DETERMINING THE OPTIMUM PLACEMENT OF A PHASE CHANGE MATERIALS (PCM) THERMAL SHIELD INSIDE FRAME WALLS USING A DYNAMIC WALL SIMULATOR

by

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ABSTRACT

This thesis presents the results of an experimental study to determine the optimum placement and the thermal performance of a Phase Change Materials (PCMs) thermal shield incorporated into frame wall insulation systems for the purpose of reducing space cooling load energy use in residential and commercial buildings. The performance of the walls outfitted with the PCMs thermal shields was evaluated using a dynamic wall simulator. The interior of the dynamic simulator was designed to reproduce the conditions of the exterior of a conventional residential building wall and the exterior of the dynamic simulator represented the indoor conditions of a typical residential building since the dynamic simulator was located in an air conditioned research laboratory. Measurements of heat fluxes and calculation of percentages of peak heat transfer rate reductions were evaluated for 10% and 20% PCM concentration in the thermal shields along with two control walls. The main goals of using a PCM thermal shield were to reduce peak air conditioning demand, to shift the peak load, and to conserve energy. The results of this study show that the PCM thermal shields produce greater peak heat transfer rate reductions when they are placed further away from the heat source inside of the wall cavity and are less effective when temperatures are high. The 20% PCM thermal shield was more effective than 10% PCM thermal shields. For the optimal location of the thermal shield the reductions in peak heat transfer rates were in the range of 20-25% when compared with the control walls.

ACKNOWLEDGMENTS

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~~ Silvia Reshmeen

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Chapter I

Introduction

1.1 Background

The objective of this research was to find a practical approach that would allow phase change materials (PCMs) to be incorporated into frame wall insulation systems for the purpose of reducing space cooling load energy use in residential and commercial buildings.

In the United States, buildings consume around 40% of the total annual energy used in the country (U.S Department of Energy, 2005). A large portion of this energy is used by space cooling and space heating systems in buildings. The most recent data reported by the Energy International Administration (2001) show the estimation of electricity consumed by end use in the United States households to be about 182.8 billion kWh (6.24×10^5 billion Btu) for space cooling and 115.5 billion kWh (3.94×10^5 billion Btu) for space heating. This means that around 31.2 % of the total annual electricity consumed in U.S. households is used for space heating, space cooling, and ventilation. Space cooling in the summer creates a high peak demand on the electric grid system, especially in densely populated areas. As a result, some local electricity utility companies experience difficulties such as lack of capacity, which may lead to brown outs, and/or extra operating expenses, which end up being passed on to their customers.

The demand in electric energy required for space cooling has increased significantly over the past twenty years. There is no doubt that the projected growth in the building industry will further increase this demand for space cooling energy in the near future. This motivates the need to develop more energy efficient building materials, including thermal storage systems, which could be adopted by the building industry in order to manage these energy scenarios and to conserve energy.

1.2 Approaches

There are several approaches that have been considered in building envelope (i.e., building enclosure) systems to decrease peak loads in the summer time. The two most effective approaches are the *demand exchange method* and the *thermal energy storage materials* method. The demand exchange method represents one way to decrease peak load demand via backup energy generation. That is, in this method the building is complemented by a connection for alternative power generation system, which is provided either by small independent power producers or by individual back up generator systems provided by the home owner. This helps in decreasing the demand during peak times from the main utility service. With this method, however, the actual peak load demand does not decrease or is shifted from peak times, but an extra energy supplier is added. In fact, in the global sense, with this approach more energy would be needed to generate the electricity demand. One possible reason is that smaller back up generation systems are usually more energy consuming unless the source is renewable energy. Thermal energy storage materials can store energy by heating (sensible) or melting (latent). Using thermal energy storage materials in building envelope systems is one of the prospective approaches to manage the peak cooling load demand. The use of thermal energy storage systems in the building envelope can effectively reduce peak loads by shifting a part of the load to off-peak times of the day.

1.3 Phase Change Materials (PCMs)

Thermal energy storage materials can store sensible heat (i.e., thermal energy by increasing their temperature) and latent heat (i.e., thermal energy by changing the phase -- melting -- of certain "constituents" of the materials). These "constituents" that change phase are called phase change materials (PCMs). PCMs are added to the envelope systems via encapsulated substances, usually paraffin-based or hydrated-salt-based. PCMs absorb and release relatively large amounts of heat during phase change. That is, during a typical daily cycle, heat is absorbed when the substances melt and heat is released when the substances re-solidify. Furthermore, during the phase change process the temperatures of the PCMs remain constant. PCMs are able to store up to 14 times more heat per unit volume than materials like masonry or rock or other building materials (US DOE, 2009) PCMs have the ability to fully reverse the transition throughout a specific temperature range from their congealing point to their melting point. In general, PCMs contain high transition enthalpies per unit mass, adequate transition temperatures, and are chemically stable, furthermore, PCMs are non-toxic (Dincer and Rosen, 2002).

1.4 Classification of PCMs

There are three basic categories of PCMs:

1. Inorganic: hydrated and molten salts

2. Organic: paraffin and fatty acids

3. Eutectic: mixtures of organic and/or inorganic PCMs

Inorganic PMCs are mostly hydrated and molten salts. Hydrated salts are basically crystallized forms of anhydrous salts. Potassium fluoride tetrahydrate ($KF.4H_2O$), calcium chloride hexahydrate ($CaCl_2.6H_2O$), sodium sulphate decahydrate ($Na_2SO_4.10h_2O$), sodium orthophosphate dodecahydrate ($Na_2HPO.12H_2O$) and zinc nitrate hexahydrate ($Zn(NO_3)_4.6H_2O$) are some of the most commonly used inorganic PCMs. Inorganic PCMs have high volumetric latent heat storage capacity, high latent heat of fusion values, and low volume change during phase change. Hydrated salts are also non-flammable. However all of them are corrosive and hygroscopic, which requires that these PCMs be enclosed in special corrosion- and water-resistant containers. This would certainly cause high installation costs. Moreover, these PCMs tend to have supercooling problems in solid to liquid transitions. Supercooling occurs when the temperature of a liquid becomes lower than its freezing point but without freezing.

Organic PCMs are mostly paraffins (C_nH_{2n+2}) and fatty acids ($CH_3(CH_2)_{2n}COOH$). Paraffins are extracted from crude oil, vegetable oils, and animal tallow. Paraffins are saturated chains or branched molecular hydrocarbons. They are non-toxic, non-corrosive and stable compounds. They have relatively lower thermal capacity and lower latent heats of fusion than inorganic PCMs. A disadvantage of paraffin type PCMs is that they are flammable. Therefore, adequate fire protection needs to be included either in the PCM mixture or in the envelope system to reduce their risk of fire.

Eutectic PCMs are mixtures of organic-organic, organic-inorganic and/or inorganic-inorganic combinations of PCMs used to formulate mixtures with desired properties to achieve high latent heat storage capacity, low flammability, and controlled supercooling. Paraffin-based RT-27 PCM was used in this research.

1.5 PCMs and Peak Load Demand

Phase Change Materials (PCMs) act as thermal storage in various applications such as, telecommunications, food services, transportation, clothing and hot and cold storage systems. In buildings, PCMs are usually used in combination with insulation systems. Using PCMs in building envelope systems provides thermal storage within walls, floors, and/or roof-ceiling assemblies of buildings and helps in shifting a part of the envelope space thermal load to off-peak times of the day. For example, during the summer time when outdoor temperatures are higher than indoor temperatures and heat is transferred from the outside to the inside, under these conditions the PCMs would melt and would store heat through their phase change process. The phase change process of PCMs can take up to four hours depending on temperatures and latent heat of fusion values of the PCMs. The storage capacity of PCMs delays the heat transmission through the envelope of the building at peak times, thus reducing the instantaneous amount of heat from being transferred and shifting it to off-peak times of the day. As a result, the peak demand shifts one o two hours towards the off peak time of the day. The stored heat would then be released upon later solidification of the PCMs. The solidification process is the result of the temperatures dropping in latter parts of the day, usually nighttime and/or early morning hours.

1.6 Applications of PCM in Building Envelope Systems

For several reasons PCMs must be encapsulated or packaged before applying them into the building envelope system. One reason is the phase change from solid to liquid, which may lead to PCM dripping. The second reason is that without encapsulation hydrated salts would absorb water and paraffins would undergo oxidization. Depending on the application technique of

PCMs into the wall system their performance can differ significantly. The size and location of the capsulated or packaged PCMs are essential to the optimization of the storage systems.

There are two major application techniques that have been used in the past to incorporate PCMs into building envelope systems. These are:

1. PCMs used in building fenestration systems.
2. PCMs used in building envelope systems such as walls, floors, and/or roof-ceiling assemblies.

These techniques are passive systems. Passive system is the process when the PCMs can store thermal energy automatically through phase change as indoor or outdoor temperatures drop or rise. No mechanical heating or cooling equipments are necessary in these kind of systems.

1.7 Research Objective

The objective of this research was to find a practical approach that would allow the integration of PCMs in frame walls with the highest possible efficiency in an economical way. The fundamentals of this research were based upon the following purposes:

- To select the most efficient PCM (organic, inorganic or eutectic) for the experiments.
- To determine the most economical and practical approach to encapsulate and install the PCMs into the frame walls.
- To identify the optimum location for the PCM in the frame walls.
- To verify the potential reduction in peak heat transfer rate.

A paraffin based PCM (RT-27) was chosen for the research because it had a high thermal storage capacity, was non-corrosive, non-toxic, and melted at the desired temperatures for building applications. The PCM was n-octadecane, which is white and crystallizes in its solid state. In its liquid state it is transparent. The average indoor temperature is slightly lower than its melting temperature. The properties of the PCM used are listed in Table 1.7.a.

Table 1.7.a. Properties of RT 27 Paraffin PCM (Rubitherm)

Properties	**Description**	
	Unit (SI)	**Unit (English)**
Appearance	White crystal (solid)	
Volume Expansion	10%	
Density Solid at 15ºC (59ºF)	0.87 g/cm^3	54.3 lb/ft^3
Corrosion	Chemically inert with respect to moist materials.	
Specific Heat Capacity (solid / liquid)	1.8 / 2.4 kJ/kgK	0.43 / 0.57 Btu/lbm ^{o}F
Heat conductivity	0.2 W/mK	0.12 Btu/hrft^{o}F
Melting point (approx.)	28 ^{o}C	82.4 ^{o}F
Congealing point	26 ^{o}C	78.8 F
Flash point	164 ^{o}C	327.2 ^{o}F
Latent Heat of Fusion	179 kJ/kg	77 Btu/lbm

Chapter II

Literature Review

2.1 A Brief History of the Use of Phase Change Materials in Buildings

Phase change materials have been studied as a potential thermal storage component of building envelope systems since the early 1970's (Pasupathya, Velraja, and Seeniraj, 2006) for inclusion in building architecture for thermal management. The performance characteristics of PCMs and successful past experiments have made this research area a more promising one. It has been proven through past research (Khudhair and Farid, 2003) that PCMs incorporated within building envelope system increase the thermal storage of common building envelope systems. Therefore, at this point the goal of the research presented in this thesis was to find the most effective, practical, and most economical approach to incorporate PCMs into conventional building envelope systems. Through this effort, thermally-enhanced buildings envelope systems via the use of PCMs can have more acceptances in the building industry.

Darby and Wright (1983) used commercially available phase change salt compounds with a phase change temperature of 22.8ºC (73ºF) and a heat storage capacity of 81.3 J/kg (0.03495Btu/lb) in building envelope components, such as floors and ceilings. This system provided summer cooling operation as well as winter heating operation. The concept of passive (i.e., radiation and natural convection) and active (i.e., fans) discharge were discussed.

Hawes, et al. (1991) and Feldman, et al. (1991) researched a range of gypsum wallboards with different combinations of PCMs. The PCMs were formulated using butyle stearate, dodecanol, propyl palmitate, and capric-lauric acids. The wallboards were immersed into liquid

PCMs for several minutes to let the wallboard absorb the liquid PCMs to predetermined uptake percentages. The characteristics changes of wallboard as a result to PCM absorption were studied. The research concluded that the imbibed wallboards were comparable to regular wallboards in terms of their strength, durability, stability, moisture content and weight limits. The experiment concluded that the PCM-imbibed wallboards had heat storage capacities of about 12 times the heat storage capacity of commonly used conventional wallboards.

Ghoneim, et al. (1991) reviewed the results of simulation studies of PCMs. The conclusion of the research was that PCMs were more effective in solar passive systems and acted well as latent storage in the enclosure of the system. It was recommended that appropriate combinations of PCMs should be selected, which should then be installed in those components of the enclosure where the probability of enhancement was higher. That is, chemically compatible packaging and sealing methods were necessary for maintaining and prolonging the life cycle of the PCMs. It was recommended that the PCMs should be packaged in such way that an effective heat transfer surface area would be provided.

Feldman, et al. (1991) and Scalat, et al. (1996) tested PCM-imbibed wallboards. In this approach wallboards were directly imbibed by dipping them into melted PCMs baths. The PCM-imbibed wallboards performed well in terms of reducing the peak heat transfer rate and shifting a part of the load to off-peak times. One drawback was that the PCM-imbibed wallboards became moisture resistant. The water absorption capability of PCM wallboards became one third of that of a standard board, which may led to material deteriorations.

Stovall and Tomlinson (1992) studied wallboards with PCMs for passive solar application like Salyer and Sircar (1990). But this effort was more focused on investigating the economical benefits of using PCM-imbibed wallboards. It was reported that the PCM-imbibed wallboards produced about 30% reduction in heat transfer when the PCM uptake was around 20-22% of the weight of the wallboard.

Scalat, et al. (1996) analyzed the latent heat storage capacity of PCM saturated wallboard with regular wallboard in a small- scale experimental setup. The results concluded that PCM-imbibed wallboard helped enhance the thermal storage capacity of the walls and helped in time-shifting the peak heat transfer loads and thus reducing peak demand loads into the building conditioned space. This reflected on to the building energy performance and resulted in less energy consumption.

Salyer and Sircar (1997) researched hollow-core concrete blocks and hollow-core cement outfitted with PCMs that were used in building envelope systems. They used a series of linear crystalline alkyl hydrocarbon phase change materials in passive-solar applications. The PCMs used were dry powder, PCM/silica and PCM/HDPE (high density polyethylene) capsules that were incorporated into plaster, plasterboard, cement and blocks of cements. A high thermal storage capacity of walls was reported. However, the night temperature required to drop down significantly to complete the solidification process of PCM capsules inside the building blocks, which did not occur. As a result, this would also probably render the use of PCM-hollow-core concrete/cement blocks unacceptable. This research was productive in terms of understanding the performance of PCMs in various installation set ups with various kinds of structural systems. Using PCMs in plasterboards was the most promising arrangement. Since PCMs are flammable, Salyer and Sircar considered different combination of fire retardant substances. Their results concluded that the wallboards could provide efficient load management in buildings.

Kissock et al. (1998) studied the thermal performance of PCM-imbibed wallboards. Two cells with dimension of 1.22 m (4 ft) x 1.22 m (4 ft) x 0.61 m (2 ft), in a light frame walled simulation set-up were used. One cell-wall contained a transparent acrylic sheet to allow solar radiation to penetrate while the other cell-wall was oriented in such way that glazing faced south. The PCM used was n-octadecane. The two cell-walls were compared with a conventional gypsum wallboard which was installed as control cell-wall. The PCM-imbibed walls produced a reduction of approximately 10˚C (18˚F) in the cell that contained these thermally-enhanced walls. It was reported that there were difficulties with the oxidation of the n-octadecane. For example, the properties of n-octadecane changed as a result of oxidation over time. Therefore, it was recommended to use anti-oxidant materials in future applications. It was also concluded that PCMs needed to be selected according to their use in either heating or cooling because the building operation temperatures would vary depending on the season.

Stetiu and Feustel (1998) used a finite difference program to study PCM-imbibed wallboard performance in a commercial office building in California. Their research reported that indoor nighttime temperatures were not low enough to complete the phase change cycle after the PCM had melted. It was reported that the indoor nighttime temperature increased by approximately 18 ºC (32.4 ºF) above the solidification temperature of the PCM. Therefore, because no solidification was occurring, the system (e.g. PCM-imbibed wallboards) required an alternate technique to cool down the PCM to its solidification point. This would probably render the use of PCM-imbibed wallboards unacceptable.

Schwarz (2002) designed an envelope component called "Power Glass" that used PCMs as latent heat storage medium. Schwarz placed a 4 cm (1.6 in) thick PCM layer between two glass sheets. The melting temperature of the PCM was 27 ºC (80.6ºF). In this design the glass absorbed solar energy and transferred the energy to the PCM layer. The PCM melted as the temperature rose to its melting temperature of 27 ºC (80.6ºF). This temperature stayed constant until all the PCMs melted. This design could store as much heat as an 30 cm (11.8 in) thick brick wall at 50 ºC (122 ºF). This system cooled down at night as the temperature outside of building dropped and the PCM layer released the stored energy to the surrounding.

Zhang, et al. (2005) developed a thermally enhanced frame wall that reduced peak air conditioning demand and energy savings in residential buildings by the use of pipe-encapsulated phase change materials. They used a frame wall that integrated a highly crystalline paraffin phase-change material (PCM. This prototyped wall was evaluated and referred to as phase change frame wall (PCFW). The results of the PCWF showed that it reduced wall peak heat fluxes by much as 38% compared to the conventional wall system. The average wall peak heat flux reduction was approximately 15% when PCFWs had a PCM concentration of 10% (based on indoor sheathing weight) and approximately 9% heat flux reduction when PCM with a concentration of 20% was used. The level of insulation in the PCFWs was R-11.

King (2004), evaluated the thermal performance of PCM embedded in Structural Insulated Panels (SIPs). She did the field measurements made on two test houses. Both houses were kept in air conditioning internal temperature. One house had the PCM enhanced structural insulated panels and other one was a control house without the PCM embedded into the SIPs. The main goals of this research was to measure the peak air conditioning demand reduction and thermal load shifting by using PCM embedded in SIPs into building envelope system. The results indicated that on average, the experimental peak heat flux reductions produced by the SIP walls in combination with 10% PCM concentration were 37% and 20% for the south and west walls, respectively. The results also showed that on average, the experimental peak heat flux reductions produced by the SIP walls in combination with 20% PCM concentration were 62% and 60% for the south and west walls, respectively. Furthermore, the results indicate a path toward improved thermal comfort inside buildings

Medina, et al. (2008) and Zhu (2008) further evaluated the performance of PCMs in structural insulated panels (SIP) in a dynamic wall simulator under different arrangements, which included SIPs with polystyrene and polyurethane cores, PCM encapsulation in copper and PVC pipes, pipe arrangements in vertical and horizontal orientations. This research concluded that the polystyrene core SIPs that were outfitted with PCM encapsulated in copper pipe, which were placed in a horizontal configuration, performed better, in terms of reducing the heat transfer rate across the SIP, that the other configurations.

