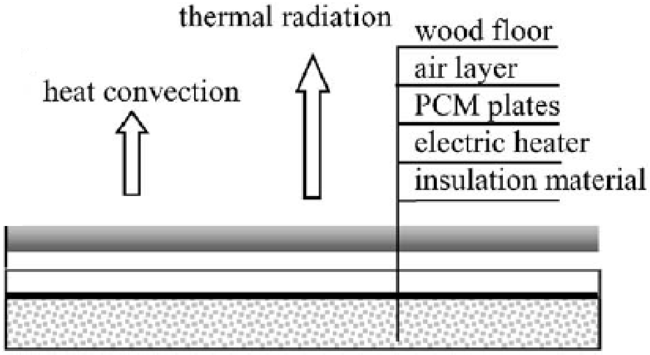

Figure 2 - Underfloor electric heating system with shape-stabilized PCM (Lin et al., 2004).

2.3 Application of PCM Wallboards to Reduce/Shift Peak Heating/Cooling Demand

The heating and cooling demands of an indoor space arise from heat loss and gain through the walls, floor, roof, windows, and doors of the enclosure, as well as internal loads. Considering the walls, space-heating demand evolves from the convection heat transfer between the wall's interior surfaces and the indoor air. Thermal storage capacity and convective heat transfer coupling between the interior surfaces and indoor air are the main factors for assessing the heating demand of a space. Reducing or shifting a portion of peak heating and cooling is of significant interest. One approach to reduce peak heating and cooling demands is to utilize a building structure's thermal mass as a means of thermal storage (Lee and Braun, 2008). However, latent heat thermal energy storage through the application of PCM wallboards is a promising approach to thermal energy storage that offers several advantages. Several studies in the literature show the potential of using a building's thermal mass for shifting loads and reducing peak heating/cooling loads, but there are limited number of studies evaluating the potential of PCM wallboards as latent heat storage systems toward peak load reduction. Some of the studies consider PCM wallboard application for solar energy thermal storage.

Kosny et al. (2006) introduced some new applications and placements of PCM wallboards between 2003 and 2006. They proposed that the PCM layer does not have to be placed at the interior of the wallboards exposed to indoor air. They proposed two state-of-the-art PCM applications in wallboards: dispersed PCM application in cellulose insulation, and concentrated application with batt-fiber insulations or as a part of a novel attic insulation system. The cool-painted metal roof using reflective insulations and sub venting in the field-tested residential attic exhibits a 70% reduction in peak heat flow transmitted through the roof; a cool roof containing PCM causes an additional 20% of peak hour heat flow reduction.

Kissock (2000) simulated the addition of 10% K-18 (a paraffin phase change material) and three enclosure assemblies to the concrete in concrete-sandwich walls, low-mass steel roofs, and gypsum wallboard in frame walls. It was shown that the addition of PCM to gypsum wallboard reduces the peak cooling load by 16% and annual cooling load by 9%, while the higher night ventilation was imposed as outside air ventilation was increased from 0.25 ACH to 4 ACH. In this case, the cooler outside air was employed to cool down the interior walls, which resulted in less cooling requirements during the daytime. In his study, the indoor air temperature was held constant.

Diaconu and Cruceru (2010) proposed a novel PCM wall assembly in which two different PCM layers were placed on either side of a middle layer of conventional insulation. The function of the exterior PCM layer with a higher melting temperature is to be active during the cooling season, and the function of the interior PCM layer with a melting temperature near the indoor set-point temperature is be active during heating season. They used a finite difference method to solve the transient heat equation. The enthalpy method was used to account for thermophysical properties of the PCM wallboard. They simulated the annual thermal performance of a room with this novel PCM wall assembly and found that there is a peak cooling load reduction of 24.3%, a reduction in total cooling load of 1%, a peak heating load reduction of 35.4%, and annual heating energy savings of 12.8%. Stetiu and Feustel (1998) investigated the impact of a PCM wallboard coupled with mechanical night ventilation and found that it provides a 28% load reduction in peak cooling, which makes it possible to downsize the required air-conditioning system.

Zhang et al. (2005) considered two PCM wallboards, one with 10% and one with 20% paraffin, and applied the PCM walls to two test houses to study the possible reduction in peak air-conditioning demand with PCM. Results from their field measurement showed that there is a possible reduction of peak heat flux of up to 21% for the PCM wall with 10% concentration, and up to a 15% reduction in peak heat flux for the PCM wall with 20% concentration.

Childs and Stovall (2012) investigated the optimal PCM characteristics and the total electricity needed for the annual cooling requirements for two different climates. The PCM wallboard was a frame wall with cellulose insulation that included distributed microencapsulated paraffin as a PCM. Their study showed a minor impact on the total cooling electricity usage for both climates. In their work the impact of PCM was small, which can be credited to low heat transfer inhibited by cellulose insulation.

Zhu et al. (2011) studied the impacts of PCM wallboard along with different control strategies of set-point temperature for different climates. In their studies, the imposed control strategies were according to electricity pricing policy and not considering PCM charging and discharging. Also, the impact of PCMs' thermal properties and internal convective heat transfer coefficient on peak load reduction was not considered. Scalat et al. (1996) investigated the thermal performance of two identical rooms, one lined with PCM wallboard and one with ordinary wallboard. Their study showed that by turning off the heating/cooling system, the indoor temperature remains within the comfort range for a longer time in a room lined with PCM wallboard than in a room lined with ordinary wallboard. In their experiment, the outdoor temperature was considered to be constant and real weather data were not considered. Their experimental work showed the practicality of employing PCM wallboard to shift utility peak load, but the thermal behavior of the case study was not simulated or modeled numerically. Also, the impact of PCMs' thermal properties and heat transfer coefficient on thermal charge and discharge of PCM wallboard was not assessed. Tabares-Velasco et al. (2012) showed how whole-building simulation tools (an algorithm used for PCM modeling in Energy Plus) can provide outputs such as peak load reduction and energy savings, which can be used to select the location, type, and amount of PCM to improve energy performance. They did not, however, carry out parametric studies to show how the amount and thermal properties of PCM can result in peak load reduction and energy savings.

A review of peak load reduction using PCM wallboard in literature is listed in Table 3 .

Table 3 - Literature summary for peak heating/cooling demand reduction

Effectiveness can be maximized by Application	**Objective**	**Methodology**	**Results and Conclusions**	**Reference**
TES within envelope insulation system	Optimal PCM characteristics to reduce annual cooling demand	Finite difference model along with optimization analysis	Optimal melting range and optimal thickness	Childs and Stovall (2012)
Room with 2 different PCM layer – Insulation wall assembly	Investigating potential of a novel PCM-insulation wall toward energy saving	Simulation - finite difference – enthalpy method	35.4% peak heating load reduction, 24.3% peak cooling load reduction	Diaconu et al. (2010)
Micro-encapsulated paraffinic PCM in Wallboard	Peak heat flow reduction by including PCM within wall and roof assembly	Experimental	20% reduction of the peak heat flow compared to highly insulated roof	Kosny et al. (2006)
PCM interior wallboard containing 20% paraffin	PCM wall thermal storage with night ventilation – peak cooling load reduction	Numerical – finite difference – RADCOOL	28% peak cooling load reduction	Stetiu and Feustel (1998)
PCM wallboard containing10%, 20% paraffin	Peak heat flux reduction	Experimental	Wall peak heat flux reduction by 38%	Zhang et al. (2005)
K-18 (a Paraffin PCM) added to Concrete sandwich walls, steel roof and frame wall assembly	Peak and annual cooling load reduction	Simulation – explicit finite difference method	For PCM-gypsum wallboard, reduction in peak and annual cooling load by 16% , 9% respectively	Kissock (200)

2.4 Parametric Studies

To improve the approach effectiveness, it is essential to carry out parametric studies. The more influential factors can be determined by parametric analysis. In the literature, several parameters are identified to be influential on thermal performance of the building with PCM-integrated wallboard, ((Lin et al., 2004), (Zhang et al., 2008a), (Stovall and Tomlinson, 1995)). The influencing parameters are PCM's thermal properties such as thermal conductivity, latent heat capacity, phase change temperature range, also PCM's thickness and the convective heat transfer coefficient between PCM layer and indoor air. In order to assess the impact of the each parameter and determine which parameter is more influential on thermal performance of the building with PCM wallboards, parametric analysis in literature investigated effect of each parameters by assuming different values for the studied parameter and keeping the other parameters constant.

In order to store heat within a PCM wallboard thermal storage system, the PCM phase change temperature must be within the defined set-point temperature range for enclosure. If PCM wall temperature never reaches the PCM phase change temperature, PCM will not be melted and the latent heat storage potential of PCM will never be employed. Therefore, PCM with a phase change temperature within an indoor temperature range must be selected for latent thermal storage.

Drake (1987) and Peippo et al. (1991) studied the optimal phase change temperature to maximize stored heat during heating season in a passive solar building, based on standard stud walls and depending on all conditions imposed on the wall. Different behavior can be expected depending on a number of factors, including whether the wall is internal or external, weather conditions, and the thermal resistance of the wall. Estimations for the optimal transition temperature are based on the amount of heat flux during the day and the amount of flux during the night, and are necessary to know that all the stored energy is discharged during the discharge cycle.

Peippo et al. (1991) only considered charging PCM in the direct-gain room by solar radiation. In the case that a PCM slab melts and solidifies diurnally, Peippo et al. (1991) approximated the optimal phase change temperature to maximize stored heat during heating season in a passive solar building as the following:

$$T_{m,opt} = \overline{T_r} + \frac{Q}{hT_{stor}} \quad (1) \qquad \textit{(Optimal phase change temperature)}$$

$$D_{opt} = \frac{t_n}{\rho \Delta H}\left(T_{m,opt} - T_n\right) \quad (2) \qquad \textit{(Optimal thickness of the wall)}$$

While $T_r = \frac{t_d T_d + t_n T_n}{t_d + t_n}$ is average room temperature, *U* is the overall thermal heat transfer coefficient. The equations above on optimal transition temperature and optimal thickness of the PCM slab are based on static daily conditions and cannot necessarily be applied directly to maximize the energy storage over a period of days with varying solar radiation. Therefore, the heat transfer equations have to be solved numerically (Baetens et al., 2010). Asan et al. (1998a) investigated the effects of wall thermal properties (thermal conductivity and heat capacity) and wall thickness on time lag and the decrement factor of the indoor temperature in passive solar buildings. They found that a wall's thermal properties have a significant impact on time lag and the decrement factor. Considering the combined effect of heat capacity and thermal conductivity, it was shown that heat capacity has a mild effect on the decrement factor whereas thermal conductivity has a significant impact. They assumed thermal conductivity range from 0.01W/mK to 100W/mK which is not the real case for phase change materials. Zhang et al. (2008a) proposed two new parameters to evaluate the thermal performance of PCM-impregnated wallboard. These two parameters are the modifying factor of the inner surface heat flux, α, and ratio of the thermal storage, β, introduced as follows:

$$\alpha = \frac{q_w}{\acute{q}_w} \quad (3)$$

In which q_w is the inner surface heat flux, considering that heat capacity of the wall is negligible as below:

$$\acute{q}_w = (\acute{T}_{out} - T_{in})U = \frac{(\acute{T}_{out} - T_{in})}{\left(\frac{1}{h_{w,in}} + \frac{L}{K} + \frac{1}{h_{w,out}}\right)} \quad (4)$$

And $q^{/}_{w}$ is the inner heat flux of PCM wallboard. If $\alpha < 1$, it means that thermal storage of PCM adds to the wall’s thermal resistance, inhibiting heat flow through the wall.

Internal walls can charge heat ($q_w < 0$) and discharge heat ($q_w > 0$), if $q_w < 0$ and T_{in} is higher than desired set-point temperature or if $q_w > 0$ and T_{in} is lower than desired set-point temperature. Internal walls thus help decrease the indoor air variations and provide increased thermal comfort and reduce energy consumption. The thermal storage β is defined as the ratio of the charged or discharged heat to the total thermal capacity of the wall area.

Zhang et al. (2008a) investigated the effects of PCM properties such as heat of fusion, thermal conductivity, and melting temperature on the thermal performance of PCM wallboards. They claimed that for external PCM walls, more energy can be saved by PCM wallboards with higher heat of fusion and lower thermal conductivity, and by selecting proper melting temperature. For the internal walls, more energy can be saved by PCM wallboards with higher heat of fusion, and by selecting proper thermal conductivity and melting temperature. They also mention that for a passive solar building, it is more energy-efficient to implement PCM in internal walls.

Stovall and Tomlinson (1995) investigated the potential advantages of using PCM as a load management tool and thermal comfort enhancer. In their study, variables such as thermostat set-point, dead-band width (the temperature range out of which the heater turns off/on), PCM melting temperature, amount of PCM, and internal convective heat transfer coefficient were considered to evaluate the improvement in load management and thermal comfort using PCMs. In the building model considered in this study, the window and door area were assumed to be opaque surfaces, so only the thermal storage due to convection heat transfer between the interior wall surface and indoor air were considered, and no credit was given for thermal storage from solar radiation. In the case studies, the convective heat transfer coefficient was doubled and tripled to study the impact on energy storage and thermal comfort. In the load management case studies, the heater was supposed to be turned off during the on-peak time; however, in some cases, the override feature was considered and the heater was turned on during the on-peak time to keep the indoor temperature within a reasonable range. It was found that the application of PCM wallboard does not have a significant impact on thermal comfort and has only a slight impact on the indoor temperature profile. Increasing the convective heat transfer coefficient improves the thermal storage within the PCM wallboard; in terms of thermal comfort, this has a negative impact on occupant thermal comfort by increasing indoor air circulation.