Evers (2008) and Fang (2009) used cellulose insulation mixed with PCM in building frame wall systems using a dynamic wall simulator (Evers) and test houses located side by side under full weather conditions (Fang). They filled the cavity inside the frame walls of the simulator and test houses with cellulose mixed with PCMs. It was reported that the thermally-enhanced cellulose insulation (i.e., cellulose mixed with the PCMs) increased the thermal efficiency of the frame walls, which resulted in a reduction in heat transfer rate. Evers studied various types of PCMs - hydrated salts (TH29-F127, TH24), paraffin based (RT-27), Eutectic (SP25) and powdered based (PX27). This research concluded that RT-27 PCM performed better than the hydrated salts, powdered and eutectic PCMs. On average this PCM reduced the peak wall heat transfer rate by 9.2% when the concentration of PCM was 20%. Fang's research concluded that the peak heat transfer rate was reduced by 21% when a concentration of 30% PCM was mixed with the cellulose insulation. This was verified with numerical analysis.

Although most of the past PCM applications showed successful results in terms of reducing heat transfer rates and shifting the thermal load, many of these efforts reported difficulties in terms practicality of installation, costs, moisture problems, and discharge issues.

The focus of this thesis work was to find the most efficient and optimum way of integrating PCMs into wall systems without compromising building humidity transfer.

Chapter III

Experimental Set-up

3.1 Phase Change Materials (PCMs) Used in the Present Work

The PCM used in this research was n-octadecane, an organic paraffin wax sold under the trade name RT-27 by Rubitherm GmbH (Berlin, Germany). Both the solid and liquid states of RT-27 are shown below Figures 3.1.1 and 3.1.2. The density of RT-27 is 870 kg/m^3 (54.3 lbm/ft^3) in the solid state and 750 kg/m^3 (46.82 lbm/ft^3) in the liquid state. The properties and characteristics of this PCM are shown in Chapter 1, Section 1.7.

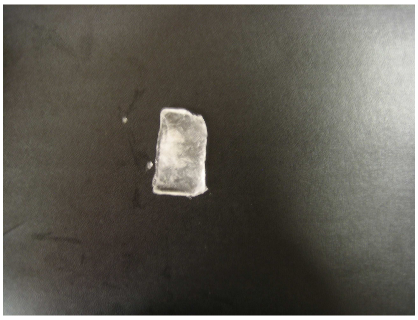


Figure 3.1.1. Solid State of RT-27

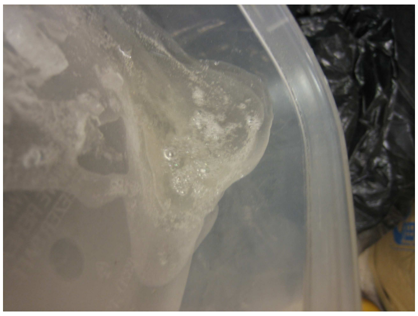


Figure 3.1.2. Liquid State of RT-27

The main objective of this research was to develop a practical PCM integrating method.

3.2 Incorporation of PCMs into the Wall System

Thermal shields were developed, which held the PCM within the wall cavities. The following materials were used to develop the thermal shields.

1. Cardboard sheets

2. Small thermally-resistant 10.15cm x 5.07cm (4 in x 2 in) plastic sealable bags

First, the small plastic bags were filled with RT-27 (Figure 3.2.1). Each bag contained about one third of an ounce of PCM. Only two thirds of each plastic bag was filled to allow for the volume expansion of the PCM (Figure 3.2.2). After the plastic bags were prepared they were stapled in a 0.38 m x 1.07 m (15 in x 42 in) cardboard (Figure 3.2.3). The plastic bags were arranged uniformly on the cardboard sheets in two columns of 12 rows for a concentration of 10% (Figure 3.2.4). For a 20% PCM concentration, the plastic bags were arranged in four columns of 12 rows (Figure 3.2.5).

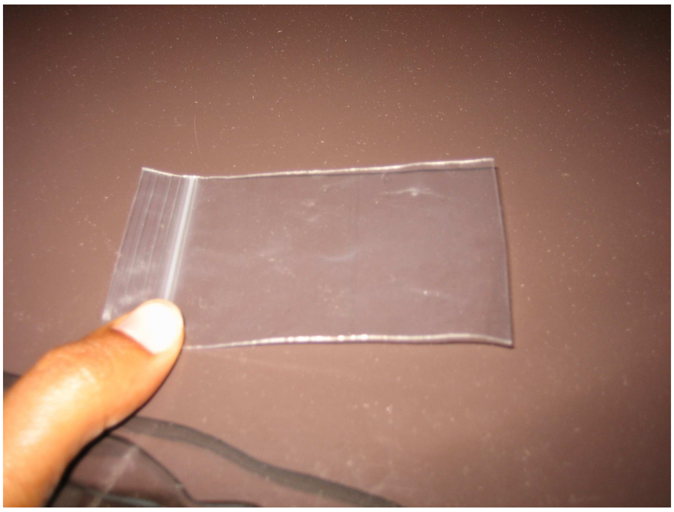


Figure 3.2.1. A 10.15 cm x 5.07 cm (4 in x 2 in) plastic bag (Empty)

Figure 3.2.2. Plastic bag filled with RT-27 (to 2/3 capacity)

Figure 3.2.3. Cardboard (0.38 m x 1.07 m (15 in x 42 in)) used to hold the plastic bags.

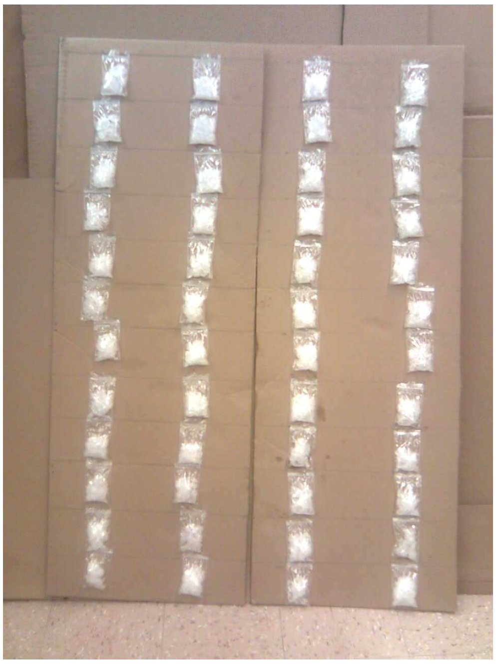


Figure 3.2.4. Arrangements of packets on cardboard with 10% PCM concentration

Figure 3.2.5. Arrangements of packets on cardboard with 20% PCM concentration

3.3 Dynamic Wall Simulator

The thermal performance of the walls outfitted with the PCM thermal shields was evaluated using a dynamic wall simulator (Figure 3.3.1). The simulator was a cubic box where each side had dimensions of 1.19 m x 1.19 m (47 in x 47 in). The structure of the box was made with angle-shaped steel beams (Figure 3.3.2). Each side of the box was designed to hold 1.19 m x 1.19 m (47 in X 47 in) dimensioned wall panels. A heat source of six 200-W light bulbs was placed at the center of the simulator's interior (Figure 3.3.3). These light bulbs were connected to two dimmers and two digital timers (Figure 3.3.4). This arrangement controlled the heat flow, which was programmed to replicate the hourly solar exposure in exterior walls. This arrangement simulated a full daily cycle (day and night) for total of 24 hours. In this manner interior surface of the wall panels in the simulator represented the exterior surface of building walls exposed to the outside environment.

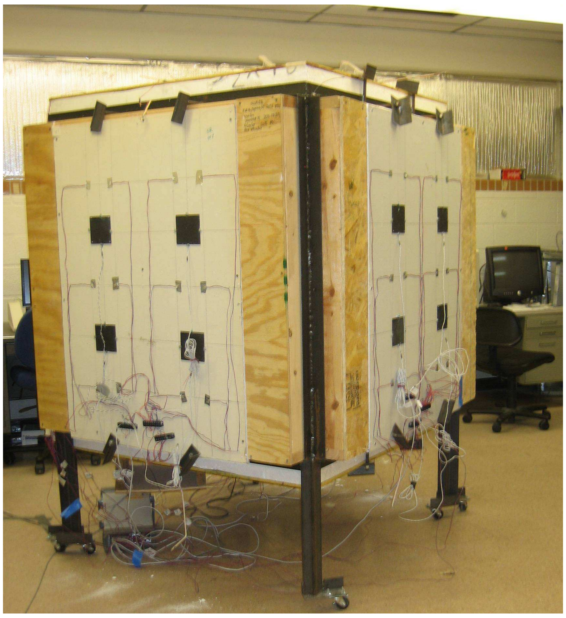


Figure 3.3.1. Exterior view of the Dynamic Wall Simulator

Figure 3.3.2. Structure of the Dynamic Wall Simulator

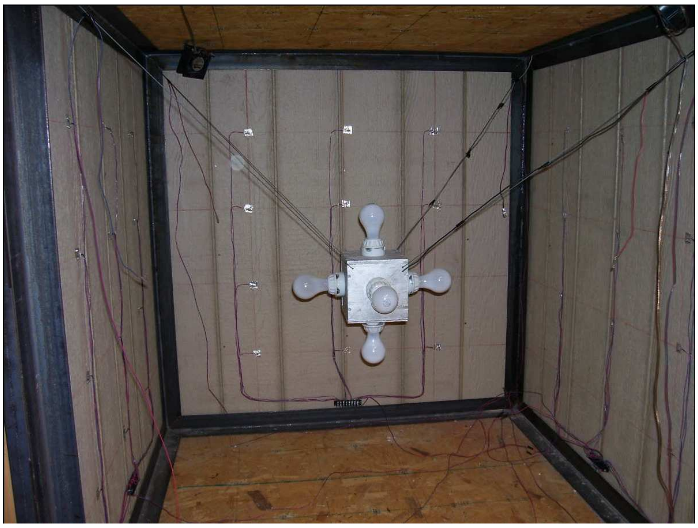


Figure 3.3.3. Heat source (6-200W light bulbs) inside of the Dynamic Wall Simulator

Figure 3.3.4. Digital timer and dimmer to control heat sources

Two 80 mm x 80 mm (3 in x 3 in) fans were placed inside of the simulator (Figure 3.3.5). These two fans helped stir the air uniformly inside of the simulator. The simulator was located inside the air-conditioned laboratory; thus the exterior walls of the simulator were exposed to the lab air-conditioned space. This orientation replicated the interior space of a typical residential building during the summer time.

Figure 3.3.5. Interior Fans

Each wall testing section was constructed using typical wood frame structure with two layers of fiberglass batt insulation (Figure 3.3.6) inside the wall cavity. The resistance level of the insulation was 1.94 m^2K/W (R-11). A 1.27cm (½ in) thick drywall was used to seal the wall cavity from the exterior of the simulator (Figure 3.3.7).

Figure 3.3.6. Fiberglass batt insulation with resistance level of 1.94 m^2K/W (R-11).

Figure 3.3.7. Gypsum drywall of dimension 1.27 cm (1/2 in.)

Thermocouples were used to measure air and surface temperatures of the interior sides and exterior sides walls (Figure 3.3.8). Twelve type-T thermocouples were attached on each side of the wall surfaces. Each thermocouple was protected with a small piece of aluminum tape. This secured the contact of thermocouples on the wall surfaces and also minimized radiation from the thermocouples contact points at the wall surfaces. Each 12-thermocouple sets, from each side, were connected in parallel to a wire terminal strip to get the average wall temperature from each side.

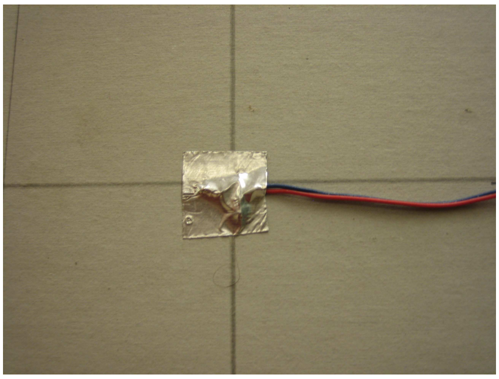


Figure 3.3.8. Thermocouples

Four 10.16 cm x 10.16 cm (4 in x 4 in) heat flux meters were attached via pressure contacts on each exterior top of the drywall (Figure 3.3.9). These meters measured the heat flow rate through the walls. Table 3.1.a shows the ranges and accuracy of heat flux meters and thermocouples.

Table 3.1.a The accuracy and the range of heat flux meters and thermocouples

Sensor	**Range**	**Accuracy (Deviation)**
Heat Flux Meter	0 - 3.1x105 W/m^2 (98.3 MBtu/hrft^2)	2%
Type T Thermocouples	18 ºC to 93 ºC (0 ºF -200 ºF)	0.6 ºC

Figure 3.3.9. Heat flux meter attached via pressure contacts

The thermocouples were uniformly attached on the exterior and interior surfaces of the walls (Figure 3.3.10). Four heat flux meters were arranged uniformly in each exterior surface of each gypsum board (Figure 3.3.11).

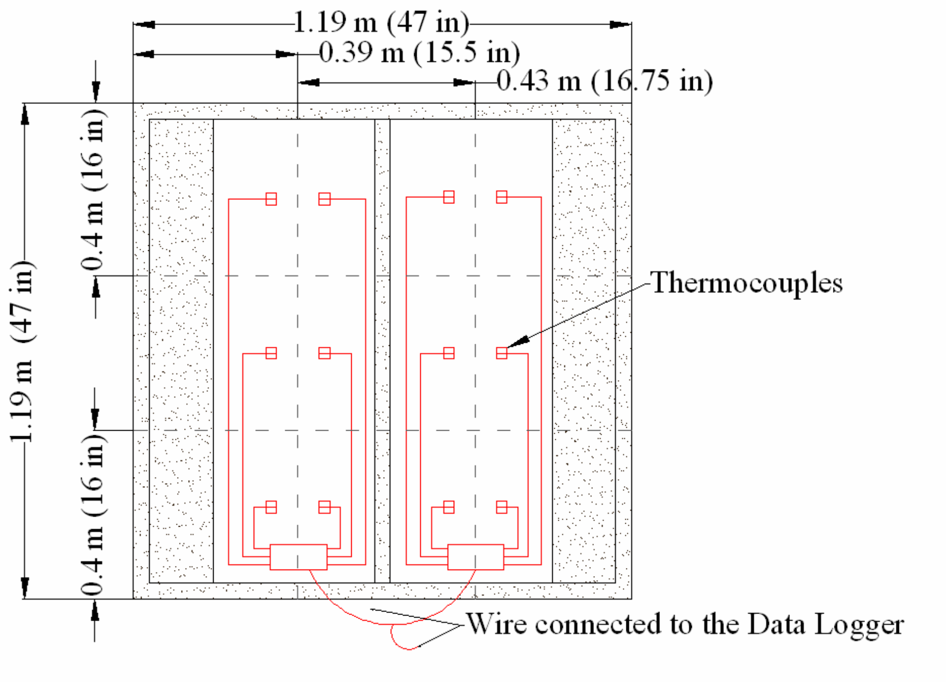


Figure 3.3.10. Thermocouple arrangements on the surface of the gypsum boards

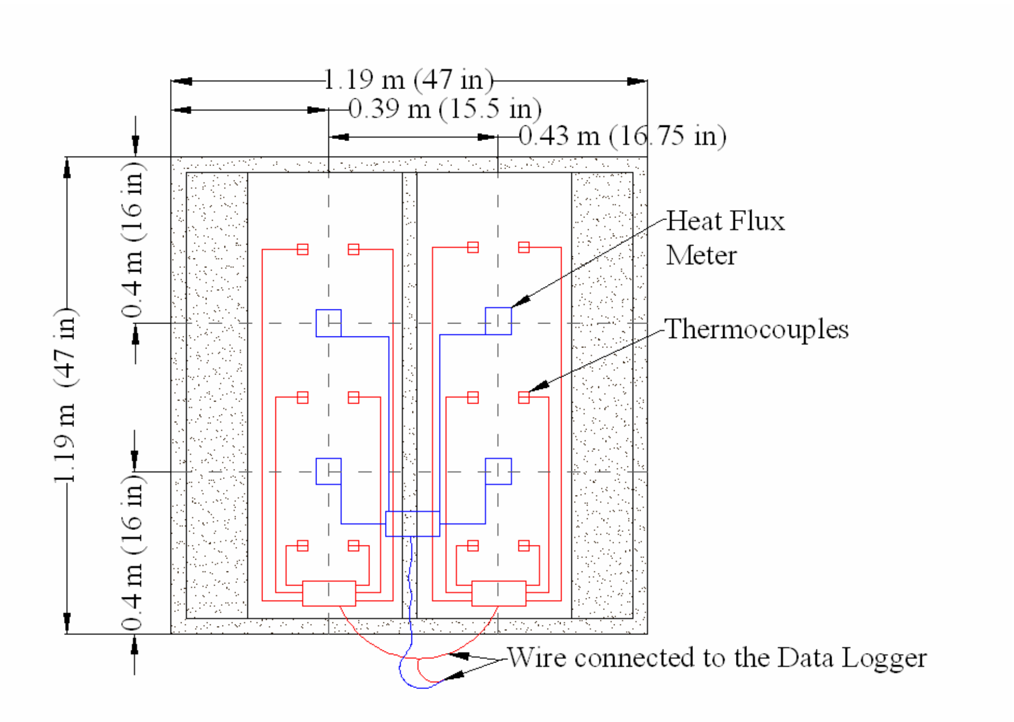


Figure 3.3.11. Thermocouples and heat flux meters arrangements on the exterior of each gypsum board.

3.4 Test Series

First a calibration test was carried out to check the consistency of all the heat flux meters and thermocouples. During this test, all walls had the same configuration inside the wall cavity. In this test all the walls performed the same thermally. This set the baseline against which all modification were to be compared once the walls were outfitted with the thermal shields.

There were three series of tests that were performed to evaluate the performance of the thermal shields into the wall system as the thermal shields were changed to three different locations within the wall cavity. Two concentrations of PCM were used: 10% and 20%. The concentrations were defined as weight of PCM over the total weight of the gypsum wallboard of each wall. In each series, two of the four walls of the simulator walls were integrated with the thermal shields. Of the remaining walls, one was used as a control wall and the other was outfitted only with a replica of the cardboard that contained the PCM in the thermal shields. This helped to isolate the performance of the PCM from the PCM-cardboard shield. The north and south walls were outfitted with the PCM shields. The south wall's PCM thermal shield consisted of 0.49 kg (1.09 lb) PCM, which represented 10% of the total weight (4.99 kg or 10.89 lb) of the wallboard. The north wall's thermal shield consisted of 0.98 kg (2.17 lb) PCM which represented 20% of the total weight (4.99 kg or 10.89 lb) of the wallboard. Each wallboard was 1.09 m x 0.81 m (42 in x 32 in).