Aldoss (2011) investigated the effect of amount of PCM and PCM properties such as specific heat capacity and thermal conductivity on heating/cooling load fluctuation. It was shown that the C_p-value does not affect the mean value of a heating/cooling load but does affect the fluctuation of the loads and dampen the variation; in the other words, this shaves the load peaks. It was also shown that changing thermal conductivity does not affect the degree of load fluctuation; however, due to the increase in the overall thermal u-value of the wall assembly, the mean heat load increases by higher thermal conductivity values. It was also shown that the part of the PCM layer closer to the inner portion was less effective, effectiveness can be maximized by increasing PCM thermal conductivity. It was concluded that integrating PCM within building walls affects the load peaks, resulting in a decrease in the size and steadiness of the HVAC system. PCM application did not affect the mean value of heating/cooling loads, although reducing the load peaks.

Kuznik et al. (2008b) investigated the optimal thickness of PCM wallboard. First, by means of numerical simulations, they showed that an optimal value for PCM wall exists that depends on external and internal temperature variations; they then calculated the optimal value. The objective of optimization was to achieve the highest storage capacity with the least amount of PCM.

Zwanzig et al. (2013) simulated the thermal performance of a residential building with PCM-incorporated walls and roof in three different climate zones. Their results show that the performance of a PCM wall depends a great deal on weather conditions, suggesting that different PCMs should be chosen for different climates. They also considered different configurations of PCM layer within the wall assembly. The results suggest that the optimal placement of PCM layer within the wall assembly depends on resistance values between PCM layers and the outdoors. It was found that a centrally located PCM layer does have better performance than an externally or internally located PCM layer. They concluded that PCM application can reduce peak heating/cooling load and shift peak cooling load without significant heating load shift.

2.5 Numerical Models to Simulate PCM Wallboards

To assess the thermal behavior of a building with PCM-impregnated wallboards, it is essential to carry out a numerical simulation. Numerical simulation makes it possible to study building performance quickly and cheaply instead of carrying out experimental tests. Recently, various building energy performance simulation tools have become available. However, only TRNSYS, ENERGYPLUS, and ESP-r have the capability to simulate walls with PCM, Chandrasekharan et al. (2013).

Castell et al. (2009) reviewed models available in the literature to simulate the impact of PCM wallboards on building thermal performance. The evaluated models were namely TRNSYS type 232, TRNSYS type 241, TRNSYS type 204, PCM Express (ESP-r), and Energy Plus. A summary of available PCM modules in TRNSYS is listed in Table 4.

Table 4 – PCM modules in TRNSYS

PCM Modules	Numerical Method	PCM Simulation	Validation	Reference
Type 101	Finite Difference	Effective heat capacity	Yes	Ahmad et al. (2006)
Type 222	Finite Difference	Active Layer - TRNSYS	No	Ibanez et al. (2005)
Type 204	Finite Difference	Effective heat capacity	No	Lamberg et al. (2000)
Type 241	Finite Difference	Enthalpy method	No	Schranzhofer et al. (2006)
Type 260	Finite Difference	Effective heat capacity	Yes	Kuznik et al. (2010)

For instance, Ibanez et al. (2005) simulated the effect of PCM using the active layer tool in TRNSYS type 56. PCM functions as a controller; wall and air temperatures are inputted to the PCM module and outputted to the active layer in TRNSYS type 56, which simulates the effect of the PCM.

Heim and Clarke (2004) simulated the thermal behavior of a highly glazed and naturally ventilated passive solar building with PCM-impregnated gypsum wallboards employing ESP-r special materials capability. This capability in ESP-r makes it possible to model the building elements with time-varied thermal properties; however, their studies did not consider variable thermal conductivity or density for phase change material. They also assumed the internal heat gains from occupants and devices to be zero. The PCM-gypsum board was applied to the inner lining of all surfaces except the floor. Solar gain through the large glazed areas of the building resulted in rising indoor temperatures. Nevertheless, use of PCM decreased the indoor temperature during seasonal transition periods and made it possible for the heat stored during summer to be released at the beginning of the heating period.

Athienitis et al. (1997) studied the thermal behavior of a passive solar test room with PCM-impregnated gypsum wallboards. They carried out a full-scale experiment and attached PCM-gypsum boards of the same thickness as the inside wall layer to the regular gypsum boards. The PCM-gypsum boards were made by immersing regular gypsum boards in liquid butyl stearate with a melting range of 16.0–20.8°C. They developed an explicit finite difference model and simulated thermal performance of the cell with the assumption of unidirectional heat transfer and uniform thermal properties for the PCM-gypsum board. Simulation results were in good agreement with the experimental results and showed there could be a reduction of about 4°C in the maximum room temperature during the day and a 15% decrease in the night heating load.

Kuznik et al. (2008a) carried out a full-scale experiment to investigate thermal performance of a lightweight internal partition wall. They added PCM layers to three walls of a test room placed within a climate chamber to simulate summer climate conditions. Comparison of the cases with and without PCM walls revealed that PCM walls can reduce temperature fluctuations by 4.7°C.

2.6 Limitations and Study Objectives

Considering the review of previous studies, there is still limited information regarding the application of PCM wall to shift and shave peak demand. First, most of the earlier studies considered the application of latent heat storage through PCM wallboards in passive solar buildings; however, the studies investigated energy performance of the air-conditioned buildings (active buildings) with PCM wallboard are still limited and insufficient. Regarding the real scenario in the actual buildings, there is need to study active environments with PCM Walls.

Second, the appropriate control strategy along with PCM thermal energy storage is desirable to result in shifting and shaving the peak demand. Majority of the studies on air-conditioned buildings considered simple and/or conventional set-point temperature control strategies, however these scenarios were not considered based on PCM charging and discharging, also not according to peak demand periods.

Finally, the studies mentioned in this chapter have considered different cases such as under-floor heating systems, passive solar buildings etc. Within each case, various parameters (i.e. PCM's thermal properties such as PCM's thermal conductivity, PCM's heat capacity, convective heat transfer coefficient and PCM's layer thickness) were identified to potentially influence on thermal performance of the building with PCM-integrated wallboard. However for each specific application case, there is lack of conclusion addressing which parameter is more influential. Specifically, for the case of active building with baseboard heater the influence of these parameters is not well-studied.

Considering the above limitations and knowledge gaps, this study aims to pursue the following objectives:

i. Evaluating the possibility of shaving and shifting peak demand utilizing PCM thermal energy storage along with establishing the proper control strategy. The proper control strategy is proposed based on PCM phase change temperature range and according to the peak demand periods.

ii. Investigating the effect of influencing parameters on shaving and shifting the peak demand; also to determine which parameter is more influential. The influential parameters investigated are as follows:

    I. PCM’s Thermal Conductivity
    II. PCM’s Melting Temperature Range
    III. PCM’s Thickness
    IV. Convective Heat Transfer Coefficient between Indoor Air and PCM Wall Layer.

2.7 Summary of the Work

The performance of the PCM enhanced building wallboard were assessed by determining indoor air temperature during peak periods while a peak shaving and shifting control strategy is applied. A real gypsum wallboard of one zone of an actual building is replaced with a real PCM-gypsum wallboard.

The impact of influencing parameters on indoor air temperature during peak periods is investigated by parametric studies. It is shown that which parameters are more influential on improving indoor condition.

This thesis also includes: validation of a PCM module within TRNSYS simulation tool against experimental data from literature and implementation of PCM model to the actual building model in TRNSYS.

CHAPTER 3: METHODOLOGY

3.1 Phase Change Heat Transfer Problem

In the building simulation, the governing equation to be considered for investigating the thermal performance of a building is the energy conservation equation.

The problem to be solved in PCM wallboard application, considering energy conservation, is heat transfer across a vertical wallboard, within which a phase change of material can happen. The heat transfer across the wall consists of two regimes, conduction and natural convection within the wall. It must be decided whether or not natural convection occurs within the PCM layer. This can be investigated by considering the Rayleigh number, which is:

$$Ra = \frac{g\beta(T_w - T_C)H^3}{\nu\alpha} \quad (5)$$

Where T_w is the temperature of the warm side of the wall and T_C is the temperature of the cold side. Jany et al. (1988a) showed that in an enclosure with thickness b and height H, the convection heat transfer within PCM exists only if:

$$Ra^{1/4} < \frac{b}{H} \quad (6)$$

Considering the small thickness of wallboards versus height of the wallboards, this condition is not satisfied, so here the dominant heat transfer regime across a vertical enclosure is only conduction. Considering the energy balance equation for the wallboard impregnated with PCM:

$$\rho_{S,l} C_{p_{S,l}} \left(\frac{\partial T_{S,l}}{\partial t}\right) = \nabla(\lambda \nabla T_{S,l}) \quad (7)$$

The energy balance at the solid–liquid interface is as follows (Ahmad et al., 2006):

$$\lambda_s \frac{\partial T_S}{\partial n} - \lambda_l \frac{\partial T_l}{\partial n} = \rho L V_n \quad (8)$$

Where V_n is the moving solid–liquid interface velocity, $\partial/\partial n$ is the derivate following a normal vector at any point of the interface, and L is latent heat of the PCM.

Also at the solid–liquid interface:

$$T_s = T_l \quad (9)$$

To deal with the phase change phenomenon, either the enthalpy method or the effective heat capacity method can be used. In the enthalpy method, the sum of the sensible and latent heat can be considered by determining the enthalpy function $h(T)$ of the PCM. The enthalpy form for the energy equation is as follows:

$$\rho \frac{\partial h}{\partial t} = \nabla(\lambda \nabla T) \quad (10)$$

The enthalpy function $h(T)$ of the material can be obtained by DSC. Using the effective heat capacity method, the non-isothermal phase change of the PCM can be considered. For the phase change material:

$$\rho \frac{\partial h_{pcm}}{\partial t} = \frac{\partial h_{pcm}}{\partial T} \frac{\partial T}{\partial t} = C_{p_{pcm}}(T) \frac{\partial T}{\partial t} \quad (11)$$

In which $C_{p,\,PCM}(T)$ represents the effective heat capacity defined as follows:

$$C_{p_{pcm}}(T) = \begin{cases} C_{P_s} & T < T_s \\ C_{P_s} + \dfrac{L}{(T_l - T_s)} & T_s \leq T \leq T_l \\ C_{P_l} & T > T_l \end{cases} \quad (12)$$

Where T_l and T_s are the temperatures at which melting and freezing begin, respectively.

To assess the impacts of PCM-enhanced walls on whole-building thermal performance, it is first necessary to characterize the dynamic thermal behavior of PCM-impregnated wallboards and to determine PCM wallboard's thermal properties, such as heat capacity profile and melting and solidification temperatures.

3.2 Modeling Approach and Tools – TRNSYS

TRNSYS is the acronym for the Transient System Simulation Program. TRNSYS is a modular simulation program developed by the University of Wisconsin, based on the FORTRAN programming language. The TRNSYS software simulates the thermal behavior of buildings. In its modular structure, different components are connected to constitute a building model. Each component's mathematical description is written using the FORTRAN programming language. In the TRNSYS interface, the components are called "types." Type 56 is the multi-zone building, referring to the building with several zones, each zone conditioned or not, having different wall assemblies. Type 56 considers interactions between different zones by solving a series of differential equations. Each zone is considered to be one node, in which the heat balance is established by taking into account the convective term, the radiative term, and the coupling term between the other zones (Klein S.A. et al., 2012).

TRNSYS (version 17.01.0028) was selected to investigate the building's thermal performance in order to link the building with different building components and systems (e.g., HVAC systems) as well as its various validations (Crawley et al., 2008). The other advantage of TRNSYS is that it is a flexible simulation program, further components can be added to it conveniently, and there is access to the source code for many of the types, so they can be modified for use. Using the TRNSYS tool makes it possible to determine wall composition and wall layer configuration of the building wall assemblies, as well as to apply different control strategies for the heating/air-conditioning utilities. In the following chapter, a validated code for simulation of PCM wallboard in the TRNSYS software, type 255, was applied.

TRNSYS considers unidirectional heat transfer in walls and performs air energy balance within zones of the multi-zone building to calculate zone mean air temperature.