In the first series of tests, the PCM thermal shields were located behind the wallboard closer to the conditioned space (Figure 3.4.1). There was a 5.08 cm x 15.24 cm (2 in x 6 in) wood stud located in the middle of the wall cavities. Therefore, the PCM shields were located on each side of the wood stud just behind the gypsum boards. Each PCM thermal shield had small plastic bags filled with PCM, which were uniformly stapled in columns and rows facing towards the interior of the simulator. This was shown in Figures 3.2.4 and 3.2.5.

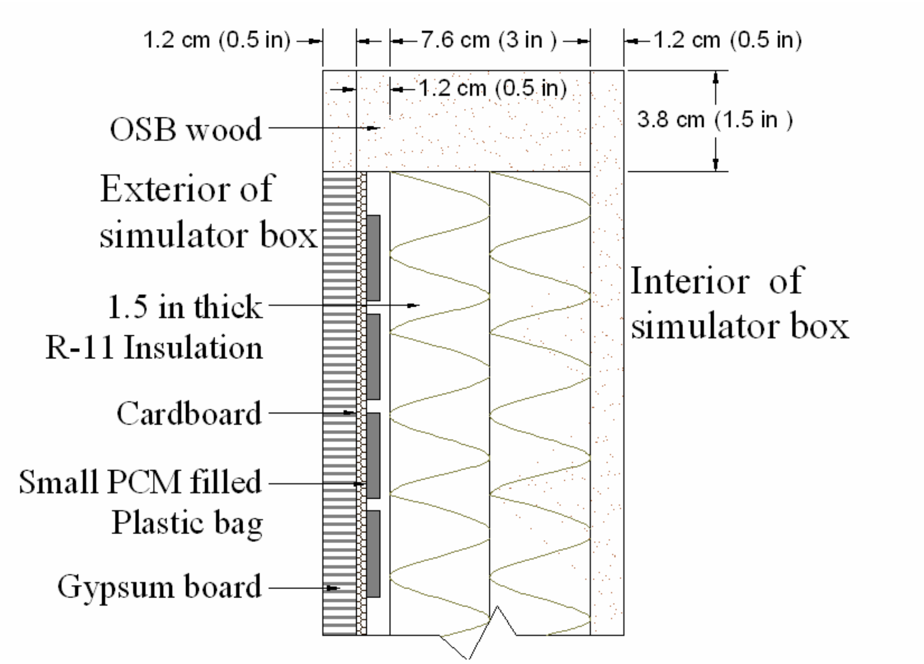


Figure 3.4.1. PCM arrangement inside the wall cavity for the first series of tests

In a second series of tests the same PCM thermal shields were used except that they were located in between the two layers of fiberglass batt insulation inside of each wall cavity on the north and south walls of the simulator. Figure 3.4.2 shows the location of the PCM thermal shield for the second series of tests.

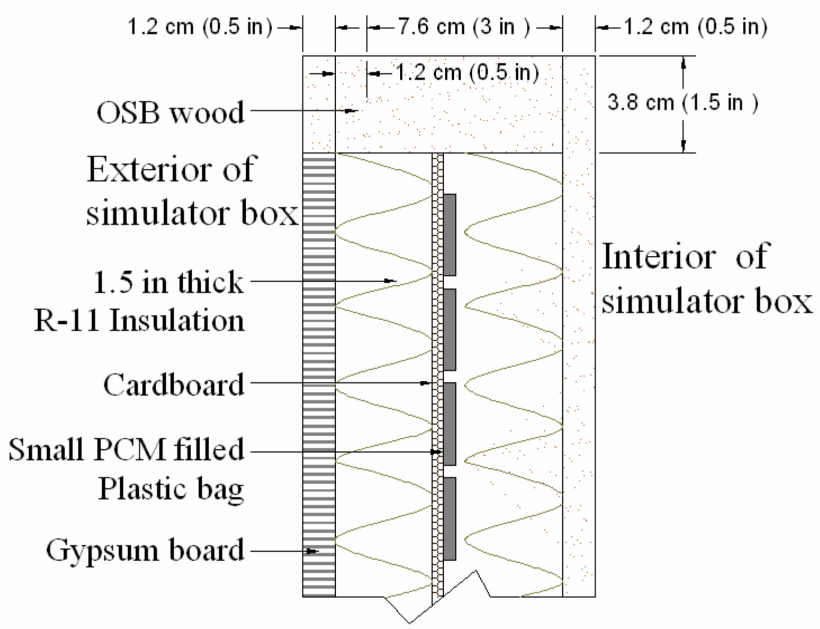


Figure 3.4.2. PCM arrangement inside the wall cavity for the second series of tests

Similarly, for the third series of tests, the same PCM thermal shields were used, but once again except for their location. The shields were located towards the interior side of the wall cavity. This is shown in Figure 3.4.3.

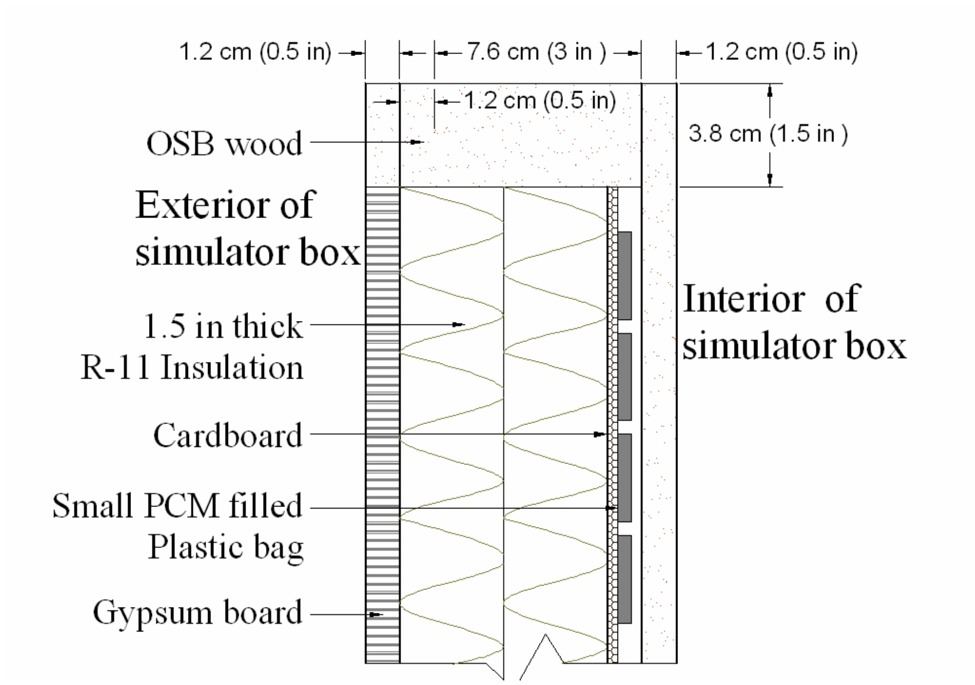


Figure 3.4.3. PCM arrangement inside the wall cavity for the third series of tests

3.5 Data Collection

Temperature and heat flow rate data were collected using the data logging system. This system was connected to all the heat flux meters, thermocouples and to a computer. The data logging system was an Agilent 34970A data logger (Figure 3.4.5). It collected temperatures and heat flow rates data in 20 second increments. A diagram of how the data logger was connected with the sensors and to the computer system is shown in Figure 3.4.6.

Figure 3.4.5. Agilent 37970 data logger

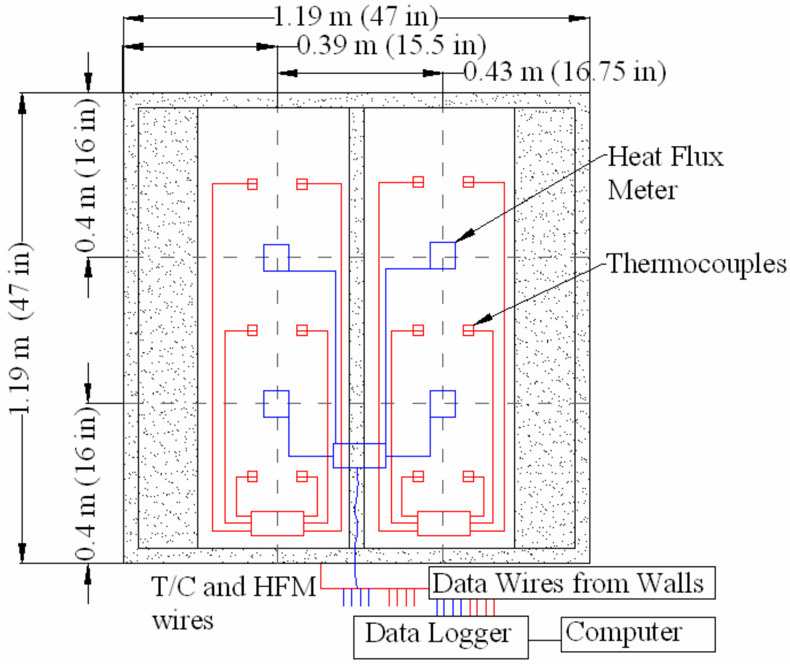


Figure 3.4.6. Diagram of data collection system

Data were collected and stored in the computer memory using proprietary software. The data was transferred to a computer for later analysis. The data were processed electronically using spreadsheets, which via macros converted the 20 second interval data to average hourly format. The average peak heat flux and the total flow rate for the test cycles were evaluated for each wall. The averaged peak heat fluxes and total heat flows of the walls outfitted with the PCM thermal shields were compared with the average peak heat flux and total heat flows of the control walls and with the walls outfitted with only a cardboard sheet. Each test lasted approximately between 72 to 96 hours.

Chapter IV

Results and Discussion

Three series of tests were performed, as part of this research, to evaluate the performance of PCM thermal shields in wall systems. In each series, two walls were outfitted with the PCM thermal shields (north and south walls). Of the remaining two walls, one was used as the control wall (east wall) and the other wall was outfitted with insulation and a replica of the cardboard sheet used to hold the PCM (west wall). This wall helped to isolate the effects of the cardboard in the PCM thermal shield. The south wall's PCM thermal shield consisted of 0.49 kg (1.09 lb) of PCM which represented 10% of the total weight of the wallboard. The north wall's PCM thermal shield consisted of 0.98 kg (2.17 lb) of PCM which represented 20% of the total weight of the wallboard. Each drywall was 1.09 m x 0.81 m (42 in x 32 in).

The inside of the simulator, together with its heating source, was designed to reproduce the conditions experienced by the exterior side of exterior walls. Because the dynamic wall simulator was located in an air conditioned research laboratory, the air conditioned room represented the indoor conditions of a typical residential building. In other words, the exterior of the dynamic wall simulator acted as the indoor space of a residential building.

Temperatures and heat fluxes data were recorded every 20 seconds. These data were later averaged into hourly data. This was done to filter out disturbances in temperatures or heat fluxes created by the laboratory's air conditioning system and/or people entering or leaving the room.

Test Series 1: PCM Thermal Shield Placed Next to the Gypsum Wallboard

A three-day test was performed in a configuration in which the PCM thermal shields were located next to the wallboard, but still inside the wall cavity. Figure 4.1.0 shows the location of the PCM thermal shield for the first test series.

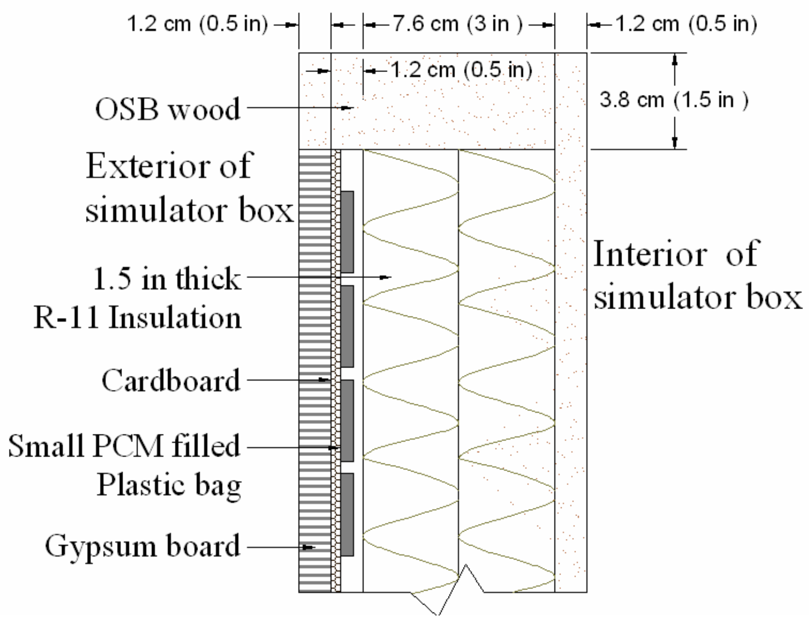


Figure 4.1.0. PCM arrangement inside the wall cavity for the first test series

In the first test of this series, both the walls outfitted with the PCM thermal shields and the control walls (one wall with only insulation and the other one with insulation and a replica of the cardboard used in the PCM thermal shields) were incrementally heated from an ambient temperature of approximately 25 ^{o}C (77 ^{o}F) to a maximum temperature of 52 ºC (125 ºF) and then allowed to cool down back to ambient temperature. This constituted a full cycle (24-hours each). For each tests two consecutive cycles were studied to analyze the performance of the walls outfitted with PCM shields. In each cycle the walls were heated for eight hours and allowed to cool down for 16 hours. This simulated one full day and one full night. The results of this test together with two other tests, when the maximum surface temperature were set at 60 °C (140 °F) and 65 °C (149 °F) are shown in Tables 4.1 a, b, and c.

Table 4.1.a. Peak Heat Fluxes for Test Series 1

			Peak Heat Fluxes							
Test no.	**Max Temperature**		**Control Wall**		**Cardboard Wall**		**10% PCM Shield Wall**		**20% PCM Shield Wall**	
	˚C	˚F	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2
4.1 Test No.1	52	125	13.22	4.04	12.88	4.08	11.55	3.66	10.53	3.22
4.2 Test No. 2	60	140	15.80	4.83	14.11	4.47	13.65	4.33	12.00	3.80
4.3 Test No. 3	65	149	20.18	6.40	18.77	5.95	17.35	5.50	15.30	4.87

Table 4.1.b. Percent Heat Peak Flux Reductions for Test Series 1

			% Peak Heat Flux Reduction		
Test no.	**Max Temperature**		**Cardboard Wall**	**10% PCM Shield Wall**	**20% PCM Shield Wall**
	˚C	˚F	%	%	%
4.1 Test No. 1	52	125	2.63	12.64	20.37
4.2 Test No. 2	60	140	8.35	16.94	25.07
4.3 Test No. 3	65	149	7.03	14.02	23.82

Table 4.1.c. Total Heat Transfer for Test Series 1

			Total Heat Transfer							
Test no.	**Max Temperature**		**Control Wall**		**Cardboard Wall**		**10% PCM Shield Wall**		**20% PCM Shield Wall**	
	˚C	˚F	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day hr ft^2
4.1 Test No. 1	52	125	150.16	47.60	149.22	47.30	148.79	47.17	114.23	36.21
4.2 Test No. 2	60	140	143.96	45.63	135.28	42.88	142.29	45.10	129.23	40.97
4.3 Test No. 3	65	149	184.45	58.47	174.00	55.16	182.78	57.94	170.14	53.93

4.1 Test No. 1

The temperature of the walls in the dynamic wall simulator ranged from 25 ºC to 52 ºC (77 ºF to 125 ºF). The maximum temperature of the walls was approximately 52 ºC (125 ºF) during the peak time of the heating period while the average indoor surface temperature of the walls was approximately 40 ºC (104 ºF) over the testing period. The surface temperature profiles of all the walls are shown in Figure 4.1.1. The graph also includes four air temperatures as indicated.

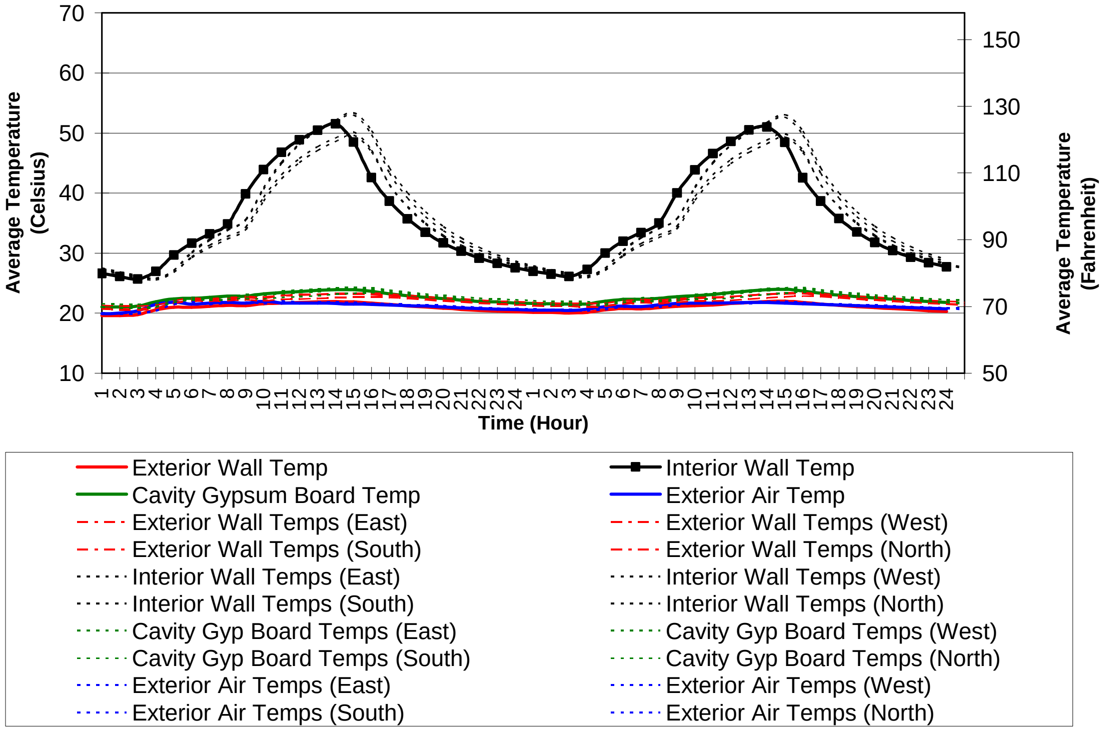


Figure 4.1.1. Average surface temperature profiles of all the walls (Series 1, Test 1)

As expected, the interior surface temperatures were higher than the rest of the interior and exterior surface temperatures in each wall. These profiles indicate the way exterior temperatures of a building would vary throughout a typical day when the average maximum exterior surface temperature would reach a temperature of about 52 ºC (125 ºF). The exterior air temperatures and the exterior wall temperatures of the dynamic wall simulator are also shown. At a maximum interior surface temperature of 52 ºC (125 ºF), the exterior surfaces of the walls increased in temperature, but not significantly. Therefore, the exterior wall surface temperatures were close to the exterior air temperature. The average hourly wall heat fluxes over a 24-hour test period are shown in Figure 4.1.2.

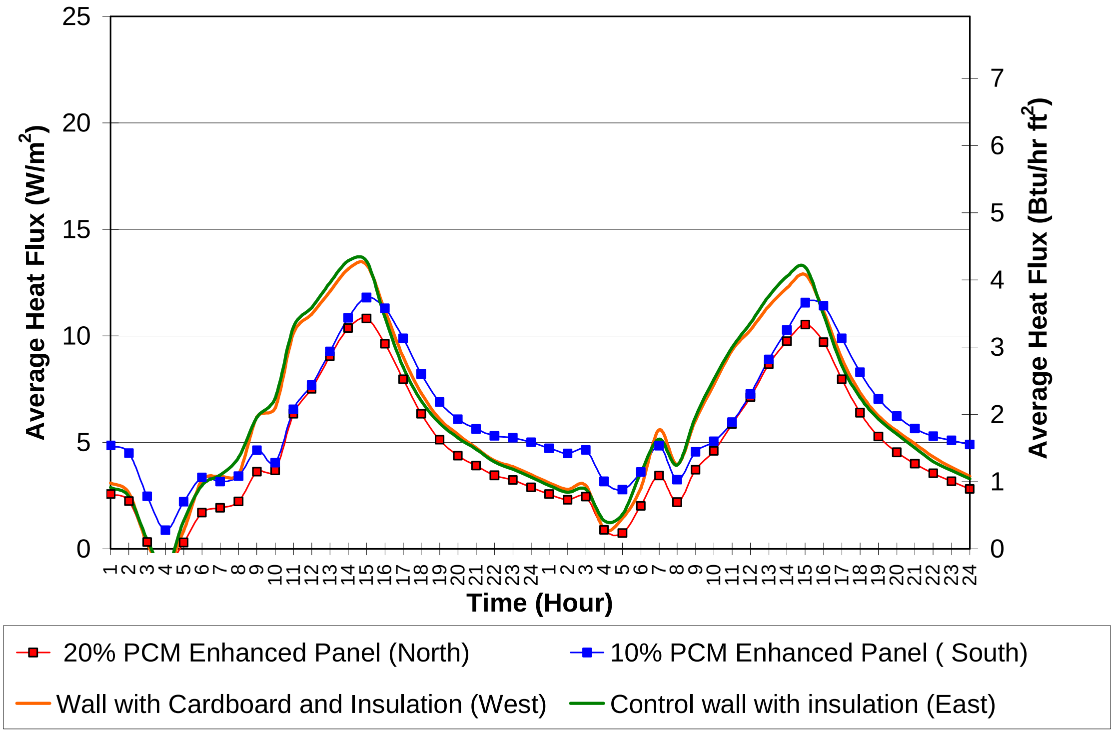


Figure 4.1.2. Average wall heat fluxes (Series 1, Test 1)

The graph shows that the peak heat flux for the control wall was 13.22 W/m^2 (4.04 Btu/hr ft^2). The cardboard in one of the control walls seemed to have a little effect in reducing the heat flux. The maximum peak heat flux for the wall outfitted with the PCM thermal shield at a concentration of 10% was 11.55 W/m^2 (3.66 Btu/hr ft^2), which was equivalent to a reduction of 12.64% over the control wall. The maximum peak heat flux for the wall outfitted with the PCM thermal shield at a concentration of 20% was 10.53 W/m^2 (3.22 Btu/hr ft^2), which was equivalent to a reduction of 20.37%. During this test the 20% PCM thermal shield outperformed the 10% PCM thermal shield by 7.73%. From the data displayed in the graph, it seemed that all of the PCM in the 10% shield may have melted, but not all the PCM in the 20% shield. This is evidenced by the location of the curves in the cool down period in reference to the curve of the control wall. The 10% PCM shield wall (south) may have released all the stored heat energy while the PCM was solidifying during the cool down period. This trend was not seen in the curve of the 20% PCM shield. The reason could be that at an average maximum exterior surface temperature of 52 °C (125 °F) there may not have been sufficient energy to melt all the PCM of the 20% PCM shield (north). In Figure 4.1.3, the average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures.

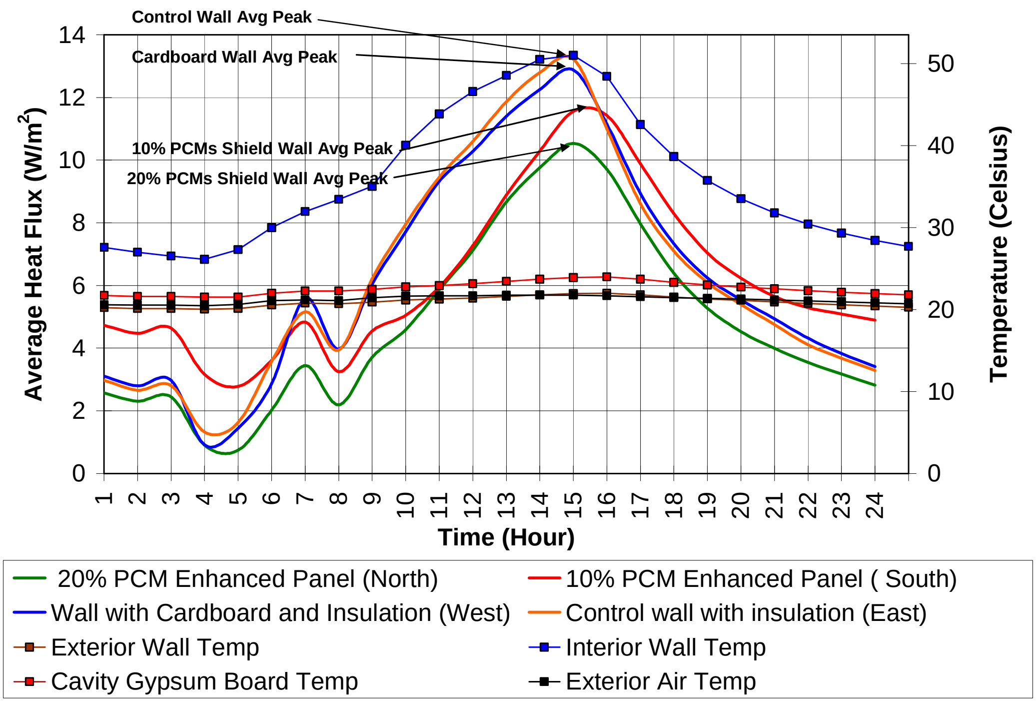


Figure 4.1.3. Peak heat fluxes with their coincident interior and exterior wall temperature profiles (Series 1, Test 1)

The figure shows the manner in which the heat fluxes in the walls outfitted with the PCM thermal shields performed as the interior wall temperatures changed over time. The graph shows how both the walls outfitted with the PCM thermal shields displayed a delayed peak heat flux of approximately one hour for the wall outfitted with the 10% PCM shield and approximately half-hour for the wall outfitted with the 20% shield. The reason for this may be that the PCM shields absorbed heat that was being transferred across the wall during the heating period. This energy was stored while the PCM in the PCM shields was melting. During this melting process the PCMs absorbed latent heat energy and thus prevented a part of this heat from being completely transferred across the wall. Therefore, it delayed the heat transfer process, in the heating period, which resulted in the peak heat flux being shifted from approximately half-hour to about one-hour. The percentages of peak heat flux reduction are shown in Figure 4.1.4.

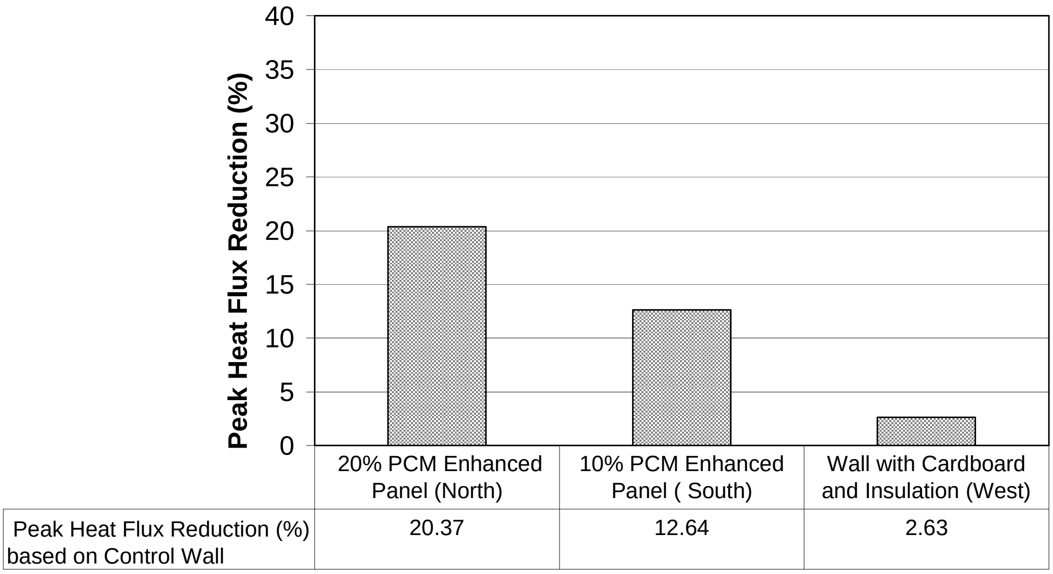
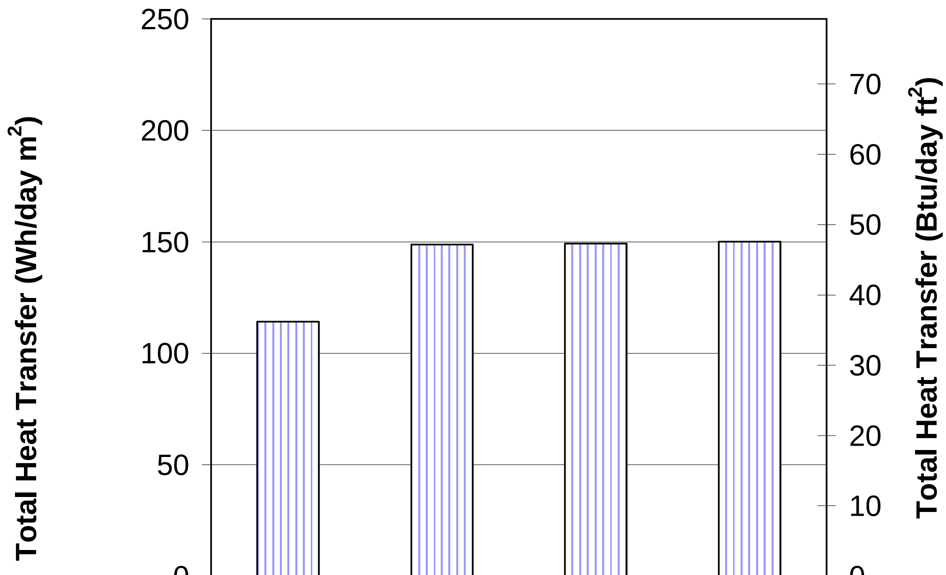


Figure 4.1.4. Percentages of peak heat flux reduction of walls (Series 1, Test 1)

According to the bar graph, the 20% PCM shield wall reduced the peak heat flux by approximately 20.37% when compared to the peak heat flux of the control wall. The 10% PCM shield in the wall produced a reduction of the peak heat flux of approximately 12.64%. The cardboard alone reduced the peak heat flux by about 2.63%. This means that the PCM alone decreased the heat fluxes by 17.74% and 10.01% when concentrations of 20% and 10% were used, respectively, and when the wall surface, which was exposed to the heat source, had a temperature range of 25 ºC to 52 ºC (77 ºF to 125 ºF). The total heat transfer for each wall over a 24-hour period is shown in Figure 4.1.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/ day m2)	114.23	148.79	149.22	150.16
Total Heat Transfer for 24 Hours (Btu/day ft2)	36.21	47.17	47.30	47.60

Figure 4.1.5. Total heat transfer for each wall over a 24-hour period (Series 1, Test 1)

During this period the wall outfitted with the 20% PCM shield (north) transferred about 114.23 Wh/day m^2 (36.21 Btu/dayft^2) of total heat. The wall outfitted with the 10% PCM shield (south) transferred about 148.79 Wh/day m^2 (47.17 Btu/day ft^2) of total heat. This reduction was not much lower than the heat transferred in the control walls; however, this was expected. The reason for this is that in a laboratory setting all of the heat energy generated within the simulator, by the heating source, would eventually always end up in the conditioned space of the laboratory. Also, the interior temperature of the simulator never dropped below the indoor temperature of the laboratory space. This would not be the case in buildings exposed to full weather conditions. The heat fluxes of the 20% PCM shield did not follow this trend. This was probably because not all the PCM was able to melt and/or re-solidify, thus trapping within itself the balance of the heat energy.

It was concluded that the PCM shield with the higher concentration performed comparatively better than the PCM shield with the lower PCM concentration for a temperature range with maximum wall surface temperature of 52 ºC (125 ºF).

4.2 Test No. 2

For Test No. 2, the maximum internal wall surface temperature was 60 ºC (140 ºF). The range temperatures for the interior surface of the wall from 30 ºC to 60 ºC (86 ºF to 140 ºF). The average (over time) temperature of the walls was approximately 40 ºC (104ºF). The surface temperature profiles of all the walls are shown in Figure 4.2.1. The graph also includes four air temperatures as indicated.

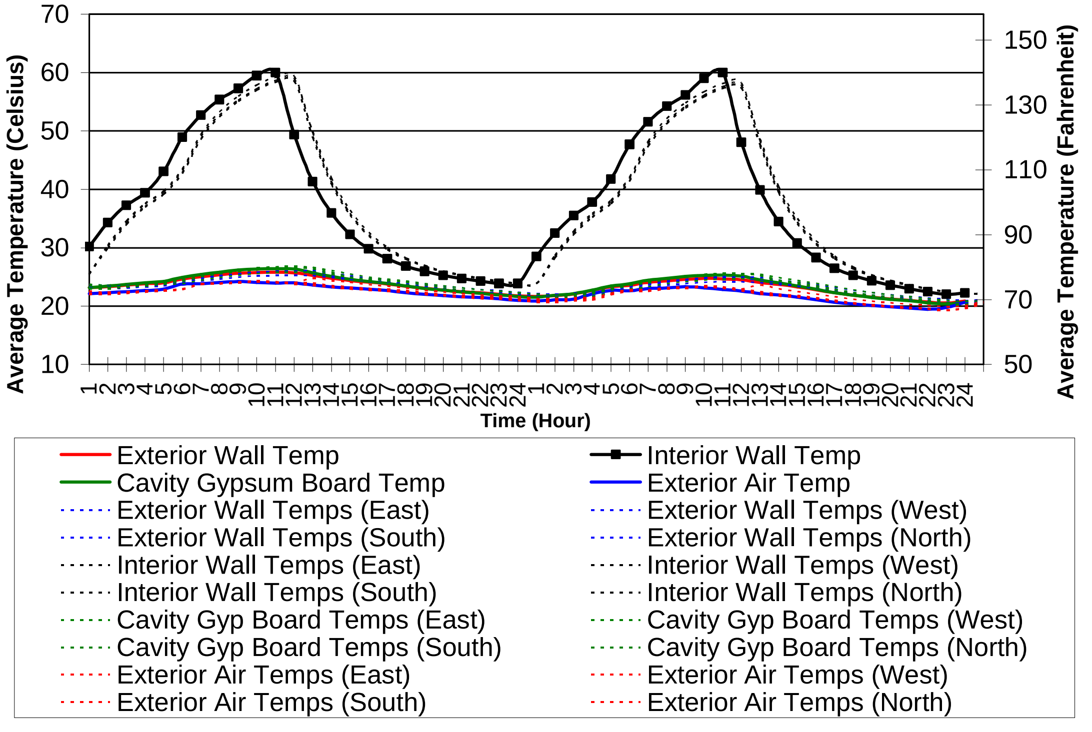


Figure 4.2.1. Average surface temperature profiles of all the walls (Series 1, Test 2).

These profiles simulate the manner in which the exterior temperatures of a building would vary throughout a typical day when the average maximum exterior surface temperature would reach about 60 ºC (140 ºF). The exterior air temperatures and the internal surface temperature of the wallboard were closer in Test 2 than in Test 1 because the temperature range in Test 2 was moderately larger. Because of the higher temperatures, it was expected that the walls would store relatively higher amounts of heat during the phase change of the PCMs than in Test 1. The average hourly wall heat fluxes over a 24-hour test period are shown in Figure 4.2.2.

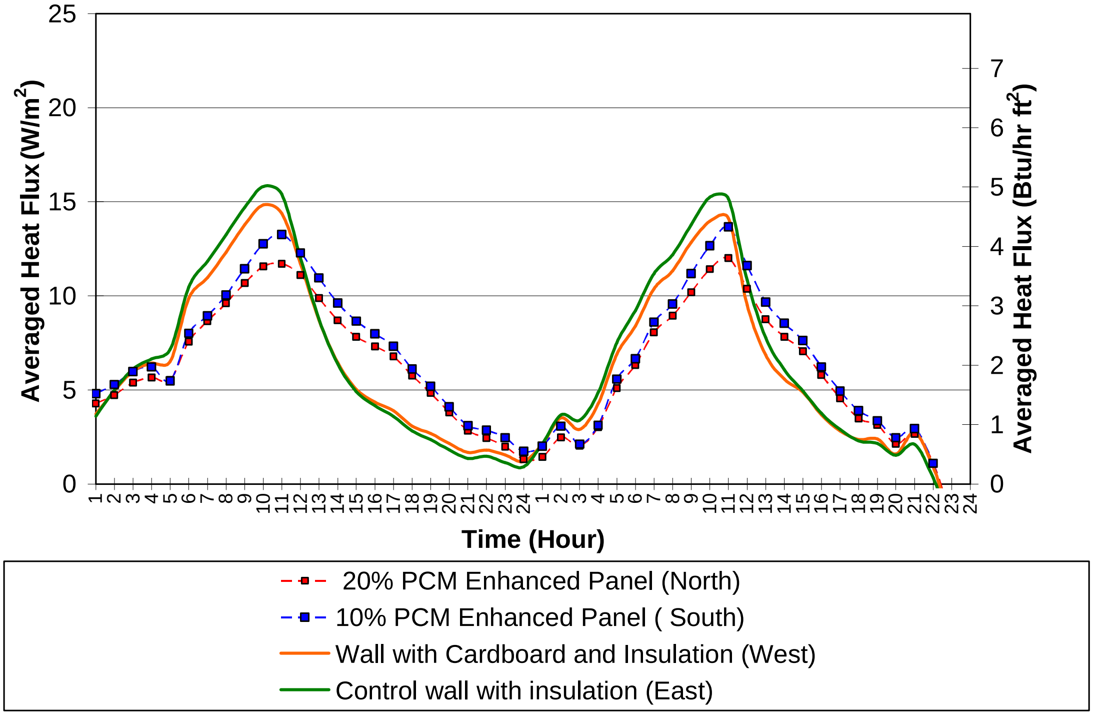


Figure 4.2.2. The average peak heat fluxes of walls (Series 1, Test 2).