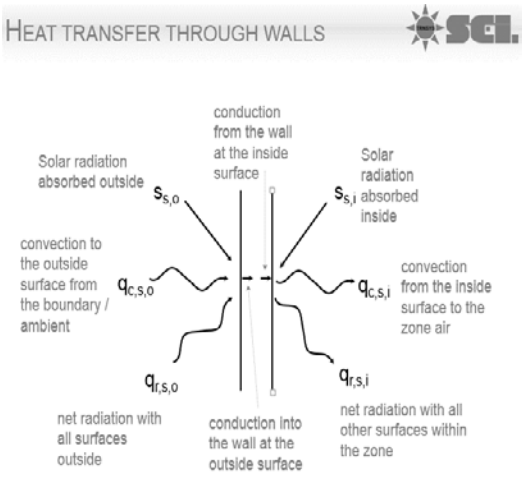

Figure 3 - Heat transfer through the wall - Blair et al. (2002), TRNSYS, Multi Zone Building Simulation

As mentioned earlier, thermal properties of conventional wallboards are independent of temperature, while thermal properties of PCM wallboards, and especially specific heat capacity is a function of temperature. Consequently, the heat conduction problem in PCM wallboard cannot be solved algebraically, because of the non-linearities. In order to solve the PCM conduction problem within the TRNSYS environment, TRNSYS type 255 is selected (Kuznik et al., 2010).

3.3 TRNSYS PCM Model Description

Among the several models to simulate a PCM wall, TRNSYS type 255/260 is selected because it allows users to simulate external walls lined with PCM layer on the interior face, and also because input parameters to this module make it possible to carry out desired parametric studies. This module has been validated using the experimental data from ANNEX 23 (2011). Task C results are presented in chapter 5.

The multi-zone building type in TRNSYS (type 56) makes it possible to simulate the thermal performance of buildings. In simulating the thermal behavior of a building with PCM-impregnated wallboards, the problem is to implement the PCM module in TRNSYS and coupling between PCM module and TRNSYS type 56. In all case studies in this thesis, the PCM-gypsum layer is placed instead of conventional gypsum layer as the interior layer of external wall assembly, and thus the PCM layer is exposed to indoor air on one side and attached to the insulation layer and the rest of wall assembly on the other side. Figure 4 and Figure 5 present illustrations of connecting the PCM module to the multi-zone building model.

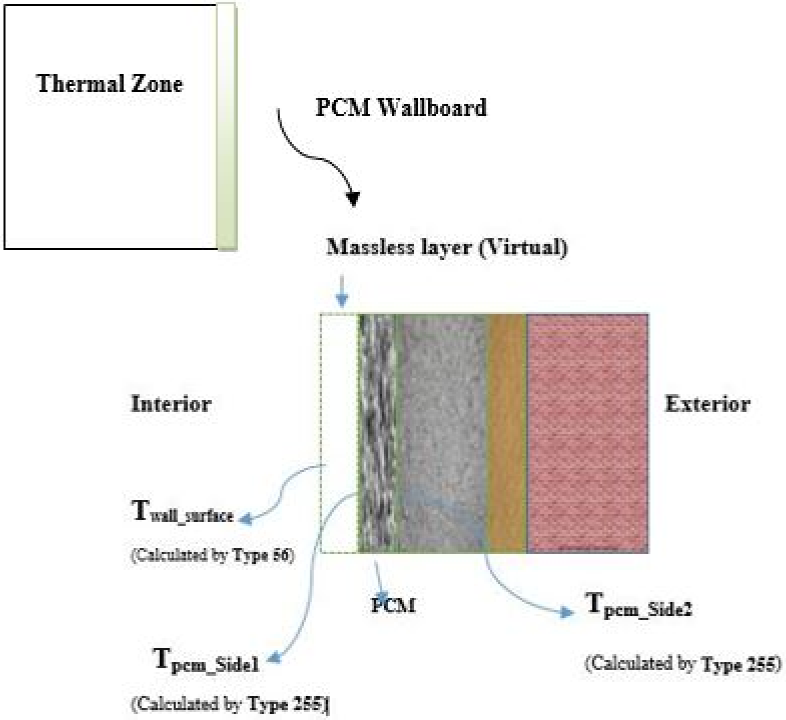

Figure 4 - Implementation of PCM module in wallboard, adapted from Kuznik et al. (2010)

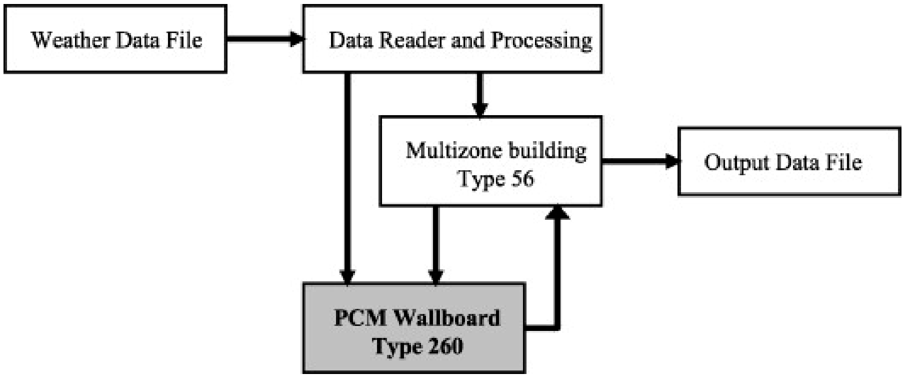

Figure 5 - Coupling of new PCM module (TYPE 255/260) with TRNSYS multi-zone building model (TYPE 56), Kuznik et al. (2010)

PCM layer is only applied to the external wall assemblies regarding that the TRNSYS type 255/260 is developed to model thermal performance of an external wall with PCM.

Here, the procedure to implement the PCM module in TRNSYS for the case of replacing regular gypsum board with PCM-gypsum is as follows: In the case studies, external wall assemblies of one zone, comprised of gypsum board, are removed in the type 56 module and replaced by a fictive, mass-less layer called PCMGYPSUM, with the wall type changed from external to boundary. This layer in type 56 is only considered as a means to associate the interior surface temperature with the PCM module component (type 255). The boundary condition to this fictive layer is T_PCM, which is later calculated with the PCM module. The surface temperature of PCMGYPSUM, TSI_SX (x = surface number of PCM layer in type 56) is considered as the input to PCM module (T_surf_side1). The thermal resistance of the PCM mass-less layer is assumed to be very low—0.005 hm^2K/kJ in case studies—so there would be negligible difference in the total resistance of the wall assembly. The interior convective heat transfer coefficient of the wall is assumed to be 36 kJ/hrm^2K (10 $W/m^2.K$), which is the default value assigned by Kuznik et al. (2010). The convective heat transfer coefficient on back of the PCM layer, in contact with the remaining layers of wall assembly, is assumed to be 10^{-6}, which implies direct contact between the PCM layer and the wall assembly.

The inputs for PCM module are as follows:

- The outdoor weather condition parameters, outdoor dry bulb temperature, long-wave radiation, short-wave radiation, and view factor. For every case study in this thesis, apart from the outdoor dry bulb temperature, all the parameters pertaining to solar radiation are assumed to be zero.
- The inside surface temperature (T_surf_side1) is calculated by multi-zone building type and given as an input to the PCM module.

The parameters corresponding to the PCM module are the following:

- Properties of the phase change material, including:
    1. Effective heat capacity of PCM, $C_{PCM}(T)$, for which the C_{PCM} curve is assumed to be linear and the arithmetic mean value for latent heat between phase transitions temperatures is given as an input in the PCM module
    2. Thermal properties of PCMs, including thermal conductivity, density, and heat capacity in solid and liquid phases
    3. Phase change temperature range: T_fusion as midpoint temperature of phase change, DELTAT_sol and DELTAT_liq.

       Melting Temperature is T_fusion + DELTAT_sol and solidification temperature is T_fusion + DELTAT_liq.
    4. Thickness of PCM layer
    5. Number of mesh nodes for PCM layer (10 nodes in this thesis)
- Initial temperature condition
- External and internal convective heat transfer coefficient
- Number of external layers
- The wall layers located between the PCM layer and the exterior, with a maximum number of four layers (thickness, density, thermal conductivity and heat capacity of layers)
- Number of mesh nodes for each external layer (10 nodes in this thesis).

The output of the PCM module, surface temperature of the PCM layer (T_{PCM}_Side1) is calculated by type 255, which is given as an input to Type 56.

On the interior side of the PCM wallboard, the boundary condition is the indoor temperature and convective heat transfer coefficient. On the other side, the thermal resistance of the layers between the PCM layer and exterior and outdoor weather condition is the boundary condition.

To input the latent heat of PCM as an effective heat capacity method, the following assumption is considered:

$$C_{p,fusion} = \int_{T_s}^{T_l} C_{p,pcm}(T)\,dt \;\cong\; \frac{L}{(T_l - T_s)} \qquad (13)$$

$C_{p,\,fusion}$ represents the effective heat capacity of PCM, $C_{p,\,PCM}(T)$ is heat capacity of PCM measured by DSC. L is the latent heat of phase change. T_l and T_s are the temperatures at which melting and freezing begin, respectively.

This is a reasonable assumption, as it is considered in the validation procedure of the PCM module in section 5.1, and the validation shows very good agreement between the experimental data and simulation results. This assumption is considered for the base case study in section 5.2 and later on in the parametric studies.

CHAPTER 4: CASE STUDIES

4.1 Building Model Case Study

The building model is a one-story house heated by electric baseboard heating; it has a ground floor and a basement.

Figure 6 - Bungalow house - adapted from Kummert et al. (2011)

A previously developed and validated TRNSYS model of this house by Hydro-Québec Laboratoire des Technologies de l'Énergie (LTE) was used. To investigate the viability of the proposed potential benefit of PCM wallboard application, conventional gypsum board was simply replaced with the same thickness of PCM-gypsum board (here, in the benchmark case studied, 13 mm of gypsum and/or PCM-gypsum board).

One wall assembly of the external facades of the case study building was composed of gypsum, insulation, fiberboard, and brick (M8_EXTFACADE). This wall assembly was taken into account because it included a gypsum layer, which was replaced by PCM-gypsum to carry out case studies. The compositions of the conventional and PCM wall assemblies are shown in Figure 7.

External Wall Composition

PCM Wall Compositions

Figure 7 - Conventional and PCM wall composition

PCM-gypsum was incorporated into the interior layer of the wall assembly, as our aim was to store energy within the PCM by means of indoor heated air, and later on to have the energy released to the indoor air from the PCM layer.

Thermal properties of wall layers of conventional wall assembly are tabulated in Table 5.

Table 5 - Thermal properties of the conventional wallboard

Material	**Density (kg/m³)**	**Specific Heat (KJ/kg °C)**	**Thermal Conductivity (W/m K)**	**Thickness (m)**
Conventional Gypsum Board	800	1.09	0.161	0.013
Insulation	49	0.94	0.050	0.089
Fiber Board	350	1.3	0.055	0.013
Brick	1980	0.84	0.42	0.102

Table 6 gives the thermal properties of the PCM-gypsum layer which is replacing the conventional gypsum layer.

Table 6 - Thermal properties of the PCM layer

Thermal Properties	**Phase Change Range (°C)**	**Latent Heat (KJ/Kg)**	**Conductivity (W/m.K)**	**Heat Capacity (KJ/Kg.K)**	**Density (Kg/m³)**	**Thickness (m)**
Wallboard with 30% PCM[1]	20	104	0.23	1.46	1000	0.013

1 Gypsum board with 30% Paraffin, Tomlinson (1991).

This PCM-gypsum wallboard is manufactured by impregnating gypsum board with liquid paraffin so that the gypsum board contains paraffin by 30%. This PCM wallboard was manufactured at Oak Ridge National Laboratory, Tomlinson (1991). While the PCM is melted, the liquid PCM is kept within the pores of host material, here gypsum board, by surface tension (Scalat et al., 1996). The phase change temperature of this PCM-gypsum board is within the desired thermal comfort range. A sensitivity analysis on PCM thermal properties has been considered by changing values according to the PCM-gypsum wallboard properties.

The house is divided into 16 zones in TRNSYS modeling. Applying PCM wallboards to all zones and all locations of the building is not practical from a cost point of view, and the payback period will be not reasonable. Consequently, one zone, **zone1 (Salon/Entrée)**, was selected for the case studies. A reason to select **zone1** was that it required the least thermal comfort criteria (COMF004, in the TRNSYS model), as it is not occupied during the entire day. This zone **(Zone1)** is heated by electric baseboard heaters with a capacity of 1890 W (6804 kJ/hr). The building's ground floor layout, showing the location of **zone1,** is shown in Figure 8. The north and west walls in **zone1** have areas of 10.94 m^2 and 8.64 m^2 respectively.

In all simulations, two wall assemblies (M8_EXTFACADE) composed of gypsum board in the west and north walls in **zone1** were replaced with the PCM-gypsum wall assemblies.