The control wall peak heat flux was 15.80 W/m^2 (4.83 Btu/hr ft^2). The maximum peak heat flux for the wall outfitted with the 10% PCM shield was 13.65 W/m^2 (4.33 Btu/hr ft^2) and the maximum peak heat flux for the wall outfitted with the 20% PCM shield was 12 W/m^2 (3.80 Btu/hr ft^2). Table 4.1 shows the peak heat fluxes, reduction, and the total heat transferred across each wall for Test 2 in this series. In this test both the wall with the 10% PCM shield and the wall with the 20% PCM shield seemed to have stored sufficient heat energy to generate the phase change in the PCMs inside the wall cavity from solid to liquid. It seemed that the PCM in both PCM shielded walls was completely melted during the heating period. This was evidenced in the graph of Figure 4.2.2 during the cool down period, where the heat flux curves of the PCM-enhanced walls were higher than the heat flux curves of the control wall. The peak heat flux of the wall with the 10% PCM shield differed somewhat significantly from the peak heat flux of the wall with the 20% PCM shield. The difference in peak heat flux between these two walls was about 1.65 W/m^2 (0.524 Btu/hr ft^2). The reason for this could be attributed to the larger concentration of PCM in the 20% PCM shield. In Figure 4.2.3, the average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures.

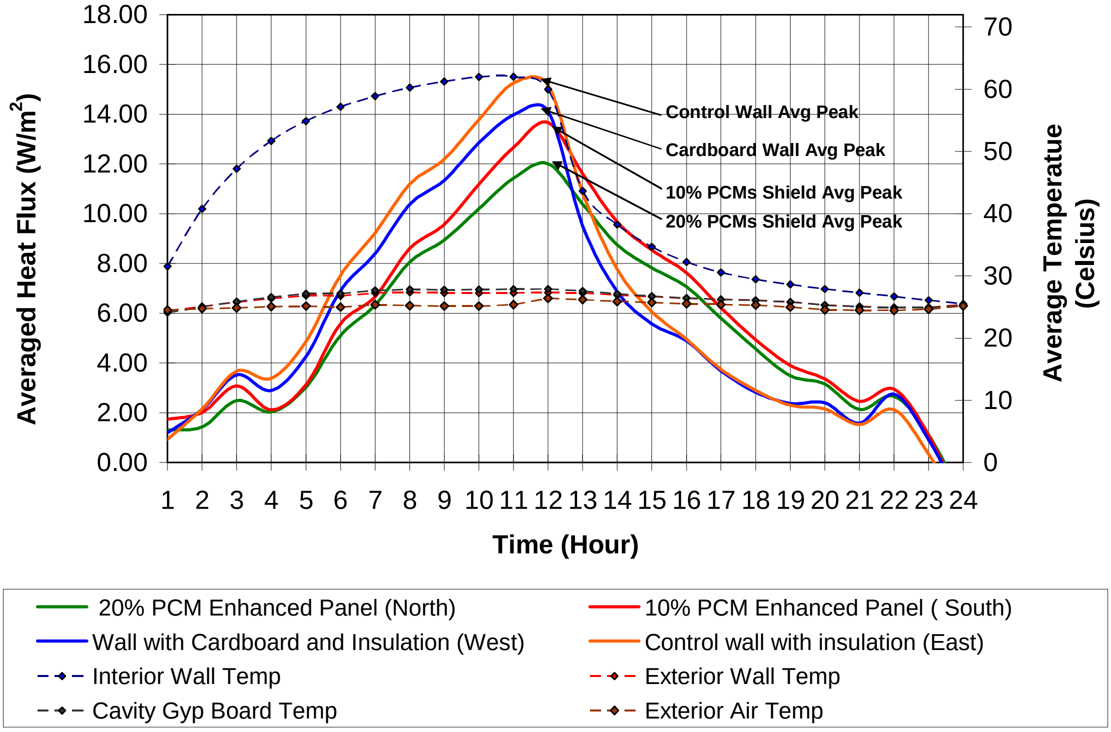


Figure 4.2.3. Peak heat fluxes with their coincident interior and exterior wall temperature profiles (Series 1, Test 2)

The figure shows how the PCM-shielded walls performed as a function of their change of temperatures over time. Both the 10% PCM shielded wall and the 20% PCM shielded wall showed a delay in their peak heat fluxes of approximately 30 minutes. The reason for this delay relates to the phase change process of the PCMs. That is, a significant amount of heat energy was used to melt the PCMs, which resulted in an interruption in the motion of the heat across the wall from the hotter side to the colder side of the wall during the heating period. The percentages of peak heat flux reduction are shown in Figure 4.2.4.

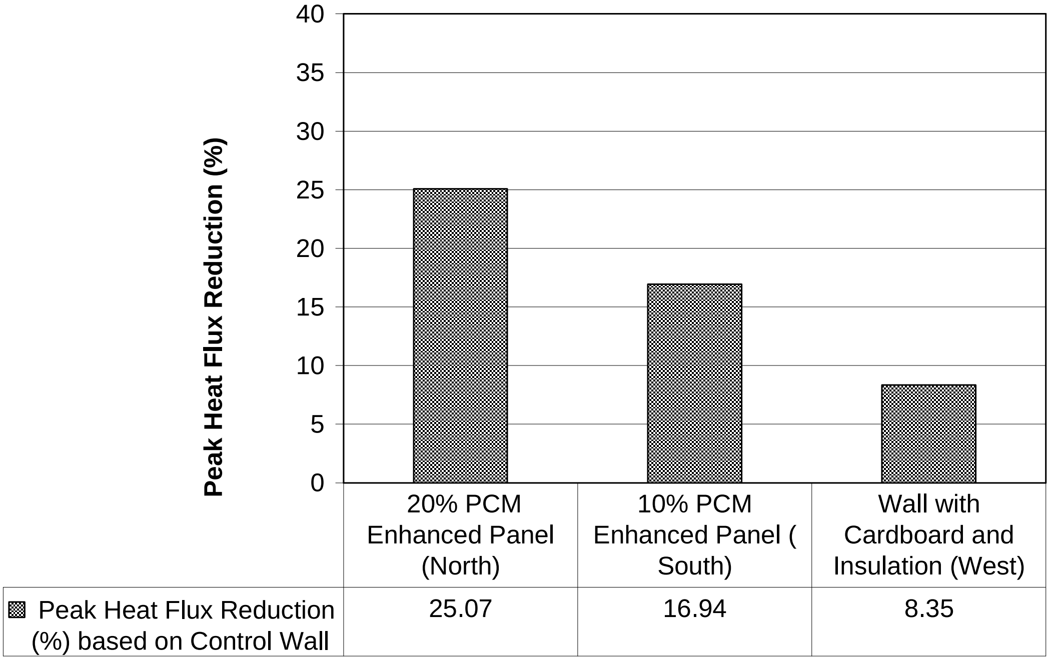
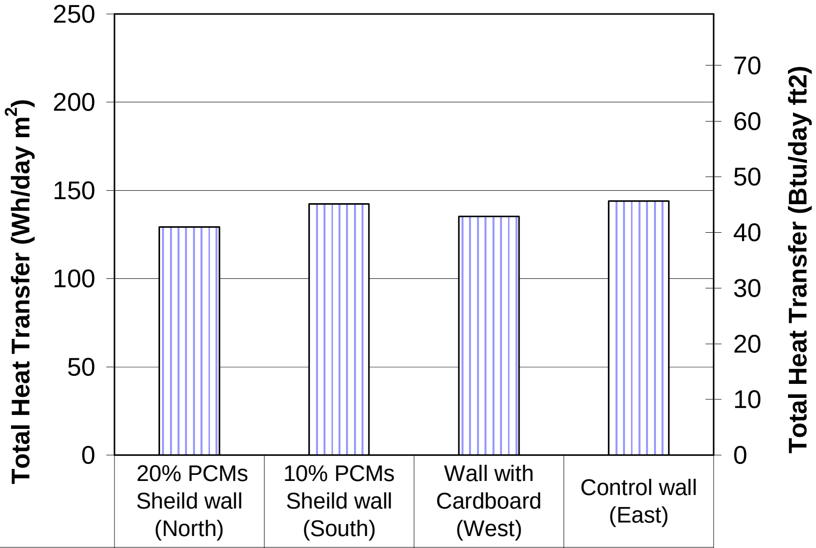


Figure 4.2.4. Percentages of peak heat flux reduction of walls (Series 1, Test 2)

According to the data, the wall with the 20% PCM shield wall had a reduced peak heat flux of approximately 25.07%, while the wall with the 10% PCM shield wall had a reduced peak heat flux of approximately 16.94%. The wall outfitted with only cardboard and insulation had reduced peak heat flux of about 8.35%. This translates to the fact that by adding PCMs at a concentration of 10% the peak heat flux could be decreased by about 8.59% when the temperature range was 25 ºC to 60 ºC (77 ºF to 140 ºF). Similarly, adding PCMs at a concentration of 20% could reduce the peak heat flux by 16.72% at the temperature range of 25 ºC to 60 ºC (77 ºF to 140 ºF). The total heat transfer for each wall over a 24-hour period is shown in Figure 4.2.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/ day m2)	129.23	142.29	135.28	143.96
Total Heat Transfer for 24 Hours (Btu/day ft2)	40.97	45.10	42.88	45.63

Figure 4.2.5. Total heat transfer for each wall over a 24-hour period (Series 1, Test 2)

In this period of time the wall outfitted with the 20% PCMs shield transferred about 129.23 Wh/day m^2 (40.97 Btu/day ft^2) of total heat. The wall outfitted with the 10% PCM shield had a total heat transferred of approximately 142.29 Wh/day m^2 (45.10 Btu/day ft^2).

This test concludes that high concentration of PCM in the shield performed comparatively better than the lower concentration PCM shield for moderate high temperature range with maximum wall surface temperature of 60 ºC (140 ºF) and average temperature of 40 ºC (104 ºF) over time.

4.3 Test No. 3

In this test the temperature of the walls were ranged from 25 °C to 65 °C (77 °F to 149 °F). The maximum temperature of the walls was approximately 65 °C (149 °F) during the peak time. The average temperature of the walls was approximately 40 °C (104 °F) over time. The average surface temperature profiles of all the walls are shown in Figure 4.3.1. The graph also includes four air temperatures as indicated.

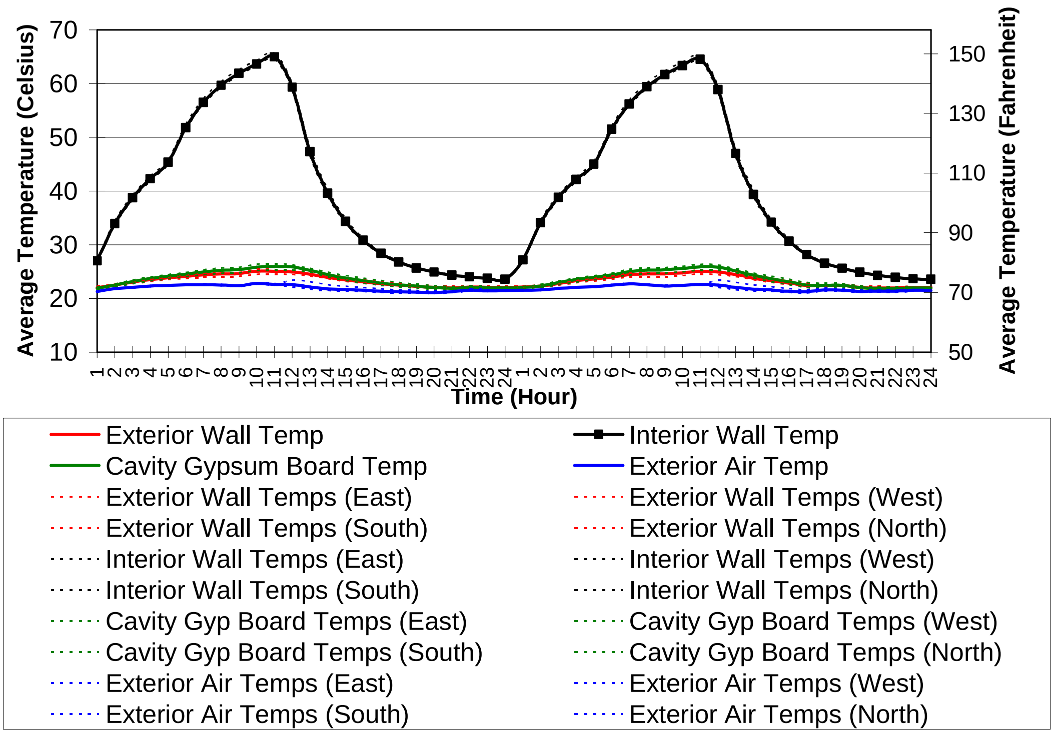


Figure 4.3.1. Average surface temperature profiles of all the walls (Series 1, Test 3)

As expected the interior surface temperatures were higher than the rest of the surface temperatures in each wall. This profile indicates how the exterior temperatures of a building would vary throughout a typical day when the average maximum exterior surface temperature would reach about 65 °C (149 °F). The average hourly wall heat fluxes were graphed over a 24-hour test period in Figure 4.3.2.

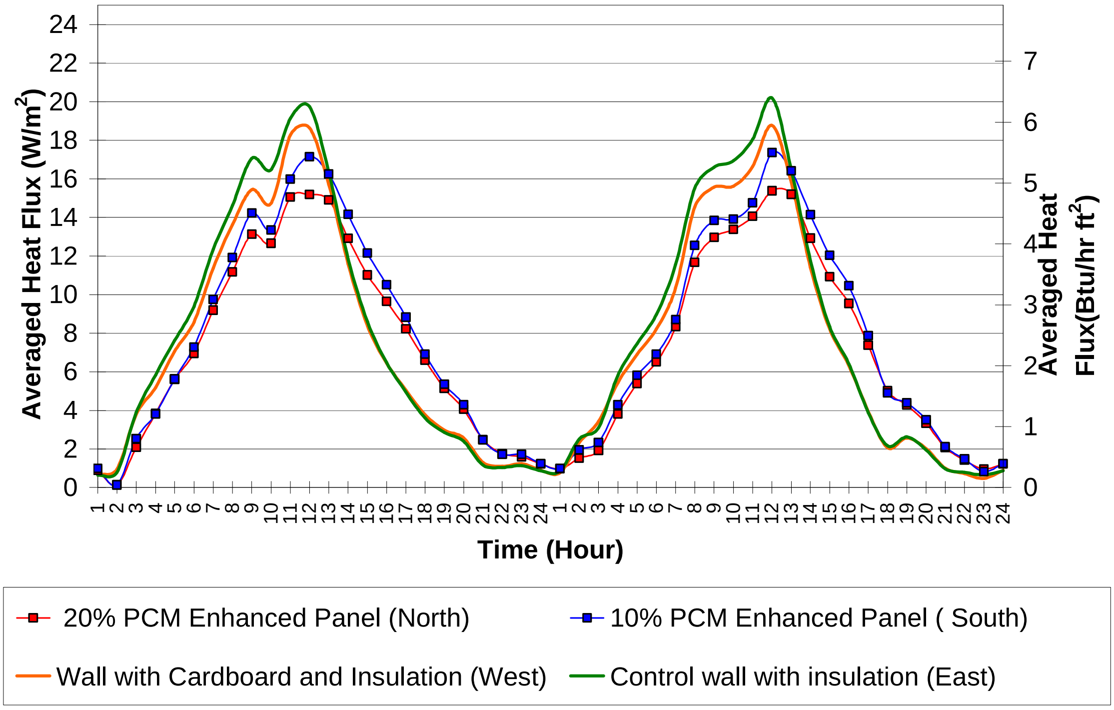


Figure 4.3.2. Average wall heat fluxes (Series 1, Test 3).

The data show that the control peak heat flux was 20.18 W/m^2 (6.40 Btu/hr ft^2). The maximum peak heat flux for the wall outfitted with the PCM shield holding a concentration of 10% PCM was 17.35 W/m^2 (5.50 Btu/hr ft^2). The peak heat flux of the wall outfitted with the thermally-enhanced shield holding a concentration of 20% PCM was 15.3 W/m^2 (4.87 Btu/hr ft^2). Table 4.1 shows the heat fluxes, reduction, and total heat transferred across each wall for Test 3 in this series. It was observed that for both walls outfitted with the PCM shields, the PCMs melted completely during the heating period. The peak heat flux across all walls differed. The difference in peak heat flux for the walls outfitted with the PCM shields between these two walls was about 2.05 W/m^2 (0.63 Btu/hr ft^2). In Figure 4.3.3, the average peak heat fluxes are indicated with their coincident interior and exterior temperatures.

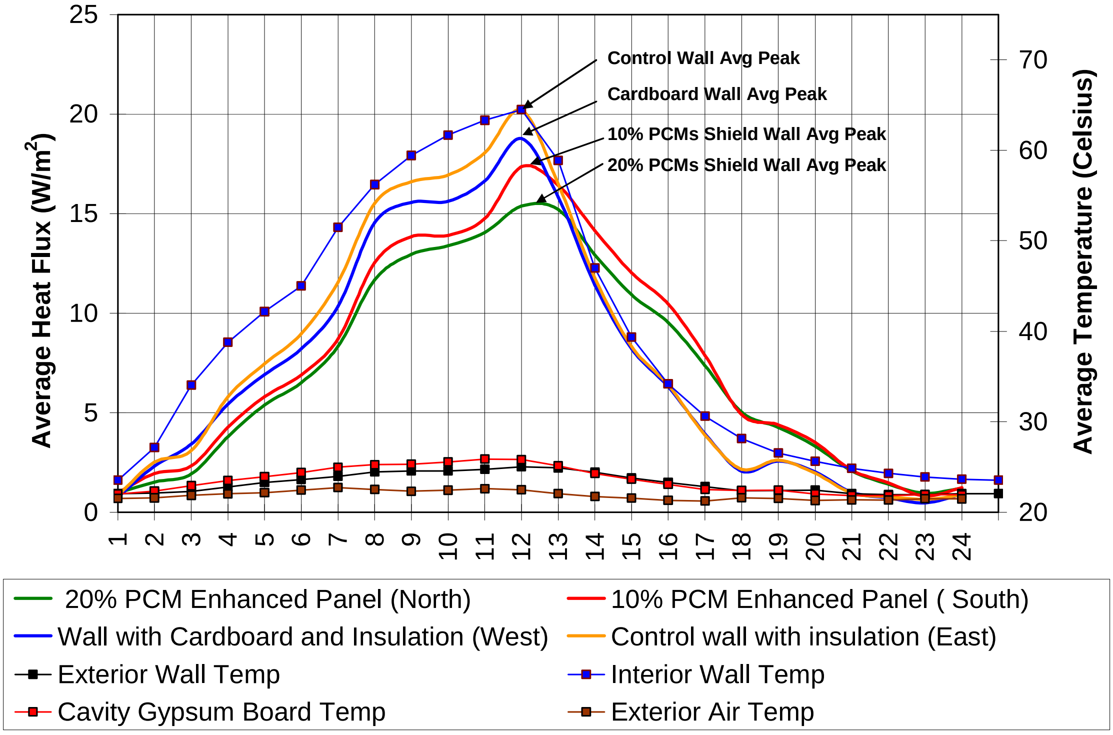


Figure 4.3.3. Peak heat fluxes with their coincident interior and exterior wall temperature profiles (Series 1, Test 3)

In this test, the time delay in the peak heat fluxes was about 15 and 30 minutes for the 10% PCM shield wall and for the 20%-PCM shield wall, respectively. This may be explained by the fact that the PCM must have melted at a faster rate, a result of the higher surface temperatures, than in the previous tests. The percentages of peak heat flux reduction are shown in Figure 4.3.4.

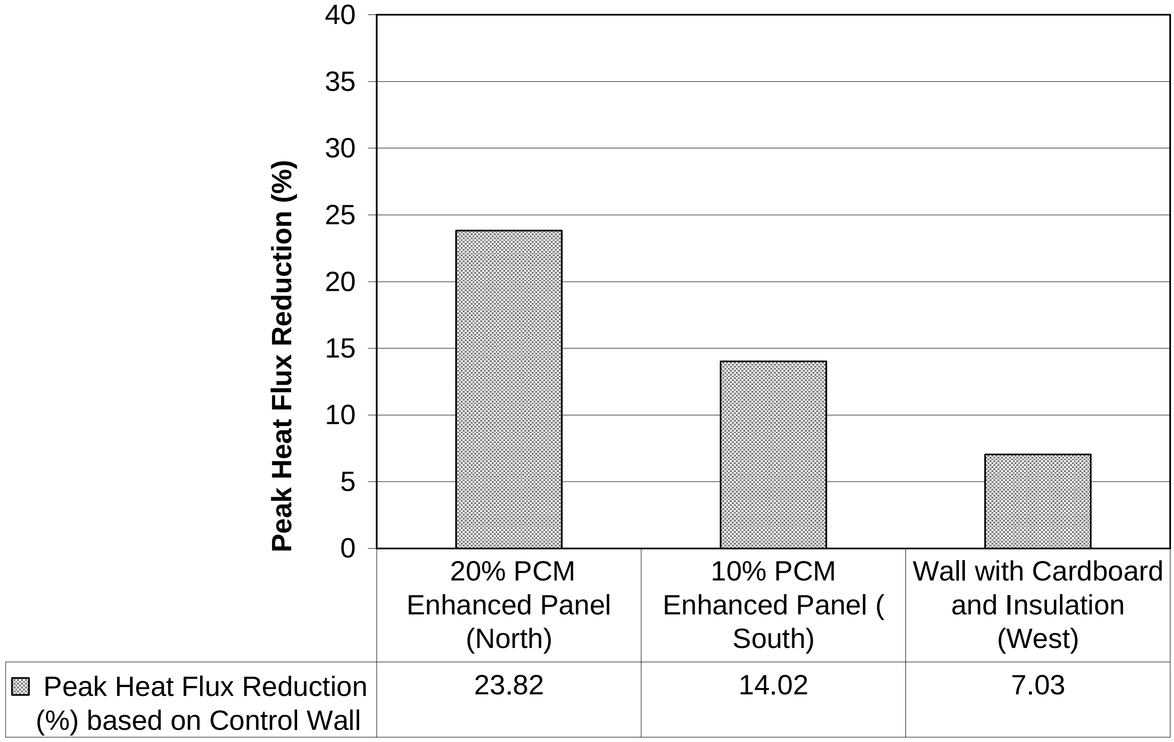
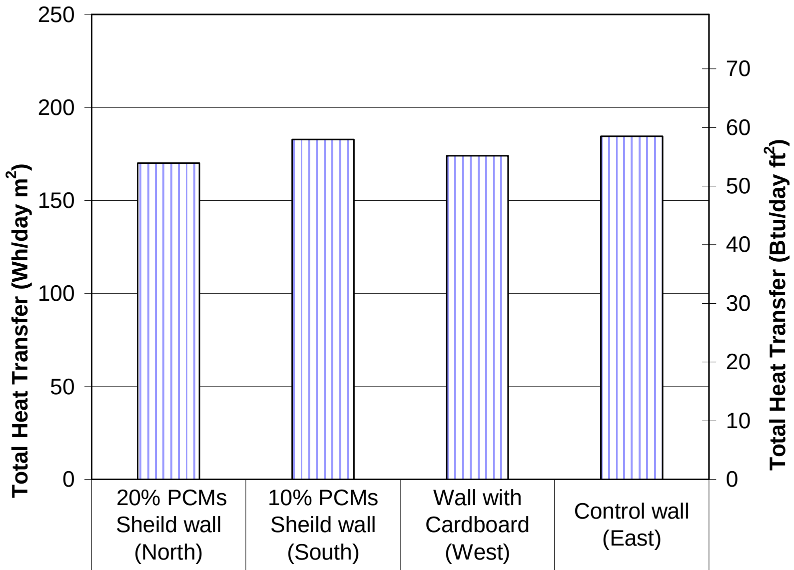


Figure 4.3.4. Percentages of peak heat flux reduction of walls (Series 1, Test 3)

From the data, it was observed that the 20% PCM shield wall had a reduced peak heat flux of approximately 23.82%. The 10%-PCM shielded wall had a reduced peak heat flux of approximately 14.02%. The wall outfitted with only the cardboard had its peak heat flux reduced by about 7.03%. This means that by adding a 10% PCM concentration to the cardboard, the control wall could decrease its peak heat flux by 6.99% at the temperature range of 25 ºC to 65 ºC (77 ºF to 149 ºF). Similarly, a 20% PCM concentration added to the cardboard could decrease the peak heat flux load of the control wall 16.72% at the temperature range of 25 ºC to 65 ºC (77 ºF to 149 ºF) average to maximum. The total heat transfer for each wall over a 24-hour period is shown in Figure 4.3.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	170.14	182.78	174.00	184.45
Total Heat Transfer for 24 Hours (Btu/day ft2)	53.93	57.94	55.16	58.47

Figure 4.3.5. Total heat transfer for each wall over a 24-hour period (Series 1, Test 3).

In this period of time the wall outfitted with the 20% PCMs shield wall transferred about 170.14 Wh/day m^2 (53.93 Btu/day ft^2) of total heat. The wall outfitted with the10% PCM shield wall transferred about 182.78 Wh/day m^2 (57.94 Btu/day ft^2) of total heat.

In summary, it was observed that the PCM-enhanced thermal shields, when integrated in walls, would tend to produce higher heat flux reductions at lower maximum surface temperature, which would decrease with increasing interior surface temperatures. That is, it seems that at lower temperatures, the PCM would melt slower, and thus allow for a higher decrease in heat flux. Between the thermal shields, however, it was observed that the 20%-PCM shield outperformed the 10%-PCM shield at all maximum surface temperatures, but more so at higher ones. This may be explained by the fact that at higher temperatures, more PCM would melt in the 20%-PCM shield than at lower temperatures. It may seem that during Tests 1 and 2, the PCM in the 20%-PCM shield may not have completely melted. This is supported by the shape of the graphs of Figures 4.1.2, 4.2.2, and 4.3.2. In fact, during the cool down period, the heat fluxes tend to get closer with increasing maximum surface temperatures. That is, the heat fluxes in the cool down period of Figure 4.3.2 are closer than in Figure 4.2.2, and much more than in Figure 4.1.2.

Test Series 2: PCM Thermal Shield Placed in the Middle of the Wall Cavity between the Insulation Layers)

In this test series a three-day test was performed in a configuration in which the PCM thermal shields were located between two insulation layers. The shields were located in the middle section of the wall cavity. Figure 4.4.0 shows the location of the PCM thermal shields for the second test series.

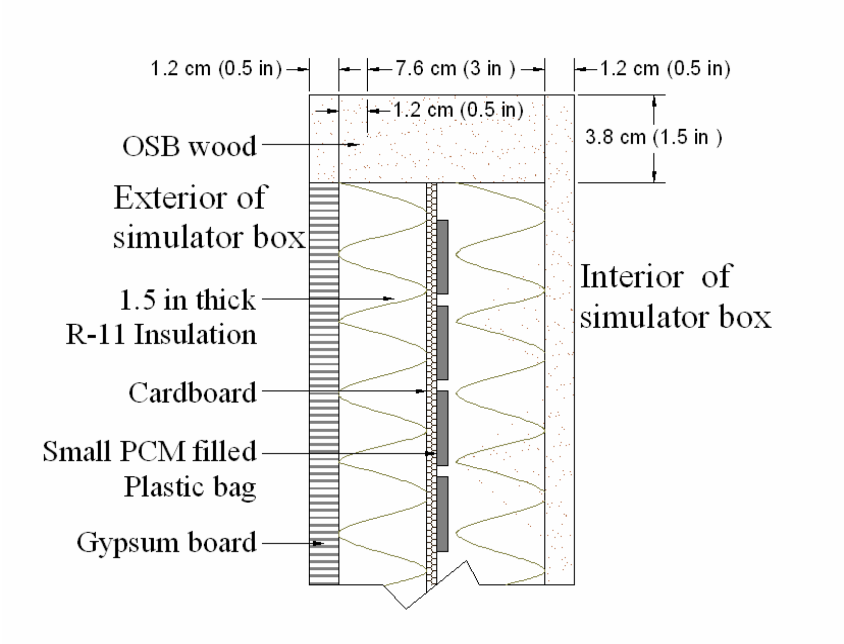


Figure 4.4.0. PCM arrangement inside the wall cavity for the second series of tests.

In the first test of the second test series the interior surface of the walls were incrementally heated from an ambient temperature of approximately 25 ^{o}C (77 ^{o}F) to a maximum temperature of 52ºC (125ºF) and then allowed to cool down back to ambient temperature. This constituted a full cycle. Three consecutive cycles of 24 hours each, were carried out. The results of this test, together with two other tests, when the maximum interior surface temperature were allowed to reach 60 ^{o}C (140 ^{o}F) and 65 ^{o}C (149 ^{o}F) are shown in Tables 4.2 a, b, and c.

Table 4.2.a. Peak Heat Fluxes for Test Series 2

			Peak Heat Fluxes							
Test no.	**Max Temperature**		**Control Wall**		**Cardboard Wall**		**10% PCM Shield Wall**		**20% PCM Shield Wall**	
	˚C	˚F	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2
4.4 Test No. 1	52	125	13.52	4.28	12.79	4.05	12.13	3.84	11.99	3.80
4.5 Test No. 2	60	140	18.24	5.78	16.18	5.13	16.09	5.10	15.34	4.60
4.6 Test No. 3	65	149	20.15	6.38	18.74	5.94	19.23	6.09	18.21	5.77

Table 4.2.b. Percent Peak Heat Flux Reductions for Test Series 2

			% Peak Heat Flux Reduction		
Test no.	**Max Temperature**		**Cardboard Wall**	**10% PCM Shield Wall**	**20% PCM Shield Wall**
	˚C	˚F	%	%	%
4.4 Test No. 1	52	125	5.30	10.20	11.20
4.5 Test No. 2	60	140	11.30	11.80	15.90
4.6 Test No. 3	65	149	7.00	4.60	9.60

Table 4.2.c. Total Heat Transfer for Test Series 2

Total Heat Transfer										
Test no.	**Max Temperature**		**Control Wall**		**Cardboard Wall**		**10% PCM Shield Wall**		**20% PCM Shield Wall**	
	˚C	˚F	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day ft^2
4.4 Test No. 1	52	125	147.00	46.75	138.88	44.03	146.00	46.33	136.00	43.33
4.5 Test No. 2	60	140	192.74	61.10	182.27	57.78	192.47	61.01	179.71	56.97
4.6 Test No. 3	65	149	222.62	70.57	209.86	66.52	221.07	70.08	206.63	65.50

4.4 Test No. 1

The surface temperature of the walls in the dynamic wall simulator ranged from 25ºC to 52ºC (77ºF to 125ºF) in this test. The maximum interior surface temperature of the walls was approximately 52ºC (125ºF) during the peak time of the heating period. The average temperature of the walls was approximately 40ºC (104ºF). The average surface temperature profiles of all the walls are shown in Figure 4.4.1. The graph also includes four air temperatures as indicated.

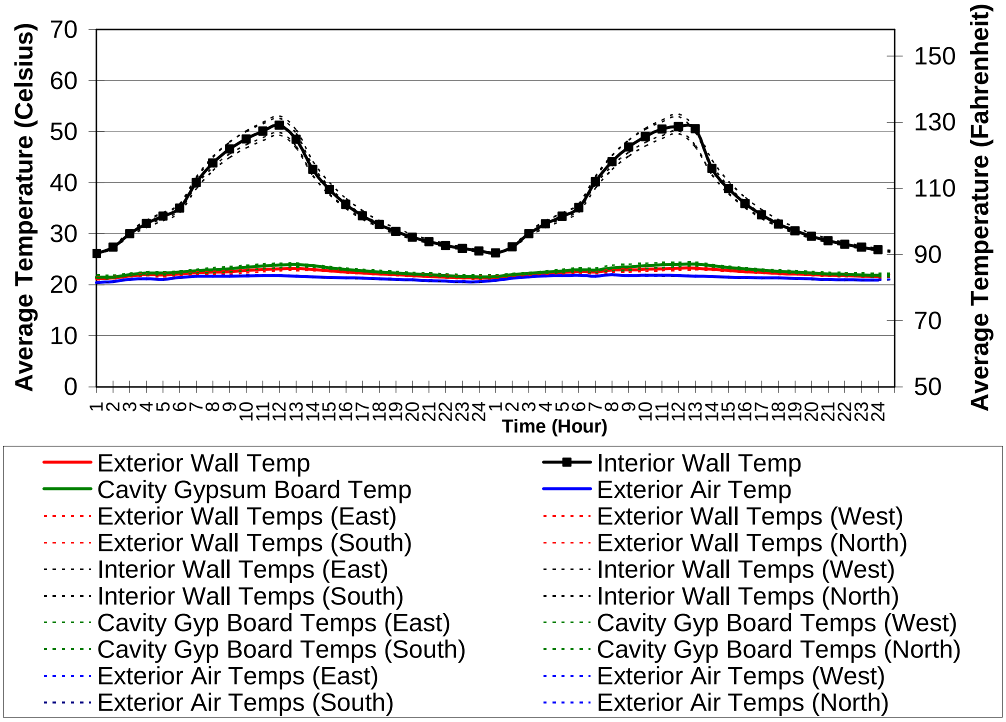


Figure 4.4.1. Average surface temperature profiles of all the walls (Series 2, Test 1)

This profile indicates the way exterior and wall temperatures of a building would vary throughout a typical day when the average maximum exterior temperature would reach at about 52ºC (125ºF). Unlike the first test of first series (Series 1, Test 1) the exterior surface temperatures and the interior temperatures of the wallboard differed less. The reason for this may be related to the placement of the PCM shield. The PCM shield was placed between the two insulation layers of wall cavity. The average hourly wall heat fluxes over a 24-hour test period are shown in Figure 4.4.2.

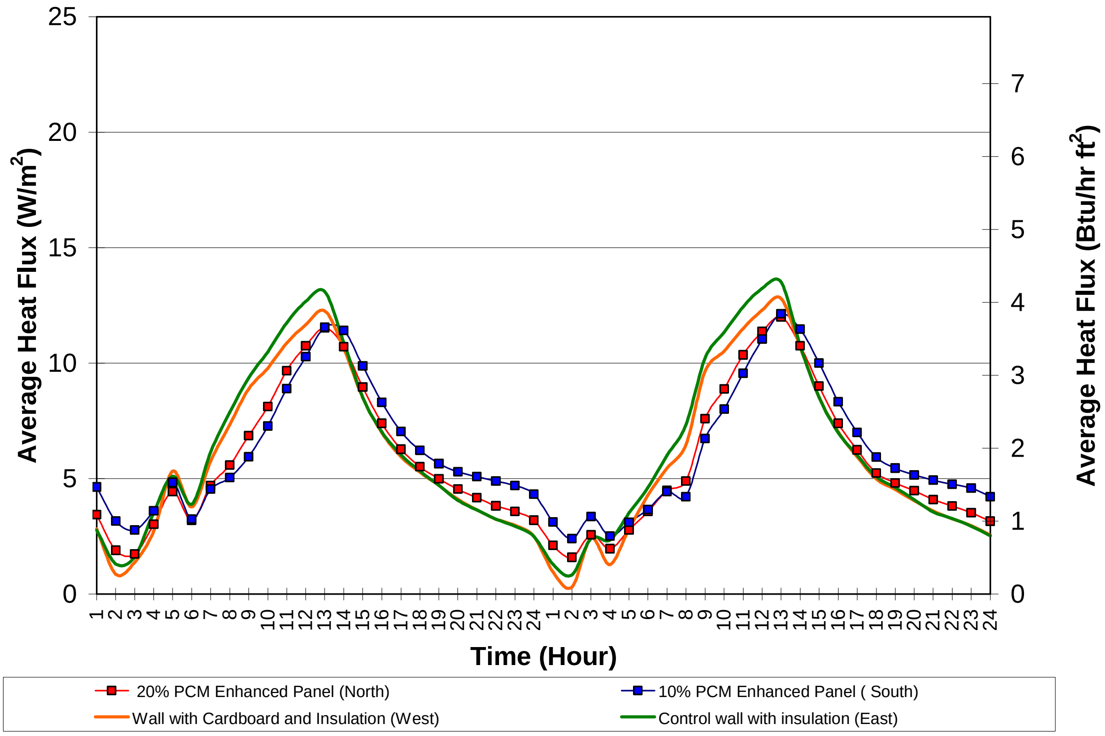


Figure 4.4.2. Average wall heat fluxes (Series 2, Test 1)

The graph shows that the control peak heat flux was 13.52 W/m^2 (4.28 Btu/hr ft^2). The maximum peak heat flux for the wall outfitted with the 10% PCM shield was 12.13 W/m^2 (3.84 Btu/hr ft^2) and the maximum peak heat flux for the wall outfitted with the 20% PCM shield was 11.99 W/m^2 (3.8 Btu/hr ft^2). Table 4.2 shows the peak heat fluxes, reduction, and the total heat transferred across each wall for Test 1 in this series. Unlike Test 1 in Series 1, in this experiment both walls outfitted with the PCM shields had approximately the same peak heat fluxes. This may be because the PCM shields were placed in between the insulation layers of wall cavity, and therefore, the amount of PCM that melted in both shields may have been about the same. That is, only about 50% of the PCM in the shield with a concentration of 20% may have melted. The insulation layers may have prevented heat from reaching the PCM shields. In Figure 4.4.3, the average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures.