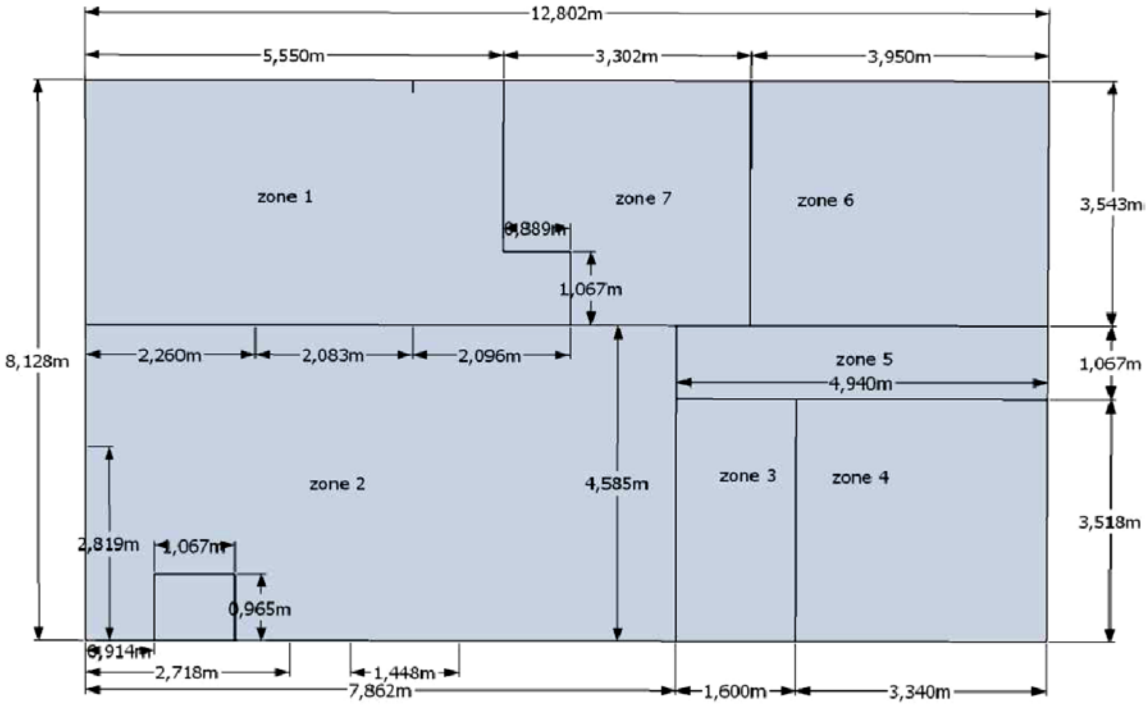

Figure 8 - The building's ground floor layout

4.2 Integration of PCM Module with the Building Model

The connections between multi-zone building (type 56), PCM module (type 255), set-point schedule imposed on the indoor air temperature, weather data, and output components in TRNSYS environment are depicted in Figure 9.

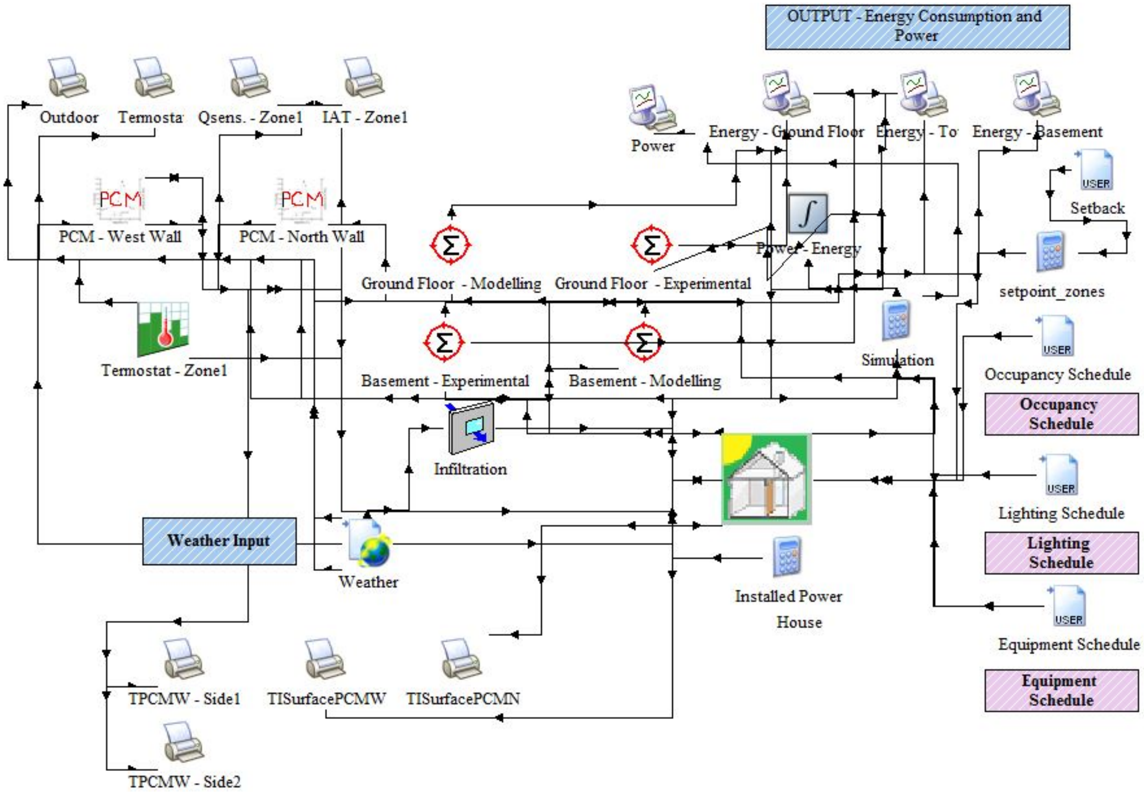

Figure 9 - TRNSYS simulation interface

Ventilation flow is given as an input, while the infiltration rate is considered as a function of local wind speed, density and volume of the room air, and ambient room temperature. It is calculated based on the correlation given in the TRNSYS manual,

$$\dot{m}_{inf} = \rho_a V_a \left(K_1 + K_2|T_a - T_z| + K_3 W\right)$$

K_1, K_2, and K_3 are empirical constants that are selected for a medium construction according to the ASHRAE Handbook of Fundamentals as 0.010, 0.017, and 0.049 respectively. T_a is ambient temperature, T_z is zone temperature and W is the zone humidity ratio.

4.3 PCM-Gypsum Wallboard

Three commercially available PCM-gypsum wallboards were identified from the literature to replace the conventional gypsum wallboard in order to carry out parametric studies. The thermal properties of these wallboards are tabulated in Table 7.

Table 7 - PCM-gypsum wallboards in literature

Material	**Density (kg/m^3)**	**Specific Heat (KJ/kg^oC)**	**Thermal Conductivity (W/m^oC)**	**Phase Change Range (^oC)**	**Latent Heat (KJ/Kg)**
A-Gypsum Board loaded with 20% Emerest 2326[1]	900	1.34	0.214	17-21	28.8
B- Wallboard with 30% PCM[2]	1000	1.46	0.23	20	104
C- Maxit Clima Plaster (PCM content of 20%)[3]	1340	1	0.6	23-26	18

1 Scalat (1996), 2 Tomlinson (1991), 3 Hill (2004).

PCM wallboard B was selected and used in simulation of case study with PCM wallboard and the parametric studies. As the PCM-gypsum wallboard "C" melting temperature range (23-26 ^oC) is not within the set-point temperature schedule imposed for case studies (18-20 ^oC) and thus PCM will not change phase, it was not considered in the parametric studies.

4.4 Climates

Three Canadian cities were selected to investigate the effects of using two PCM-gypsum wallboards (PCM type A and PCM type B in section 4.3) in different climates. Locations were selected according to ANSI/ASHRAE Standard 169-2006 and are as follows: Vancouver, a cool climate (ASHRAE zone 5); Montreal, a cold climate (zone 6); and Calgary, a very cold climate (zone 7).

Table 8 - Climates zones

City	Climate	ASHRAE Zone
Vancouver	Cool	5
Montreal	Cold	6
Calgary	Very Cold	7

4.5 Influential Parameters

The following parameters are identified in literature to be influential on thermal performance of the building with PCM-integrated wallboards. In Chapter 5, parameters studies are carried out to investigate the effect of these parameters on shaving and reducing the peak demand and to assess which parameter is more influential.

In each parametric analysis, a single parameter is changed and the other parameters are kept constant.

	Parameters
PCM Thermal Properties	Thermal Conductivity Melting Temperature Range Thickness (Amount of PCM)
	Convective Heat Transfer Coefficient

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Validation of TRNSYS Type 255

The Task C of ANNEX 23 was selected as a case study to verify the type 255 module of TRNSYS (ANNEX 23, 2011). This cubicle was chosen due to the available experimental data regarding cases with and without PCM walls, which were required for the validation procedure. Two identical cubicles with different walls were considered. The schematic of the cubicle is shown in Figure 10.

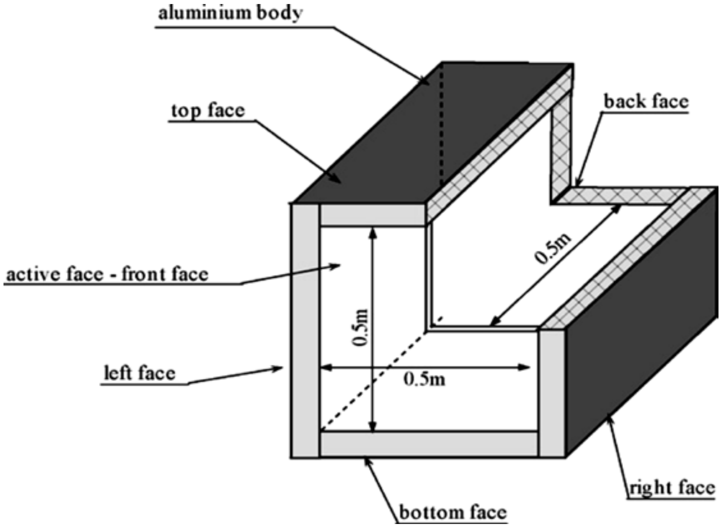

Figure 10 - Test cubicle (ANNEX 23, 2011).

In both cubicles, one of the walls is composed of 2 mm aluminum, which is called the active face, with low thermal resistance and low thermal capacity to facilitate the heat transfer between inside and outside. The three other walls are different in the two cubicles: one of the cubicles has three normal walls, while the other has three PCM walls. The floor and ceiling of the two cubicles are identical. The wall composition of each cubicle is depicted in Figure 11.

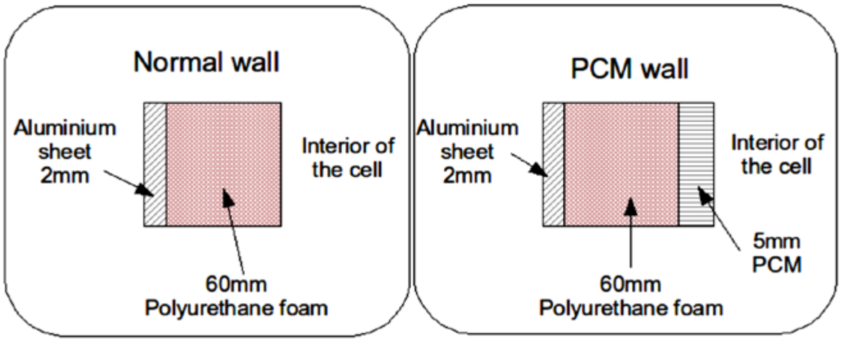

Figure 11 - Normal and PCM wall composition (ANNEX 23, 2011)

The properties of the materials used in these two wall compositions are tabulated in Table 9 and Table 10.

Table 9 - Thermal properties of wallboard materials

Material	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Density (Kgm^{-3})	Specific Heat Capacity ($KJkg^{-1}K^{-1}$)
Insulation	0.04	50	1400
Aluminium	230	2700	880

Table 10 - Thermal properties of PCM

State	Temperature (°C)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Density($Kg.m^{-3}$)
Solid	8	0.23	860
Liquid	28	0.17	860

The specific heat of PCM has been measured by differential scanning calorimeter and is shown in Figure 12 (ANNEX 23, 2011).

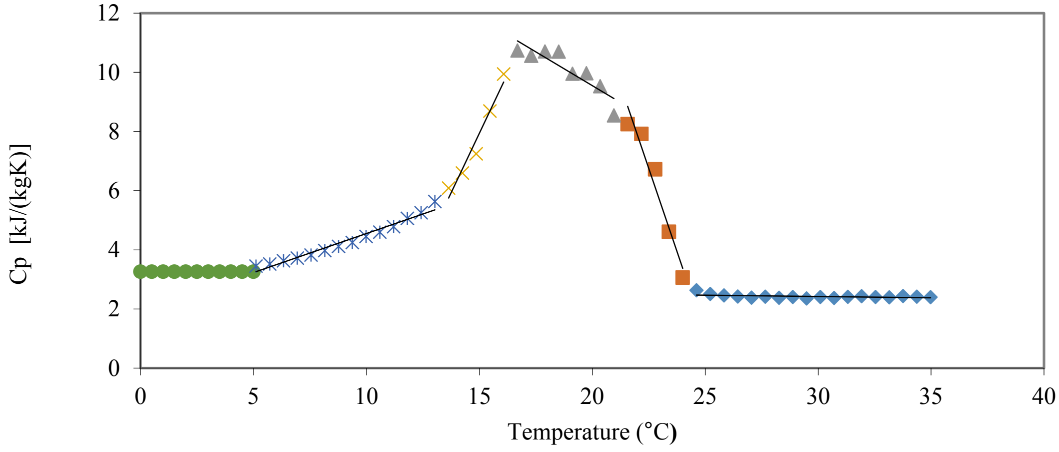

Figure 12 - Measurement of the PCM heat capacity, (ANNEX 23, 2011)

Results for the imposed step temperature profile and sinusoidal temperature profiles are presented in Figure 13 and Figure 14, respectively.