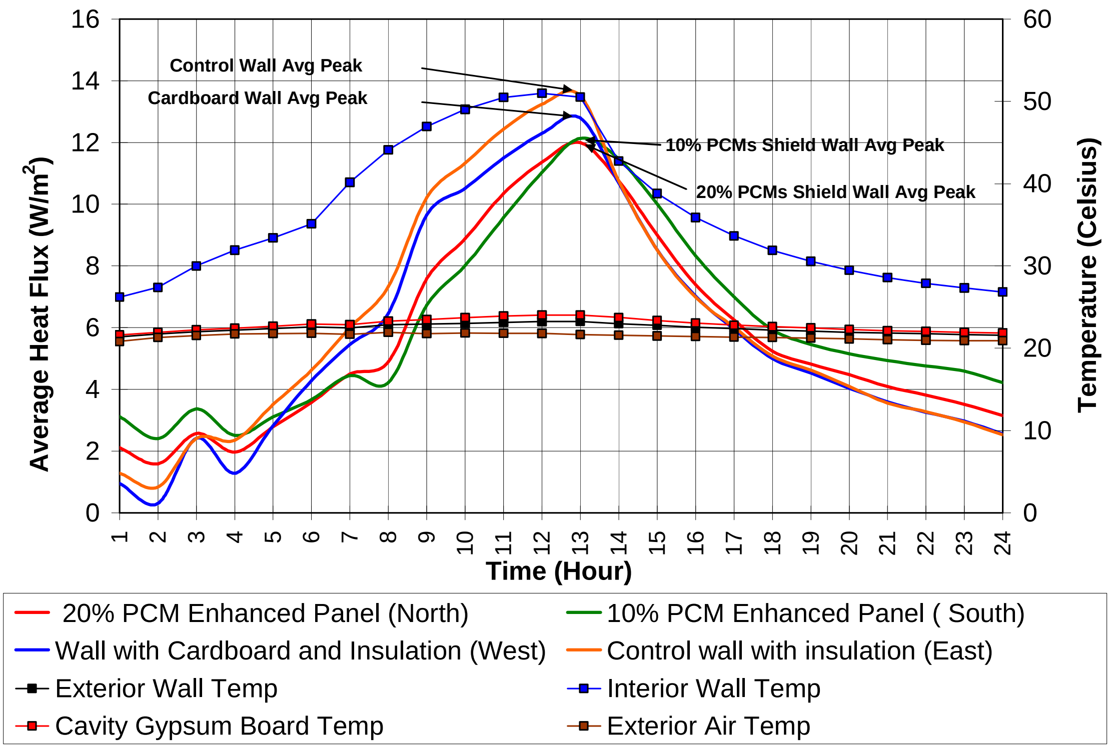


Figure 4.4.3. Peak heat fluxes with their coincident interior and exterior wall temperature profiles (Series 2, Test 1)

The figure shows how the PCM-shielded walls performed with the change of temperatures over time. Both walls outfitted with shields at concentrations of 10% and 20% had their peak heat transfer delayed by approximately 15 minutes. The percentages of wall peak heat flux reductions are shown in Figure 4.4.4.

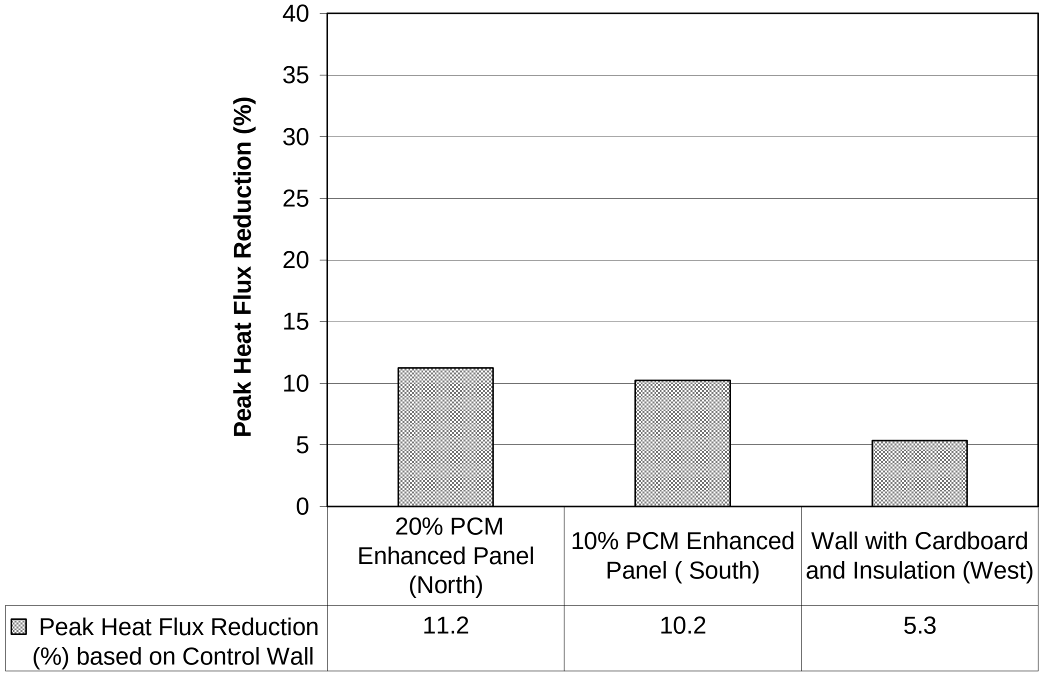
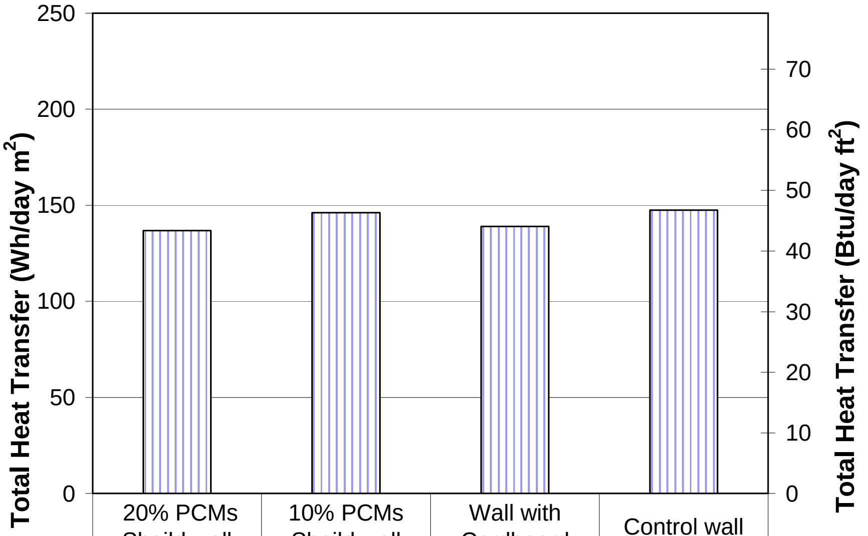


Figure 4.4.4. Percentages of peak heat flux reduction of walls (Series 2, Test 1)

According to the data the 20% PCM-shielded wall reduced the heat flux by approximately 11.20% and the 10% PCM shielded wall produced a reduction in peak heat flux of approximately 10.20%. The wall outfitted with cardboard and insulation showed a reduction in peak heat flux of about 5.30%. This means that by adding PCMs at a concentration of 10% to the cardboard, it could produce a decrease in peak heat flux of about 4.90% and adding PCMs at a concentration of 20% to the cardboard could produce a decrease in peak heat flux of about 5.90% when the temperature range of the walls was between 25ºC to 52ºC (77 ºF to125ºF). The total heat transfer for each wall over a 24-hour period is shown in Figure 4.4.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	136.69	146.16	138.88	147.48
Total Heat Transfer for 24 Hours (Btu/hr ft2)	43.33	46.33	44.03	46.75

Figure 4.4.5. Total heat transfer for each wall over a 24-hour period (Series 2, Test 1)

During this period the wall outfitted with the 20% PCMs shield (north) transferred about 136.69 W/m^2 (43.33 Btu/hr ft^2) of total heat. The wall outfitted with the 10% PCMs shield (south) transferred about 146.16 W/m^2 (46.33 Btu/hr ft^2) of total heat.

This test concluded that the high concentration PCM shield did not necessarily outperformed the low concentration PCM shield for a temperature range of 25ºC to 52ºC (77ºF to 125ºF) when the PCM shields were placed between two insulation layers and located in the middle section of the wall cavity .

4.5 Test No. 2

Similarly, a second test was executed in this test series with different temperature range. In the second test of this series the temperature of the walls varied from 25ºC to 60ºC (77ºF to 140 ºF). This is similar to the second test of the first series except for the placement of the PCM shield. The average surface temperature profiles of all the walls are shown in Figure 4.5.1. The graph also includes four air temperatures as indicated.

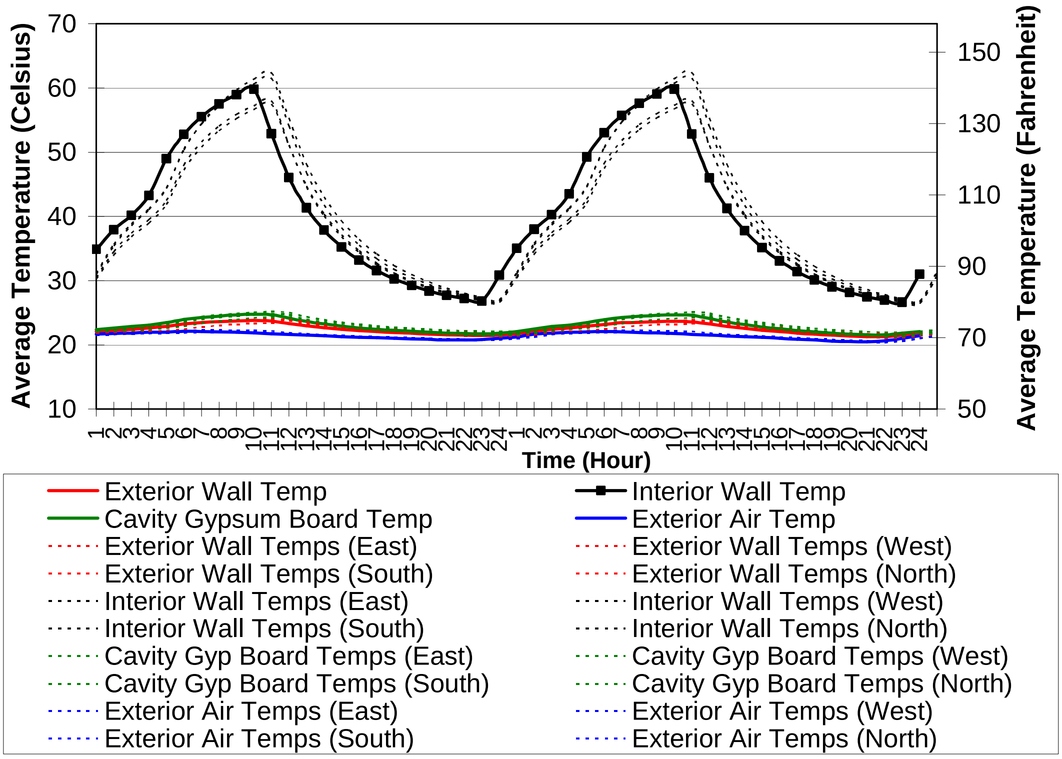


Figure 4.5.1. Average surface temperature profiles of all the walls (Series 2, Test 2).

These profiles simulate the manner in which the exterior temperatures of a building would vary throughout a typical day when the average maximum exterior surface temperature would reach about 60ºC (140ºF). As expected, the exterior air temperatures and the internal surface temperature of the wallboard were closer. Because of the higher temperatures and the placement of the PCM shield, it was expected that the walls would store relatively higher amounts of heat during the phase change of the PCMs. Therefore, the exterior wall surface temperatures were comparatively higher than the exterior air temperatures. The average hourly wall heat fluxes over a 24-hour test period are shown in Figure 4.5.2.

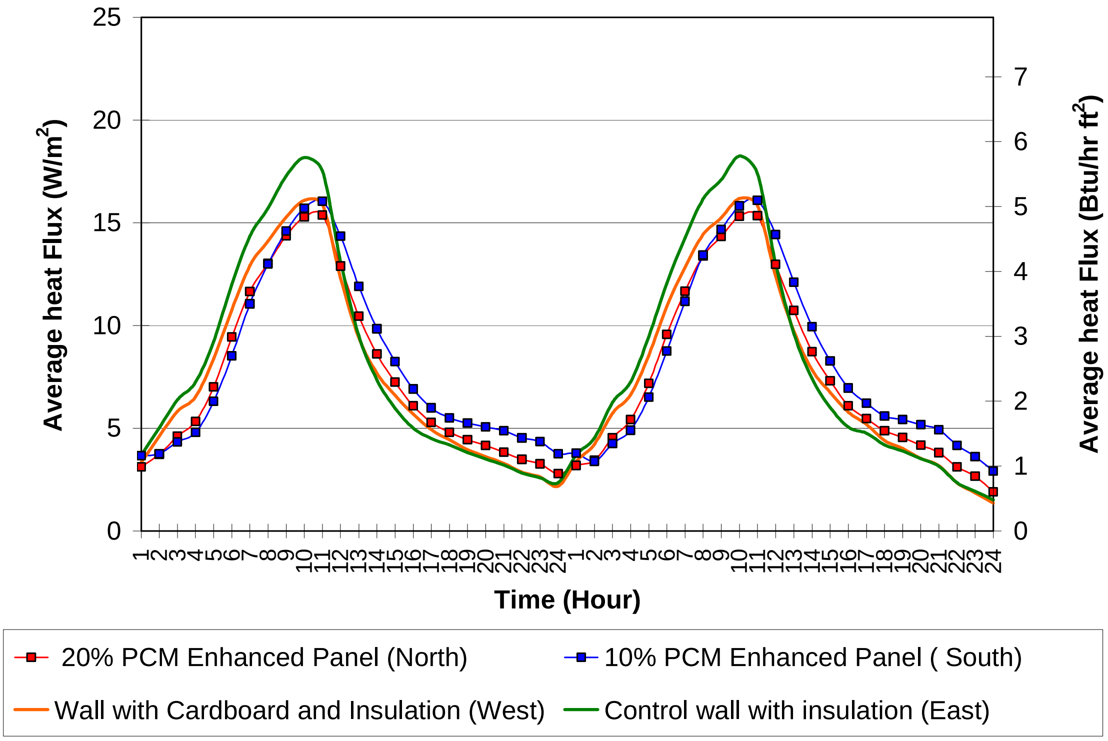


Figure 4.5.2. Average wall heat fluxes (Series 2, Test 2)

The data show that the peak heat flux across the control wall was 18.24 W/m^2 (5.78 Btu/hr ft^2). The peak heat flux for the wall outfitted with the10% PCM shield wall was 16.09 W/m^2 (5.10 Btu/hr ft^2) and the peak heat flux for the wall outfitted with the 20% PCM shield was 15.34 W/m^2 (4.60 Btu/hr ft^2). Table 4.2 shows the peak heat fluxes, reduction, and the total heat transferred across each wall for Test 2 in this series. In this test both the wall with the 10% PCMs shield and the wall with the 20% PCMs shield reduced heat fluxes during the heating period of each cycle. Although it seemed to have stored less heat energy to generate the phase change process. The reason for this may be related to the placement of the PCM shield. The PCM shield was placed between the two insulation layers of wall cavity. Therefore, it prevented the PCMs shields to absorb sufficient heat to generate the phase change. In Figure 4.5.3, the average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures.

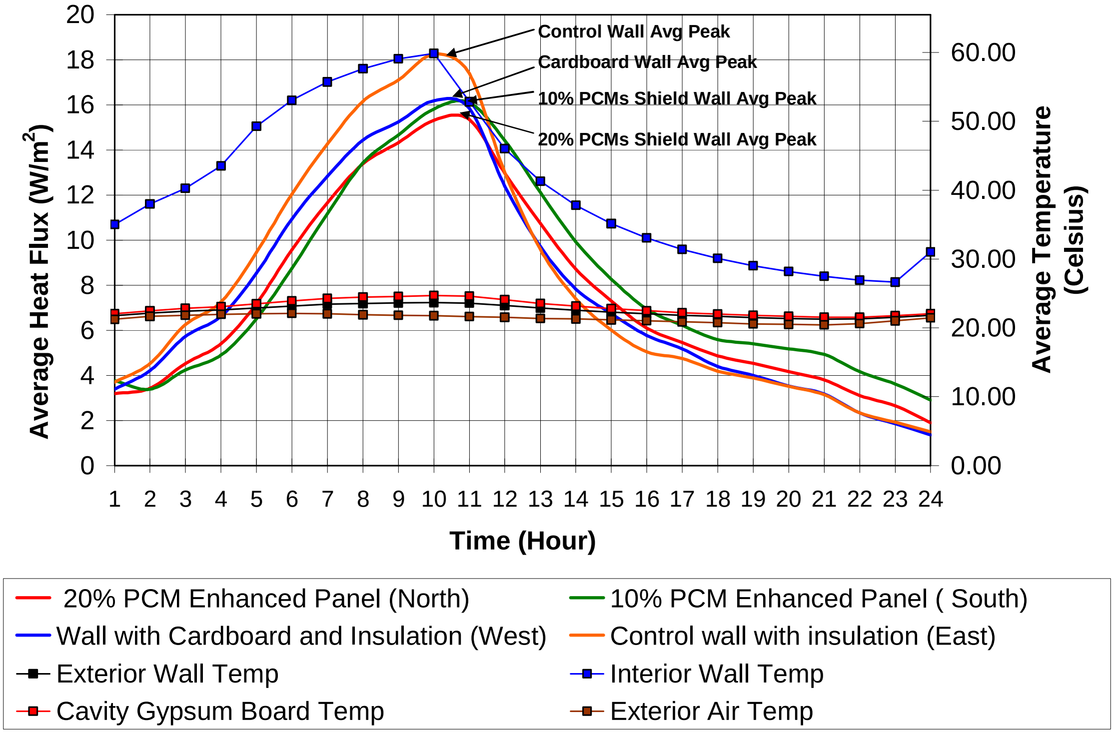


Figure 4.5.3. Peak heat fluxes with their coincident interior and exterior wall temperature profiles (Series 2, Test 2)

The figure shows how the PCM shielded walls performed as a function of their change of temperatures over time. Both the 10% PCMs shielded wall and the 20% PCMs shielded wall showed a delay in their peak heat fluxes of approximately 35 minutes. Unlike Test 2 in Series 1, in this test both walls with 10% and 20% PCM shields seemed to delay more their peak heat fluxes. The reason for this delay relates to the phase change process of the PCMs and the placements of the PCM shields inside the wall cavity. During the heating period some heat energy was used to melt the PCMs, which resulted in an interruption in the transfer of the heat across the wall from the hotter side to the colder side of the wall during the heating period. It made the PCM-shield walls delay their peak heat flux. The percentages of peak heat flux reductions are shown in Figure 4.5.4.