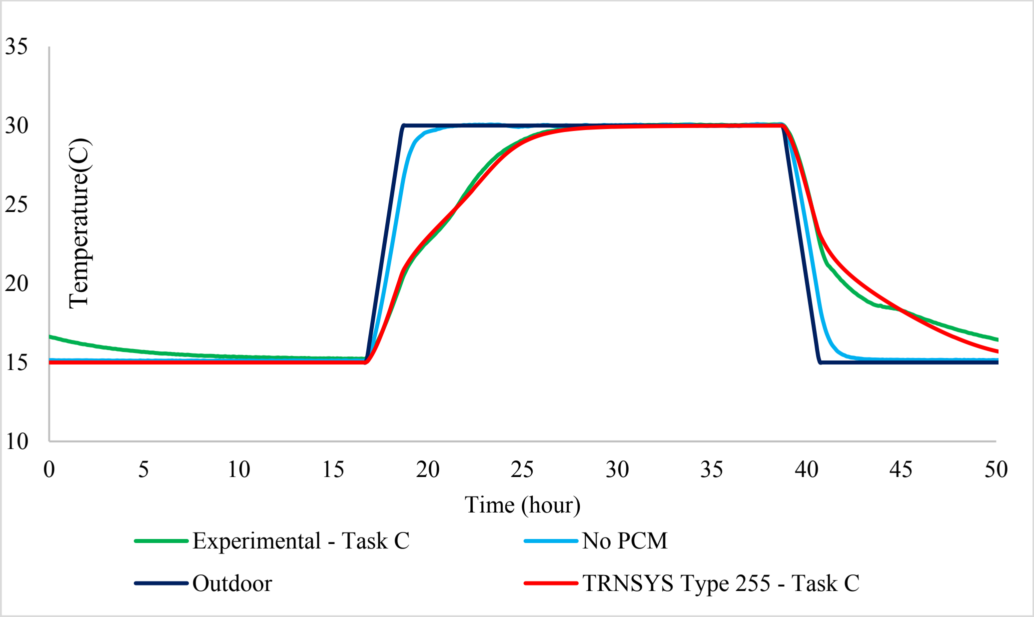

Figure 13 - Step temperature profile, (ANNEX 23, 2011)

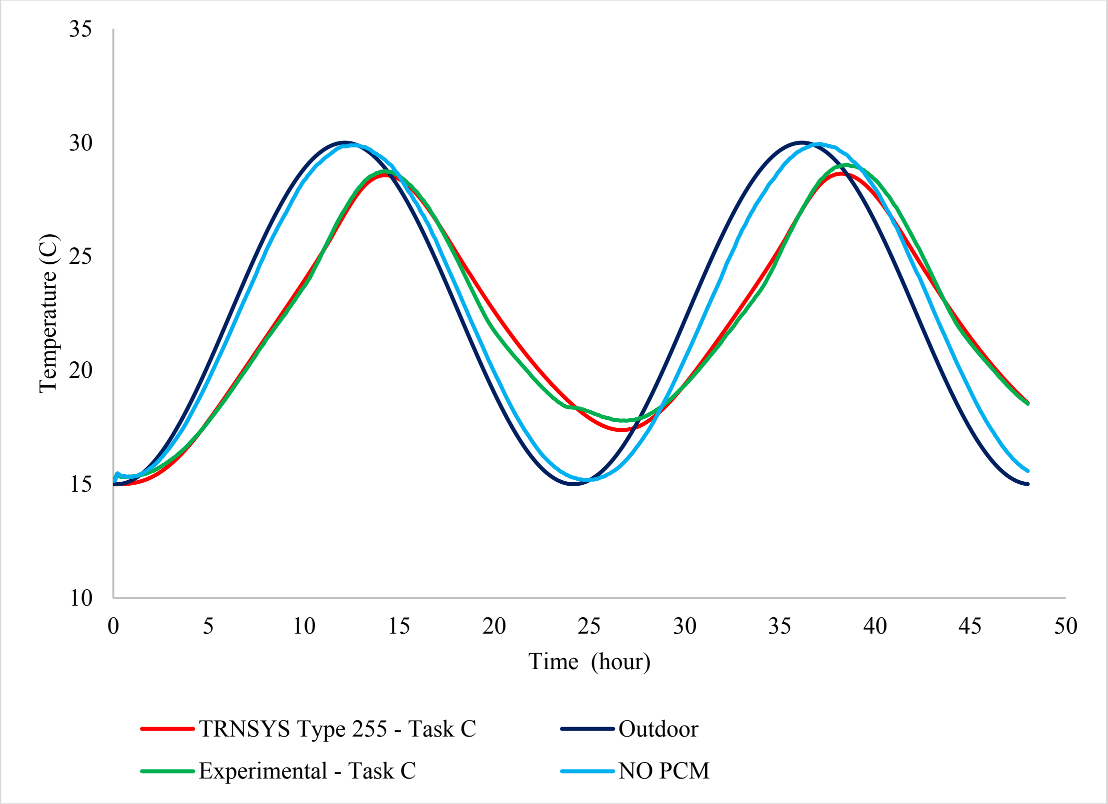

Figure 14 - Sinusoidal temperature profile, (ANNEX 23, 2011)

The inside temperature results for the cubicle, both in the case of imposed step temperature profile and sinusoidal temperature profile, are in good agreement with the measured data. In the case of the step temperature profile, the minor difference between measured data and simulation results can be attributed to measurement accuracy, numerical errors, or the initial conditions of the cubicle before the test.

During the solidification of microencapsulated PCMs, the process starts from the outer surface. Later, the increase of the solidified layer results in less melted volume and less heat transfer area, so natural convection heat transfer within the microencapsulated PCM is inhibited and the solidification process requires more time. The discrepancy in cooling between each temperature profile, which occurs around the solidification temperature (19°C) in Figure 13 and Figure 14, is attributed to the inability of the modeling by TRNSYS type 255 to predict this phenomenon (Kuznik et al., 2010).

Section 5.1 presented verification and validation of the PCM module, TRNSYS type 255. The following sections in this chapter include results pertaining to the case study of the building described in section 4.1.

5.2 Peak Heating Demand Reduction through Application of PCM Wallboards

The main objective of this thesis is to show that PCM wallboard can be utilized as a peak heating demand management tool. This means that PCM wallboard makes it possible to adjust the set-point temperature of heating system to a lower temperature during peak hours, or during a portion of peak hours, while maintaining the indoor air temperature within the thermal comfort range.

Thermal behavior of the building case study with PCM wallboards was simulated for one year, for the Montreal weather data. The coldest consecutive two days of heating season, the 15th and the 16th of January from a typical meteorological year in Montreal, was selected and demonstrated for the following case studies. This period includes 336th hour to 384th hour out of the 8760 hours of a year. In this study, the gypsum layer of an external wall assembly of one zone, **zone1** of the building described in the previous chapter, was replaced with a PCM-gypsum layer. The aim is to assess the benefit of latent thermal storage of PCM wallboard versus the sensible thermal storage of the conventional gypsum board as thermal mass.

In general, indoor air can be considered as the heat exchange medium by which thermal energy is transferred from a heating system to the latent heat storage, PCM-gypsum wallboard. The convection heat transfer is driven by the temperature difference between the interior wall surface and the indoor air. For the simulations with PCM wallboard, the **zone1** ceiling, floor, and interior walls adjacent to the other zones are considered to be identical, as are those without PCM walls. The **zone1** is the entrance room of the building. It is assumed that there is no occupant in this zone during the charging, so there is no internal gain from occupants or appliances. The external walls (Facades) of **zone1** have a total area of 19.58 m^2 and are composed of gypsum, insulation, fiberboard, and brick, with a total overall u-value of 0.366 W/m^2K (1.318 kJ/hm^2K). The two wall assemblies (M8_EXTFACADE) containing gypsum boards in **zone1** were replaced with the PCM-gypsum board.

According to Hydro-Quebec (2014), in winter, periods of high electricity demand is greatest during weekday mornings between 6 and 9 am and evenings between 4 and 8 pm. The thermostat set-point schedule was arranged in such a way that the set-point temperature of heating system was lowered by 3 degrees between 5 a.m. and 10 a.m. and also between 3 p.m. and 9 p.m. The set-point was selected to be 20°C, so the PCM-gypsum board with melting temperature of 20°C melted while the heater was on. The required time for the fully charged PCM wallboard (PCM totally in liquid phase) to release heat and become discharged (PCM totally in solid phase) could be determined based on the PCM thermal properties as well as the convection heat transfer coefficient between the indoor air and the interior PCM layer. Determining this time period is not in the scope of this study, so two peak periods, 5 a.m. to 10 a.m. and 3 p.m. to 9 p.m. was considered for the PCM discharge. The influential dimensionless numbers affecting thermal dynamics of PCM wallboard was identified in a study by Bastani et al. (2014).

The required time for the PCM wallboard to be fully liquidified and solidified can be determined, however in this study a simple control strategy based on PCM phase change temperature range and according to the peak periods was imposed to the **zone1.** The **zone1** air temperatures for the cases with conventional gypsum board and PCM wall with melting temperature of 20 and the wall surface temperature in the cases of gypsum board and PCM-gypsum board and surface temperatures of the two sides of PCM board are shown in Figure 15 and Figure 16.

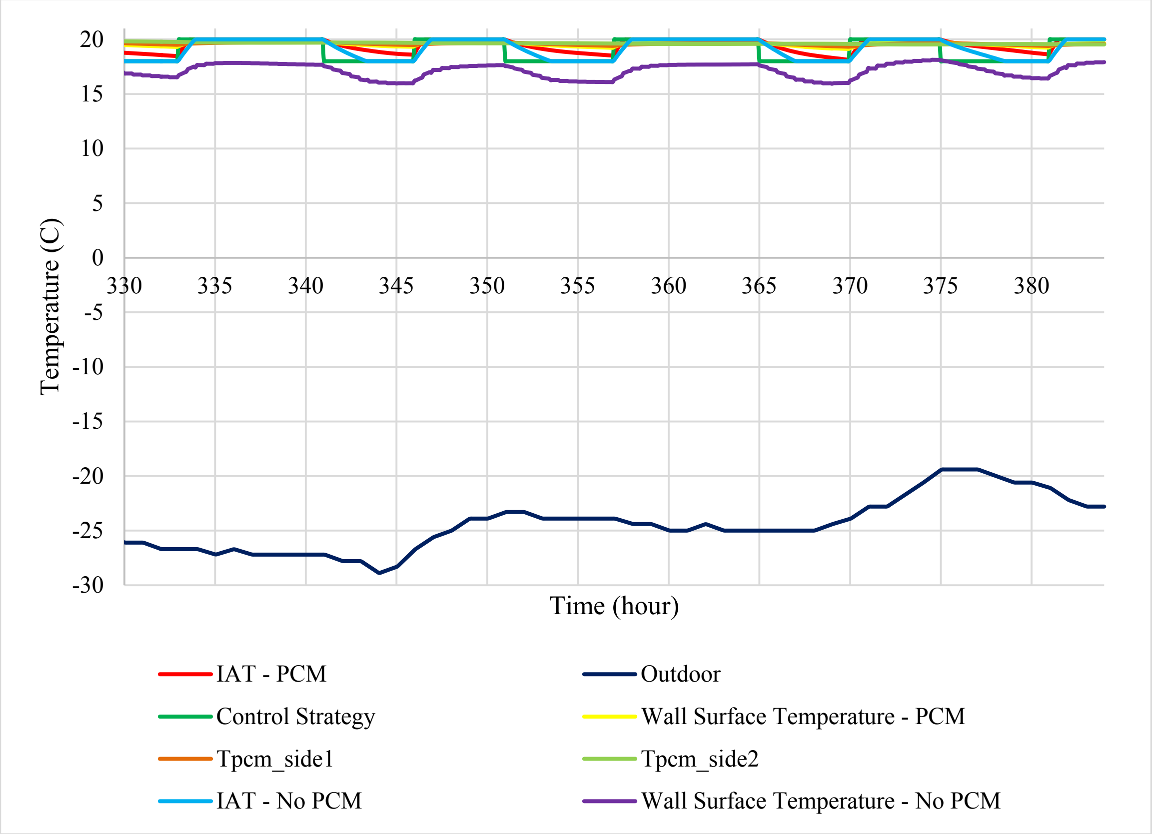

Figure 15 - Zone 1 air temperature without PCM and PCM with melting temperature of 20 and PCM

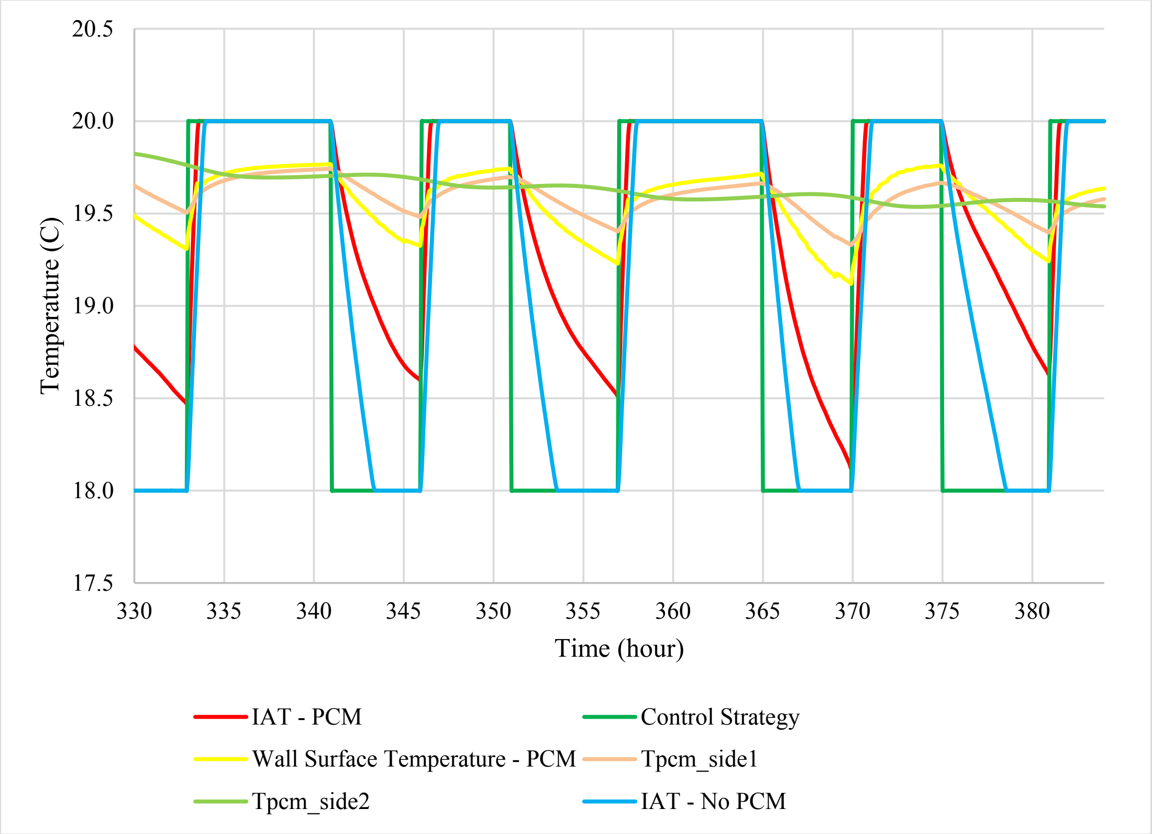

Figure 16 - Zone 1 air temperature without PCM and PCM with melting temperature of 20 (Zoomed In)

Figure 15 and Figure 16 clearly shows the thermal behavior of the zone with PCM walls. In the case of gypsum wallboard the indoor air temperature drops below 17ºC, the set-point threshold, and the heating system turns on during peak period while in the case of PCM wallboards the indoor air temperature remains above 18 ºC and the heating system does not turn on. Figure 15 shows that gypsum wallboard surface temperature drops to below 18ºC and has more variation compared to PCM wallboard surface temperature. The highest difference in wall surface temperature of the case with PCM and the case without PCM is 3.35 ºC. As seen in Figure 16 PCM wallboard surface temperature varies between the melting range (19-20) showing energy storage and release during phase change. There is a small difference between the Tpcm_side1 and PCM wall surface temperature. This is due to the thermal resistance of the massless layer (0.005 hm^2K/kJ) that was considered for connecting the PCM module to the multi-zone building module in TRNSYS. A comparison of heating load for the cases of conventional gypsum wallboard and PCM-gypsum wallboard with melting temperature of 20°C is shown in Figure 17.

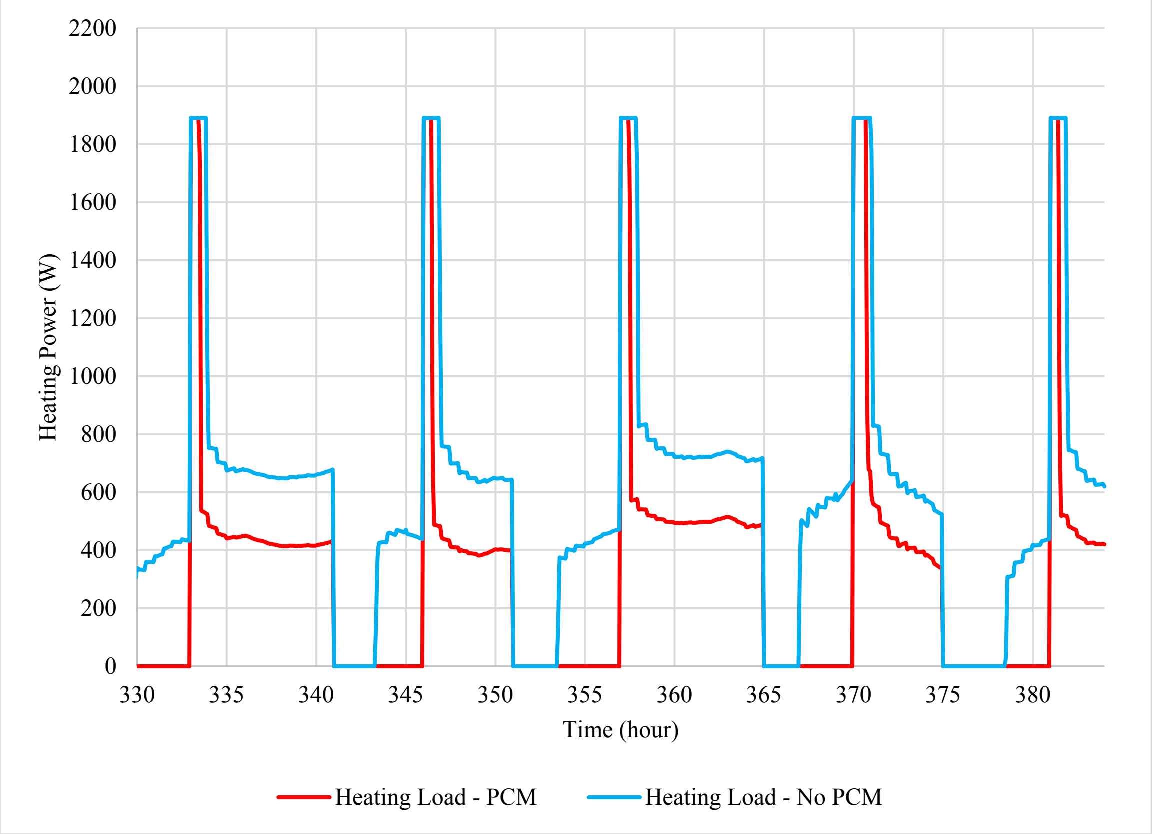

Figure 17 - Heating load of zone1 with PCM - gypsum wallboards and with gypsum wallboards

Heating load is calculated based on the following equation:

$$Q_{load,Z1} = \left(-1 * Q_{wg_{Z1}} + Q_{Z1}\right) * \left(-\frac{1}{3600}\right) \quad (14)$$

In which the $Q_{load,\ Z1}$ is the heating load of **zone1,** Q_{wg_Z1} (kJ) is the wall gain on the inside surface of the wall for **zone1,** and Q_{Z1} (kJ) is the energy demand (heating and cooling) of **zone1,** which are outputs of type 56 module in TRNSYS. For the 15th and 16th of January, heating power for **zone1** with PCM gypsum wallboard is zero as the IAT never reaches the set-point threshold and heater does not turn on while for conventional wallboard there heater turns on during the peak period. The jumps at the hours of 336 and 345 and all the hours of set-point increase are attributed to the instantaneous change on thermostat set-point, and consequent sudden heating demand increase. The set-up for PCM wallboard with melting temperature of 20°C, mentioned in section 5.2, is considered as the base case scenario to investigate impact of PCM thermal properties on the PCM wallboard performance, discussed in section 5.3.

As seen in Figure 16 and Figure 17, during the coldest period, peak heating demand shift of 3 hours was achieved. In the case of conventional wallboard, heating system turns on at 367hr, while for the case with PCM until the start of off-peak period (370hr), IAT does not drop below the set-point and thus heating systems does not turn on. Also during these 2 days, 336th hour to 384th hour (the coldest period), heating load was decreased by 36% in the case of PCM wallboard compared to conventional wallboard.

5.3 Impact of PCM Thermal Properties on Indoor Air Temperature

In this section, the influence of PCM wallboard specifications, including PCM thermal properties such as thermal conductivity, melting temperature range and thickness (amount) of PCM wall layer, on the thermal discharge of PCM, and consequently on the indoor air temperature, are evaluated.

5.3.1 Impact of PCM Thermal Conductivity

The impact of thermal conductivity on discharge of the PCM wallboard is considered by assuming values from 0.10W/mK to 0.50W/mK.

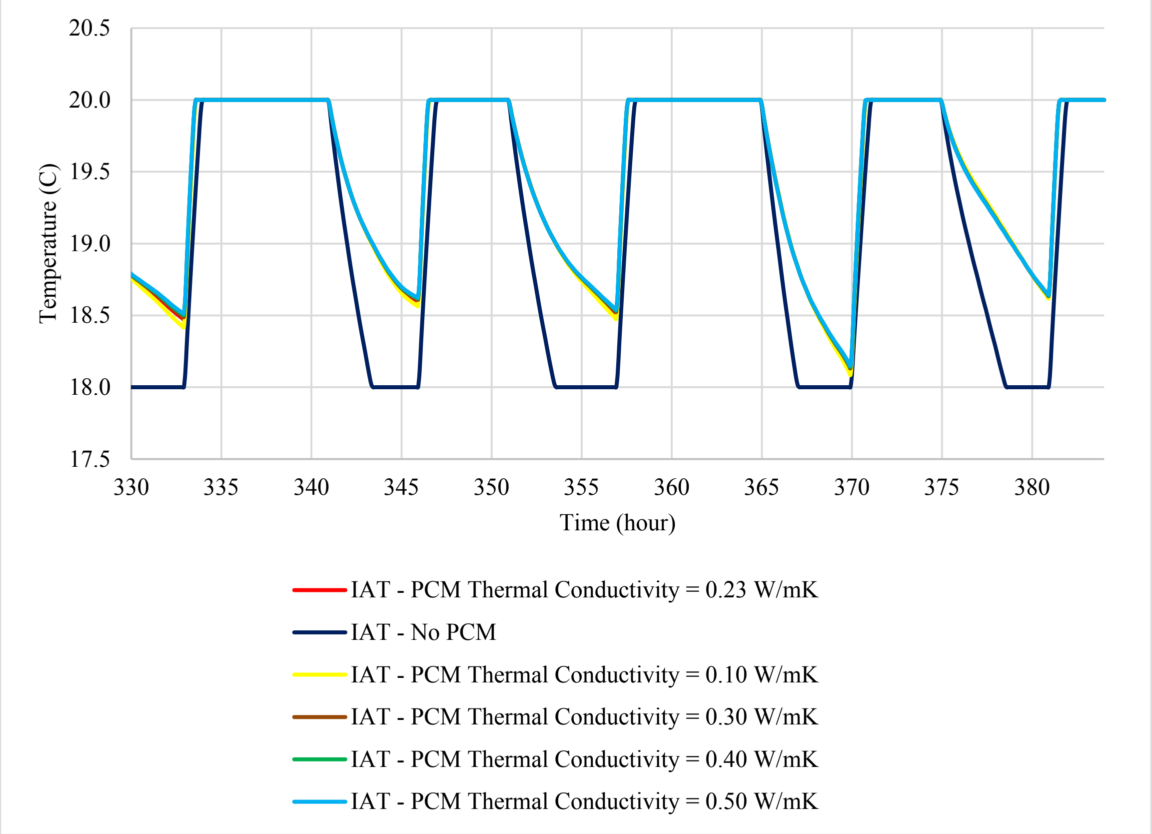

Figure 18 - Impact on thermal conductivity on discharge of PCM wallboard

It is obvious from Figure 18 that improving thermal conductivity of PCM-gypsum wallboard does not have noticeable effect on the thermal discharge of PCM, which implies that the heat stored before peak period is totally discharged. In the other words, by selecting a proper melting temperature of PCM and imposing an appropriate set-point schedule even with low thermal conductivity of PCMs, the stored heat is released. The negligible impact of thermal conductivity is in agreement with studies done by Xu et al. (2005b) and Zhang et al. (2008a). It is shown in section 5.4 that changing convective heat transfer coefficient does have effect on PCM thermal discharge. It can be concluded that during the discharge of PCM, convective heat transfer between PCM layer and indoor air is more dominant than conduction heat transfer within PCM layer.

5.3.2 Impact of PCM Melting Temperature

Here a series of simulations was carried out to investigate the effect of melting temperature on the performance of PCM during discharge. Thermal properties of PCM type "B" were mentioned earlier, in section 3.5. Thickness of the PCM-gypsum layer is assumed to be 0.013 m, the same thickness as the conventional gypsum layer in wall assembly. The base case is a PCM layer with phase change temperature range of 19–20°C.

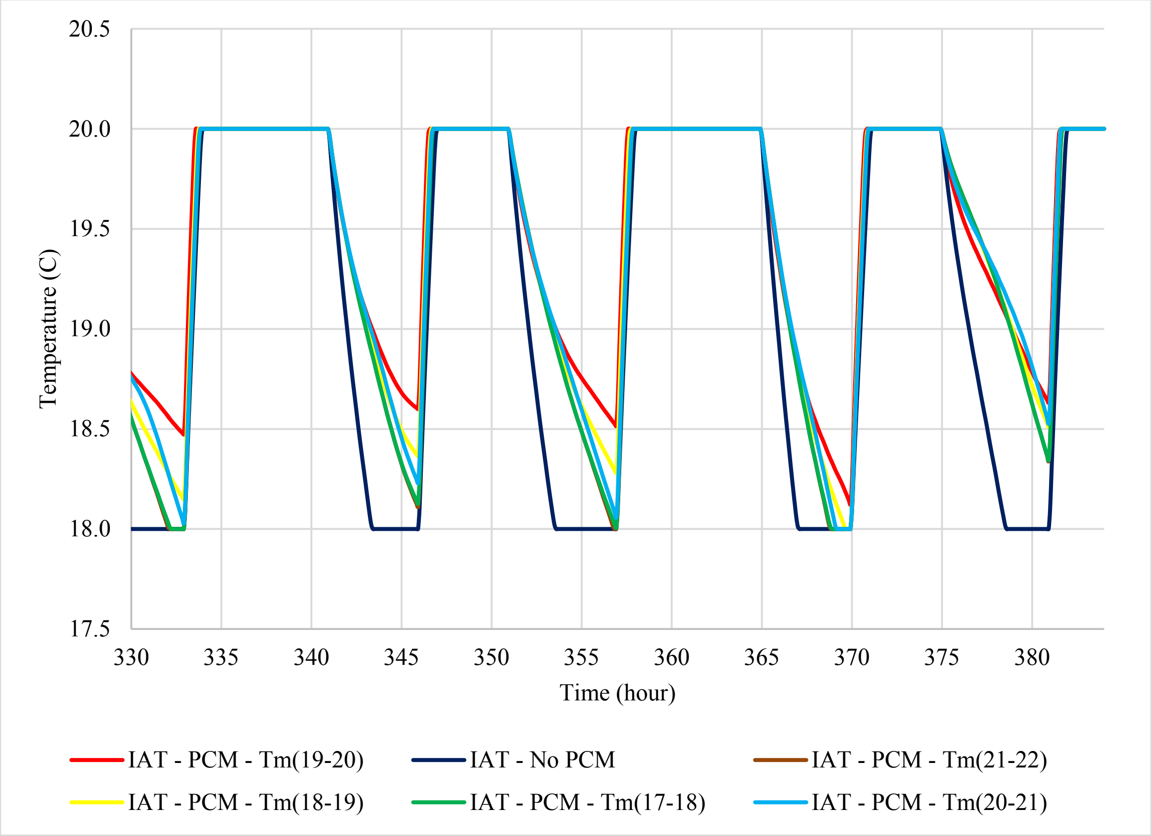

Figure 19 - Effect of PCM melting temperature on PCM thermal discharge during peak period

As shown in Figure 19, during peak time, while indoor air temperature (IAT) is above 19°C, IAT drops with the same slope for different cases. Melted PCM with phase change range of 19-20 starts to solidify below 19°C and release the stored latent heat. It is clear that the IAT slope is less for this case (red line). For the case where PCM melting temperature is above the set-point temperature imposed during off-peak time, PCM with melting temperature of 21-22°C never reaches its melting temperature, and no effect of latent heat release is observed (dark-brown line). In this case, while the PCM is not melted during the off- peak time, the difference between this case and conventional wallboard (No PCM) is only contributed to higher heat capacity of PCM which is 1.46 KJ/KgK compared to 1.09 KJ/KgK for conventional gypsum board. For the case where PCM has a melting temperature range of 17–18°C, PCM is melted during off-peak period at temperature of 20. During the peak period, the indoor air temperature drops, when the heating system set-point is changed to the lower temperature, however it never reaches 17°C, which is the solidification temperature of PCM. Therefore, melted PCM never freezes, and PCM does not release stored latent heat. PCM with phase change temperature range of 18-19 °C is melted before peak time but during the peak time it solidifies and discharges partially (yellow line).

It is obvious that the highest PCM thermal discharge is reached by applying PCM with melting temperature range of 19-20°C. It can be concluded that the best performance of PCM during discharge is obtained by selecting PCM with a melting temperature closer to the set-point temperature.

5.3.3 Impact of PCM Amount (Thickness of PCM Layer)

The conventional gypsum layer in two external walls (M8_EXTFACADE) of **<u>zone1</u>** of our building model were replaced with the PCM-gypsum layer type “B”. The different values for thickness of PCM layer were as follows: 0.013, 0.02, 0.05, and 0.005 m. The first value for PCM layer thickness is 0.013m, which corresponds to the thickness of conventional gypsum board.

Figure 20 shows the influence of PCM layer thickness on PCM thermal discharge, and consequently on **<u>zone1</u>** indoor temperature.

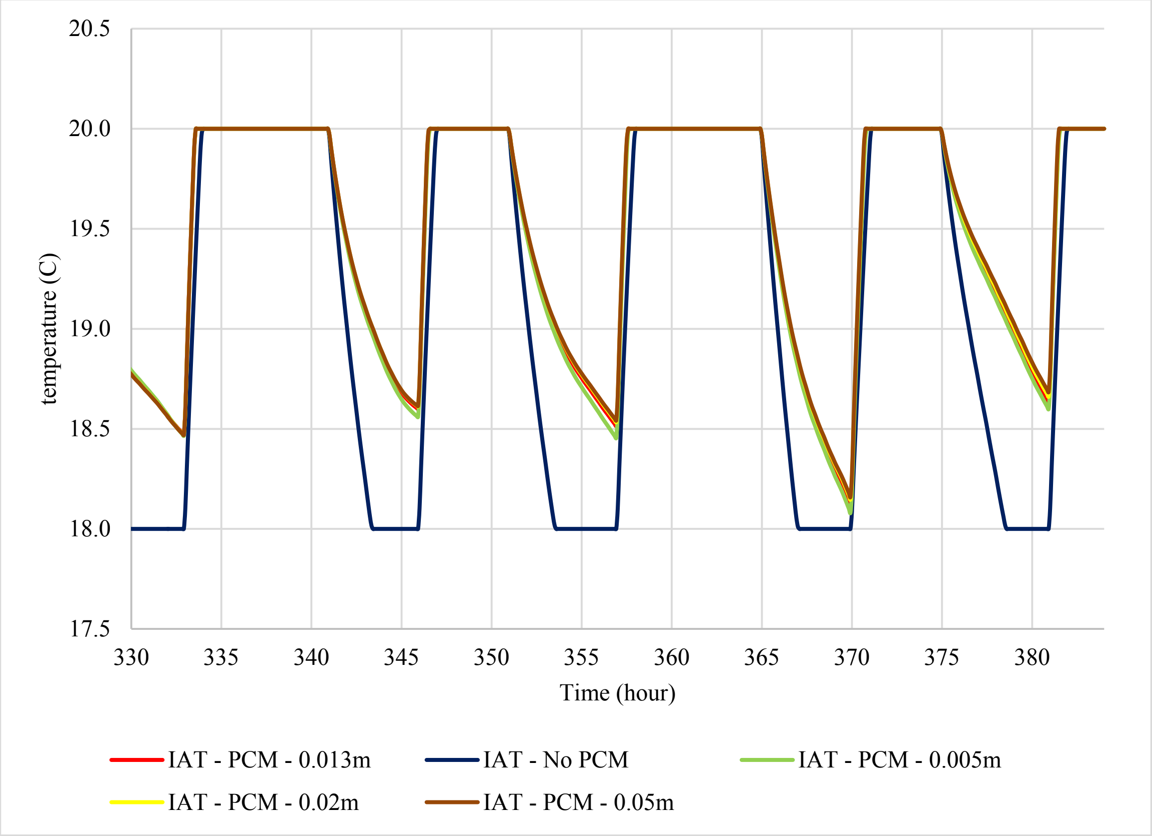

Figure 20 - Effect of PCM thickness on PCM thermal discharge during peak period

As shown in Figure 20, after increasing PCM layer thickness to 0.013 m, no further improvement can be seen on the PCM thermal discharge and accordingly on indoor air temperature. These results imply that any further increase in thickness beyond 0.013 m prevents complete melting of the PCM: There is no further storage and release of latent heat of PCM.

Ahmad et al. (2006a) investigated thermal performance of two passive test cells, one with wallboards containing PCMs and one without. The interior temperature of the test cell with PCM decreased compared to the test cell without PCM. Their investigation showed that by adding PCM thickness after a certain value there is no more decrease in interior temperature and thus PCM is not efficient anymore.

5.4 Impact of Convective Heat Transfer Coefficient (h)

To improve the thermal performance of PCM wallboard in discharging stored heat into the indoor air and thus providing indoor air temperatures within a desired thermal comfort range and temperatures closer to the desired set-point temperature, interior convective heat transfer coefficient can be increased (by means of increasing air speed). The effect of convective heat transfer coefficient on discharge of PCM during on-peak hours is shown in Figure 21.

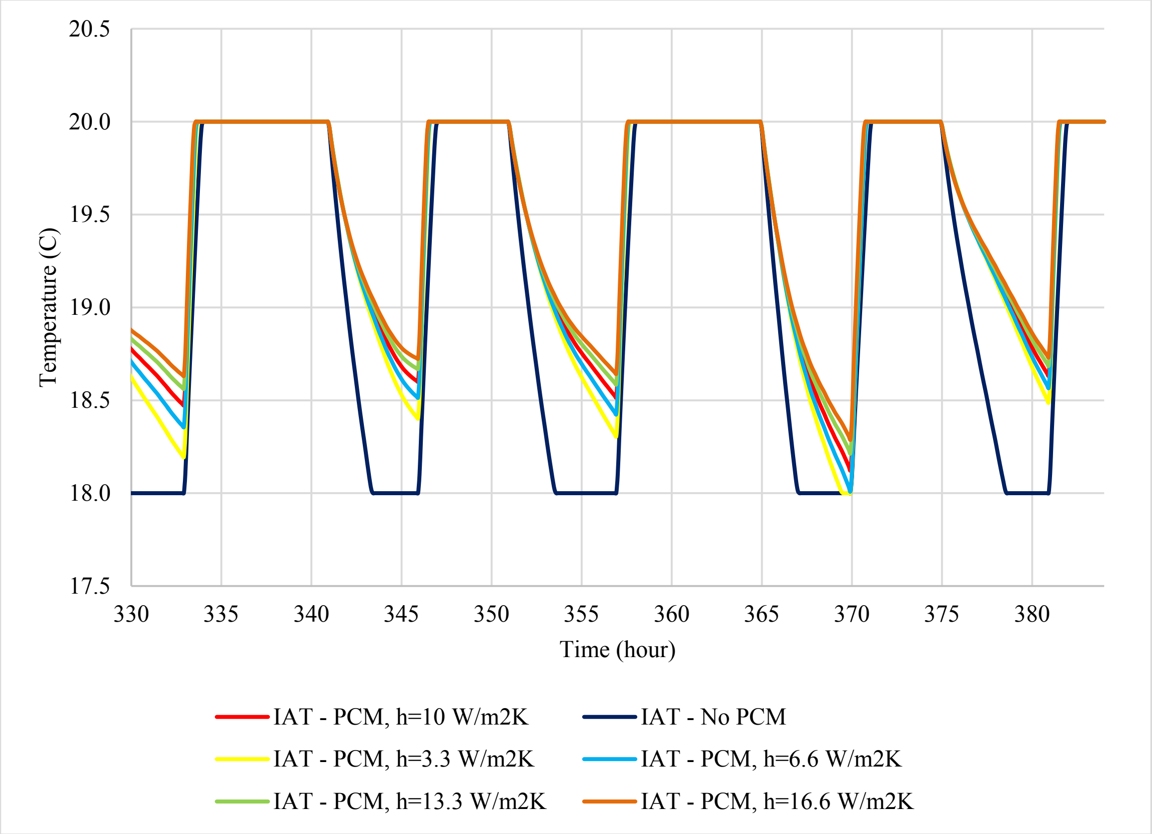

Figure 21 - Effect of convective heat transfer coefficient on PCM discharge and on-peak time indoor temperature

Simulations were carried out for different interior convective heat transfer coefficients. The convective heat transfer coefficient's value changed from 3.3 W/m^{2}K to 16.6 W/m^{2}K. As shown in Figure 21, increasing the heat transfer coefficient higher than a certain value, h = 10 W/m^2.K, is not significant in terms of influence on PCM discharge. This can be attributed to the fact that all heat stored in PCM is being released to the indoor air by convection during the considered period and increasing the convective heat transfer coefficient after a certain value will not affect the PCM discharge. Simulation of the Montreal climate was done for the 1-month period of January. It was assumed that the desired IAT threshold is 18^{o}C. To keep the indoor air temperature above this threshold in this climate required a minimum value of heat transfer coefficient of h = 6.6 W/m^2.K. For a specific climate and a PCM wallboard, it can be concluded that a minimum convective heat transfer coefficient must be considered so that thermal discharge of PCM provides the required thermal comfort conditions. Under Montreal weather conditions, the coldest hour of the year was identified to be hour 343, which is on January 15, with an outdoor temperature of –27.2°C. Simulation results for the coldest hour show that discharge of PCM's stored heat, considering heat transfer coefficient values of 6.6 W/m^2K and above can result in indoor temperatures higher than 18°C.

Poulad et al. (2011) investigated the influence of convective heat transfer coefficient on the ability of PCM to reduce building heating/cooling load. They implemented TRNSYS and a type 204 PCM module to simulate the thermal behavior of a room with walls and ceiling that incorporate PCM wallboard. They claimed that by increasing the heat transfer coefficient, heating load increases but cooling load decreases. However, in this thesis, reduction in the heating load is of concern, and results show the obvious effect of increasing h-value on the PCM discharge, and consequently reducing heating demand.

An implication of the results is that the discharge of PCM wallboard during peak times, thus resulting in temperatures closer to the set-point, is improved noticeably by h-value increase. Thus, coupling the PCM wallboard system with a mechanical system to increase air speed is beneficial toward PCM thermal discharge.

Khalifa et al. (1990) proposed an empirical equation using experimental data to estimate the required air speed providing specific h-value.

$$h = 5.34 + 3.27u \quad (15)$$

Where *u* is the air speed (m/s) and *h* is convective heat transfer coefficient (W/m^2.K). Because this equation provides an h-value of 10 W/m^2.K, the air speed has to be 1.42 m/s increasing the convective heat transfer more than 10 W/m^2.K improves PCM discharge rate but requires air speeds higher than 1.42 m/s, which is not practical and violates an indoor occupant's comfort criteria.

5.5 Performance of PCM-Gypsum Wallboards in Different Climates

In this section, series of simulations are carried out to compare PCM performance across three climate zones. Thermal performance of the zone with PCM wallboard was accessed by comparing the performance of two different PCM-gypsum wallboards against the performance of conventional gypsum board. Specifications of conventional gypsum wallboard and PCM-gypsum wallboard type "A" and "B" are given in section 4.1 and section 4.3 of this thesis, respectively. As mentioned in section 4.4, three Canadian cities were selected to evaluate the influence of PCM-gypsum wallboard on indoor conditions in different climates. According to ANSI/ASHRAE Standard 169-2006, Vancouver is a cool climate (ASHRAE zone 5), Montreal is a cold climate (zone 6), and Calgary is a very cold climate (zone 7). The weather data used in simulations are Energy Plus/ESP-r weather format (epw) which are real-time weather data from DOE, Office of Energy Efficiency & Renewable Energy. The thermal behavior of the case study (section 5.2) was simulated for the whole year in three mentioned climate zone. For each climate zone, three scenarios; conventional external walls, external walls with PCM-gypsum type A and external walls with PCM-gypsum type B was considered. Overall, year-round simulation was carried out for the 9 cases. In all simulations in this section, inside and outside convective heat transfer coefficients were considered to be 3.05 W/m^2.K (11 kJ/h.m^2.K) and 17.80 W/m^{2}K (64 kJ/h.m^2.K), respectively as the standard values in TRNSYS.

For the two PCM-gypsum wallboards, minimum indoor air temperature and its reduction compared to the conventional gypsum board is listed in Table 11.

Table 11 - Minimum IAT and reduction for different scenarios

	Cool Climate		Cold Climate		Very Cold Climate	
Wallboard	Minimum IAT (°C)	Minimum IAT Increase (%)	Minimum IAT (°C)	Minimum IAT Increase (%)	Minimum IAT (°C)	Minimum IAT Increase (%)
Gypsum Board	18.28	-	18	-	18	-
PCM - Gypsum Board A	19.07	+4.32%	18	+0.00%	18	+0%
PCM - Gypsum Board B	19.23	+5.20%	18.12	+0.67%	18.15	+0.80%

As indicated in Table 11, indoor air temperature closer to the set-point is achieved by applying PCM-gypsum board B, PCM wallboard with a narrower phase change temperature range. In case of PCM wallboard A, as latent heat of PCM in much smaller (28.8 kJ/kg) compared to PCM wallboard B (104 kJ/kg), in the cold and very cold climate the IAT reaches set-point temperature and the heating system turns on.

In the cool climate, the indoor air temperature stays above 18ºC, even with conventional wallboard. Future research is required to determine optimized control strategy regarding application of PCM wallboards in different climates.

5.6 Impact of PCM on Thermal Comfort during On-Peak PCM Thermal Discharge

Application of PCM can help to maintain thermal comfort during the peak. As mentioned in previous sections, although the set-point temperature is lowered during peak period, release of heat via PCM discharge makes it possible to keep the indoor temperature above the thermal comfort threshold. To evaluate thermal comfort during the peak period, different parameters can be considered, including indoor air temperature, convection heat transfer, and radiation heat transfer. To assess the impact of PCM wallboard on both convective and radiative heat transfers, the equivalent globe temperature is considered as follows (Kuznik et al., 2011a):

$$T_g = 0.45T_a + 0.55T_r \qquad (16)$$

Where T_g is the equivalent globe temperature and T_a and T_r are air and mean radiant temperatures. For the base case study in section 5.2, T_a and T_r are outputs of TRNSYS, and equivalent globe temperature is calculated accordingly. Figure 22 shows equivalent globe temperatures in the cases of both PCM wallboard and conventional wallboard.

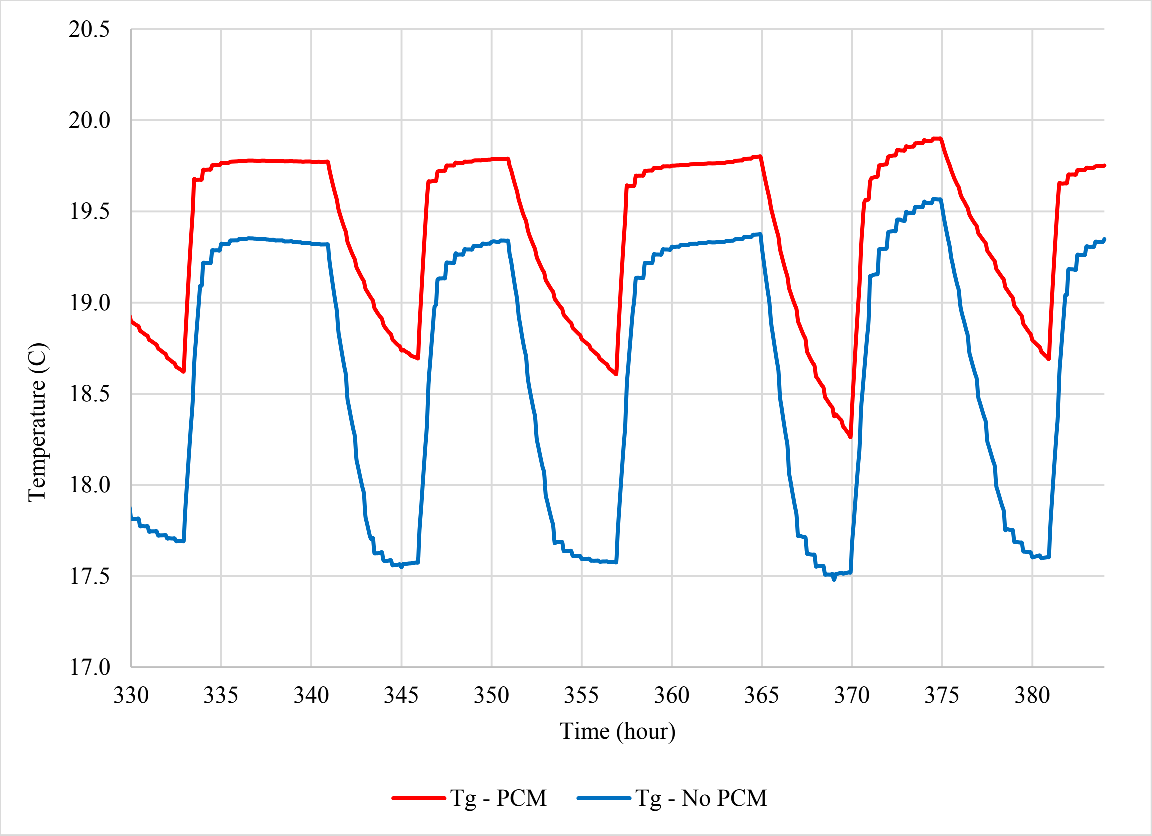

Figure 22 - Equivalent globe temperatures in case of PCM wallboard and conventional wallboard

In the case of PCM wallboard, the globe temperature range remains closer to the desired set-point temperature, resulting in an increased thermal comfort.

CHAPTER 6: CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In addition to offering a comprehensive review of the application of PCM wallboard in passive solar buildings, this thesis also evaluates the possible benefits of PCM wallboard application in conditioned actual buildings.

This thesis investigated the benefits of PCM wallboards used in pre-heating to reduce the peak hour load. A PCM module within TRNSYS software is first validated with experimental data for a simple case of one cubicle. The code is then applied to a typical one-story residential building, also modeled in TRNSYS. A series of parametric studies were carried out to evaluate the impact of PCM thermal properties and convective heat transfer coefficient on the performance of PCM wallboard.

1. The simulation results showed that it is possible to shift the peak heating demand while IAT (Indoor Air Temperature) maintained within thermal comfort by applying PCMs with proper characteristics. In Montreal, during the coldest period, it was demonstrated that there is a shift of 3 hours for peak heating demand. Case studies considering the thermal conductivity of PCM-gypsum wallboard indicate that the low conductivity of PCMs does not inhibit heat transfer through the PCM layer, and convective heat transfer is dominant.
2. Parametric study of PCM thermal discharge during peak time by considering different melting temperature ranges for PCM shows that the best performance of PCM during discharge is obtained by selecting PCM with a melting temperature closer to the set-point temperature.

3. Parametric study of PCM layer thickness within the wall assembly shows that increasing thickness beyond a certain value is not effective anymore for storing latent heat discharge. Considering low thermal conductivity of the PCM and that convection is the dominant heat transfer, adding more thickness, PCM will be not be melted or solidified.
4. Increasing the interior convective heat transfer coefficient enhances discharge of PCM wallboard during on-peak times and consequently improves indoor condition. For the building case study in Montreal weather conditions, to keep the IAT above thermal comfort threshold it was shown that heat transfer coefficient have to be above 6.6 W/m^2K. The air speed in the interior space has to at least above 38cm/s to establish this heat transfer coefficient. It should be noted that towards effective application of PCM wallboards in different climates, coupling the PCM wallboard with a mechanical system to increase air speed and thus improve heat discharge could be required.
5. A series of year-round simulation for the same residential building was carried out to access thermal performance of two PCM-gypsum wallboard across cool, cold and very cold climate zones. The simulations revealed that in cool climate, with the proposed control strategy, IAT remains above set-point during peak times with conventional wallboard. In this case the application of PCM wallboard is not beneficial as even in the case of regular board heating system does not turn on. Also results show that PCM wallboard with lower latent heat was not completely effective in cold and very cold climate and during peak periods IAT reaches below 18ºC, the set-point temperature.

6. Regarding thermal comfort improvement by utilizing PCM wallboards, it was shown that globe temperature is increased and is closer to the set-point temperature indicating enhanced thermal comfort.

6.2 Future Works

The literature focusing on the application of PCM wallboard in conditioned buildings is limited; most studies focus on passive solar building applications. In this thesis, a validated model was used to investigate PCM performance in peak load management strategy. However, the following items can be considered for the future studies:

1. PCM wallboard specifications such as melting temperature range, thermal conductivity, and latent heat capacity can be optimized according to different heating/cooling control strategies and weather conditions. For specific PCM wallboards, appropriate thermostat control can be obtained to optimize the use of LHTES in heating and cooling seasons.
2. There are some limitations to PCM modeling with PCM module TRNSYS type 255. Developing a new model to predict the phase change phenomenon more accurately is of concern.
    a. The conduction heat transfer was assumed to be unidirectional.
    b. As mentioned in chapter 4, the module is unable to predict a natural convection phenomenon in PCM capsules with decreasing heat transfer surface during the cooling (discharge) part of PCM heat charge/discharge.

In the application considered in this thesis, discharge of PCM specifically is a main concern.

   c. PCM modeling includes some simplifications, such as considering the same value for density in liquid and solid phase. This is not the case in real PCMs.
   d. There is a limitation of four possible layers to be assigned between PCM and exterior.

3. This study does not consider the potential benefits of thermal comfort that can be offered by PCM wallboards. However, considering the damped indoor temperature variation and the approximately constant wall interior surface temperature during phase change, thermal comfort criteria can be precisely evaluated.
4. Because the numerical model used in this thesis has been validated for the case of a simple cubicle and the parametric studies were carried out for a real building, there is a need for robust validation through field measurement to verify implementation of the model. The findings in this thesis should be verified by full-scale experiments.

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