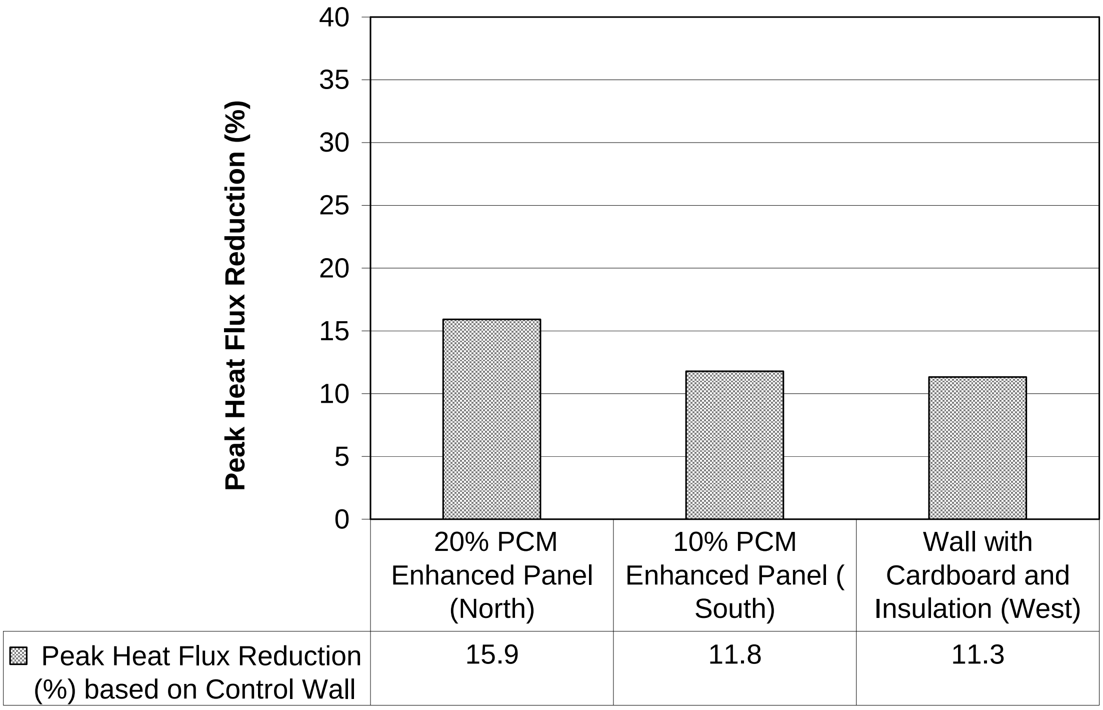
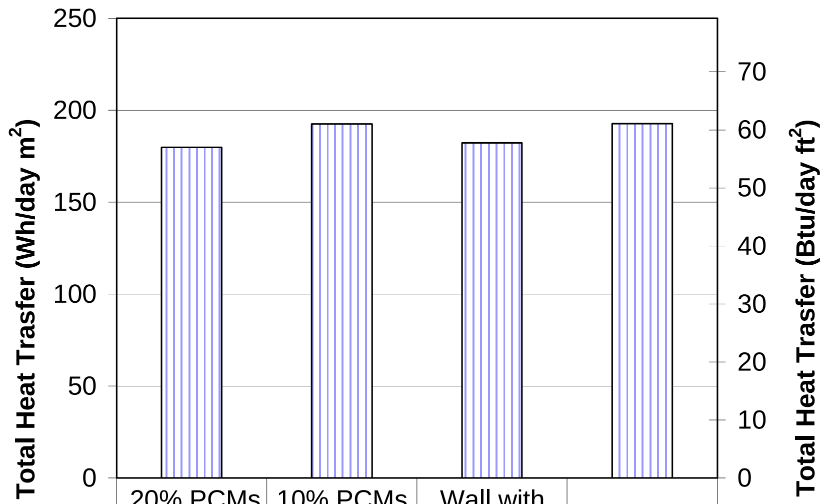


Figure 4.5.4. Percentages of peak flux reduction of walls (Series 2, Test 2)

According to the data the wall with the 20% PCMs shield wall reduced peak heat flux of approximately 15.90%, while the wall with the10% PCMs shield wall reduced the peak heat flux of approximately 11.80%. The wall outfitted with the cardboard reduced peak heat flux of about 11.30%. This means that by adding PCMs at a concentration of 10% the peak heat flux could be decreased by 0.5% when the temperature range was 25ºC to60ºC (77ºF to 140 ºF). Similarly, adding PCMs at a concentration of 20% could reduce the peak heat flux by 4.6% at the temperature range of 25ºC to 60ºC (77ºF to 140 ºF). The total heat transfer for each wall over a 24-hour period is shown in Figure 4.5.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	179.71	192.47	182.27	192.74
Total Heat Transfer for 24 Hours (Btu/hr ft2)	56.97	61.01	57.78	61.10

Figure 4.5.5. Total heat transfer for each wall over 24 hours period (Series 2, Test 2)

In this period of time the wall outfitted with the 20% PCMs shield transferred about 179.71 W/m^2 (56.97 $Btu/hr.ft^2$) of total heat. The wall outfitted with the10% PCMs shield transferred about 192.47 W/m^2 (61.01 $Btu/hr\ ft^2$) of total heat.

This test concluded that the location of the shield is not as effective as the Series 1 location in terms of reducing peak heat flux, at the temperature range of 25ºC to 60ºC (77ºF to 140 ºF). At this temperature range the wall outfitted with 10% PCM shield reduced only about 16.94% the peak heat flux at Series 1 location and it reduced about 11.8% the peak heat flux as Series 2 location. Similarly, at this temperature range the wall outfitted with the 20% PCM shield reduced the peak heat flux about 25.07% in Series 1 location and it reduced about 15.9% in Series 2 location.

4.6 Test No. 3

The third test of this test series was executed with a temperature range of 25ºC to 65ºC (77ºF to 149ºF). The maximum temperature of the walls was approximately 65ºC (149ºF) during the peak time. The average (over time) temperature of the walls was approximately 40ºC (104ºF). This test is similar to the third test of the first series except the placement of the PCM shield. The average surface temperature profiles of all the walls are shown in Figure 4.6.1. The graph also includes four air temperatures as indicated.

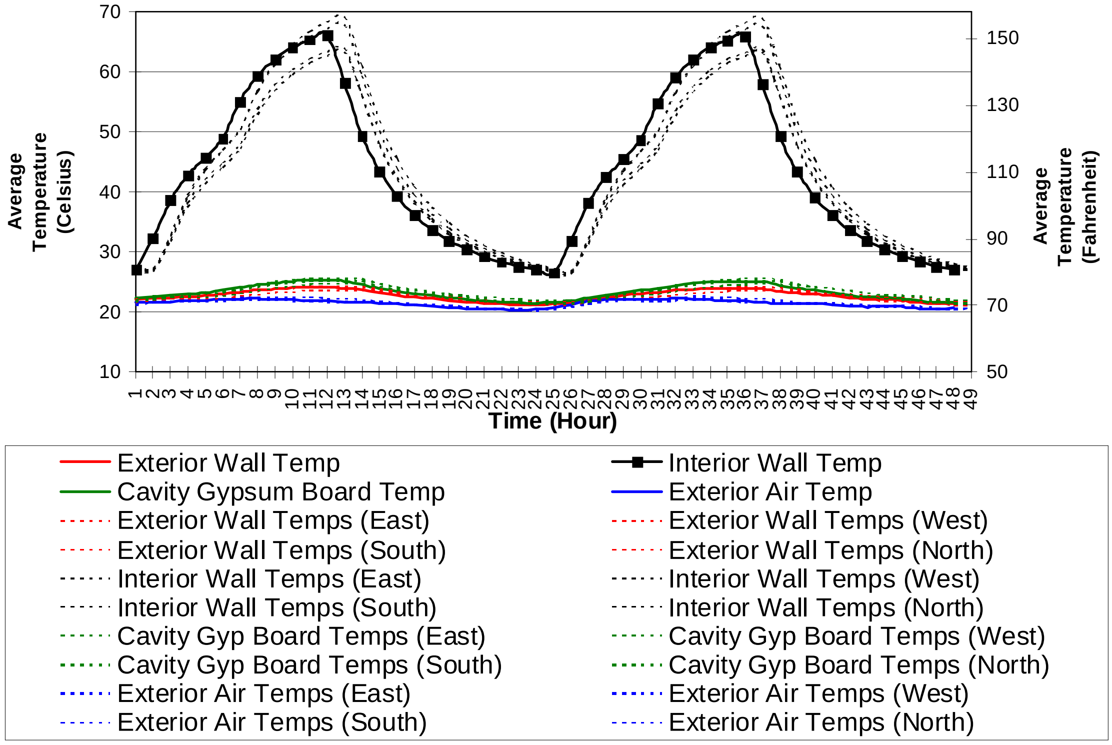


Figure 4.6.1. Average surface temperature profiles of all the walls (Series 2, Test 3)

The average hourly heat fluxes over a 24-hour test period in Figure 4.6.2.

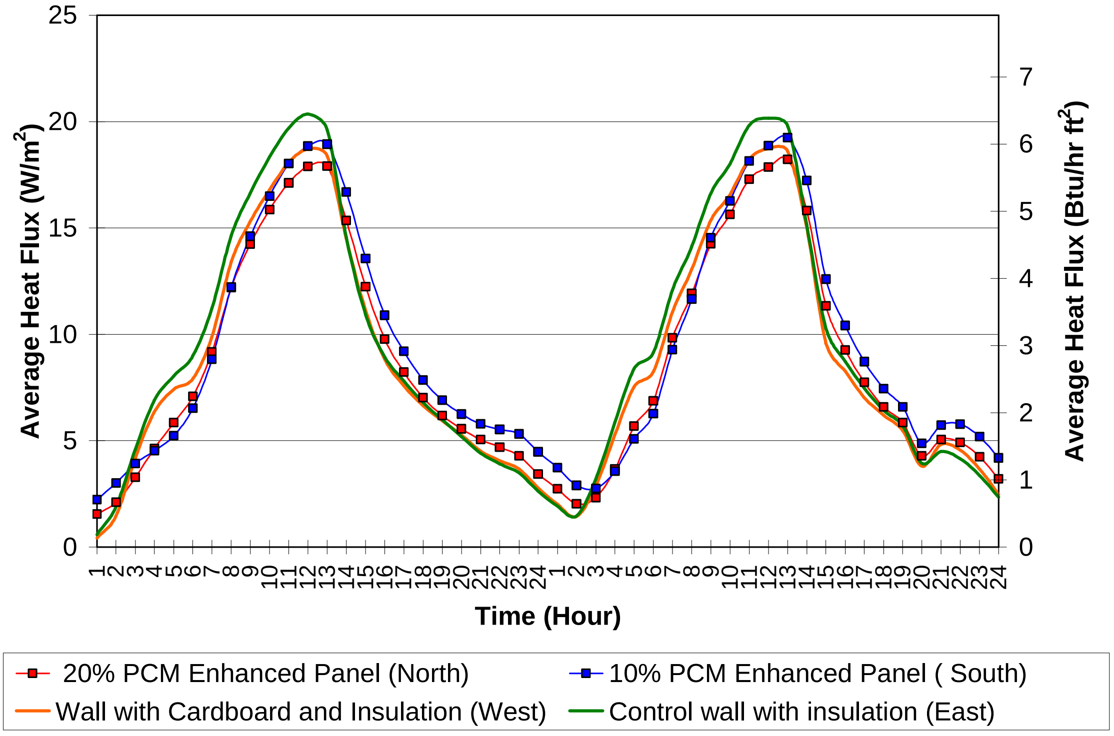


Figure 4.6.2. Average wall heat fluxes (Series 2, Test 3)

The data show that the control peak heat flux was 20.15 W/m^2 (6.38 Btu/hr ft^2). The maximum peak heat flux for the wall outfitted with the PCM shield holding a concentration of 10% PCMs was 19.23 W/m^2 (6.09 Btu/hr ft^2). For the wall outfitted with the thermally-enhanced shield holding a concentration of 20% PCM the peak heat flux was 18.21 W/m^2 (5.77 Btu/hr ft^2). Table 4.2 shows the heat fluxes, reduction and total heat transferred across each wall for Test 3 in this series. It was observed that in this test both PCM shielded walls differed their peak heat fluxes as much as they did in the Test 3 in Series 1 for the same temperature range 40ºC to 65ºC (104ºF to 149 ºF). The reason for this is related to the placement of the PCM shield. Since, both of the PCM shielded walls absorbed small amount heat energy during the heating period it was to be expected that both PCM shielded walls would release less stored heat energy while solidifying during the cool down period. Therefore, the profiles of both PCM shielded walls are showing less heat released during the cool down period. In Figure 4.6.3, the average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures.

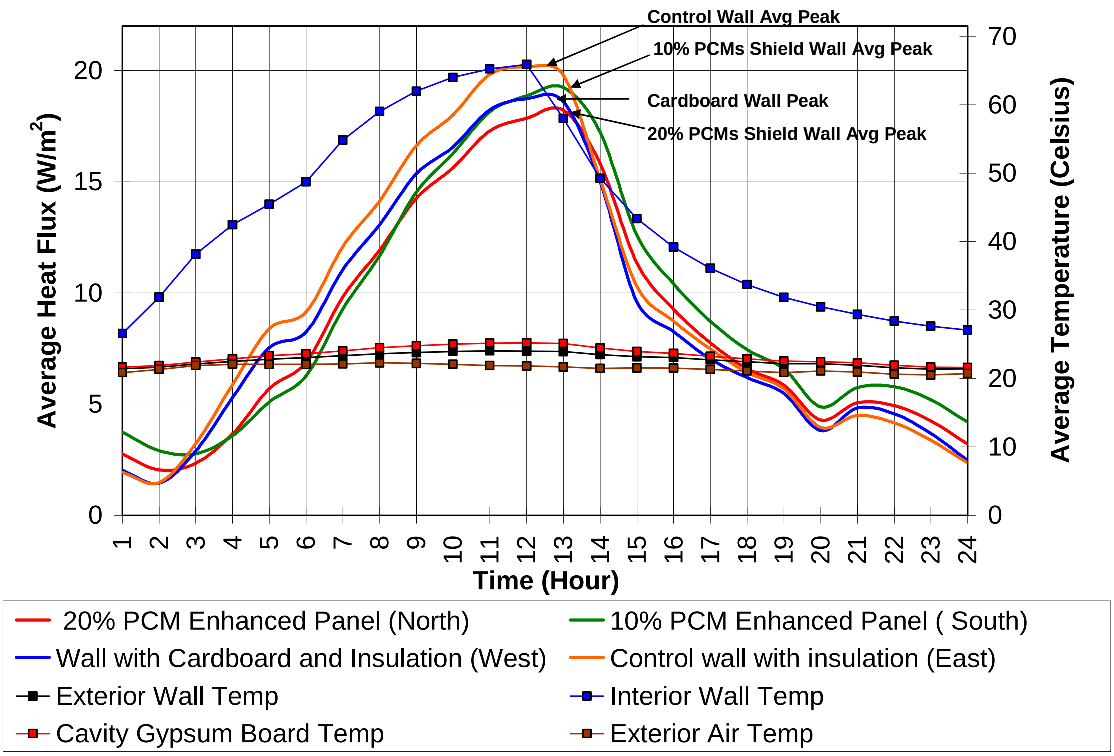


Figure 4.6.3. Peak heat fluxes with their coincident interior and exterior wall temperature profiles (Series 2, Test 3)

In this test, the time delay in the peak heat fluxes was about 45 minutes for the 10% PCM shield wall and for the for the 20% PCM shield walls. Unlike Test 3 in Series 1, in this test both walls with 10% and 20% PCM shields seemed to delay more in their peak heat fluxes. The percentages of peak heat flux reductions are shown in Figure 4.6.4.

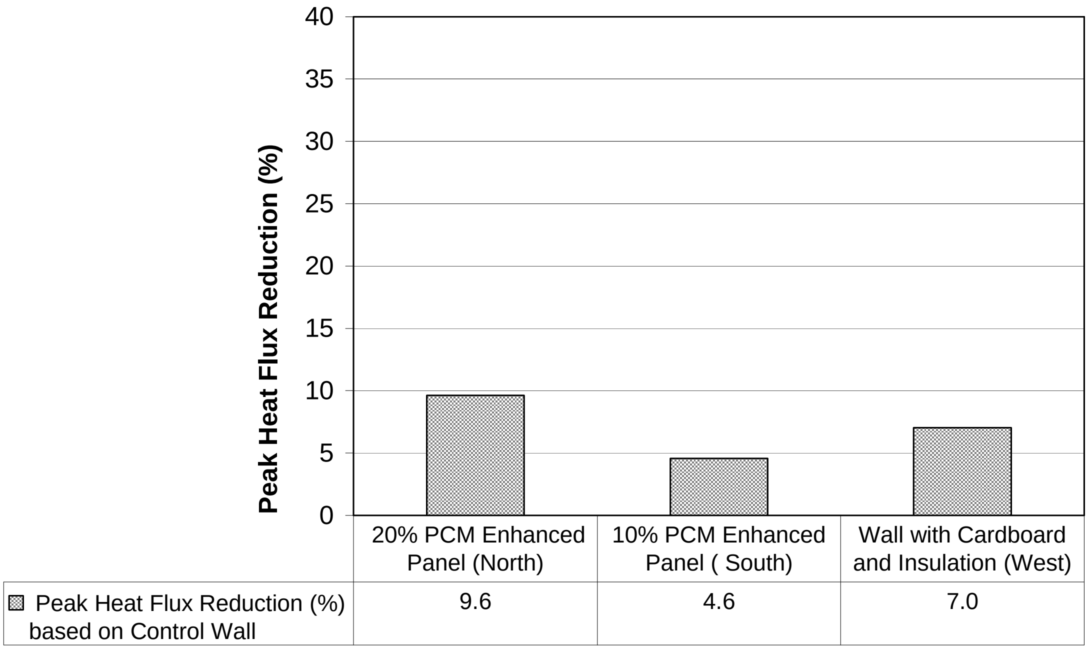
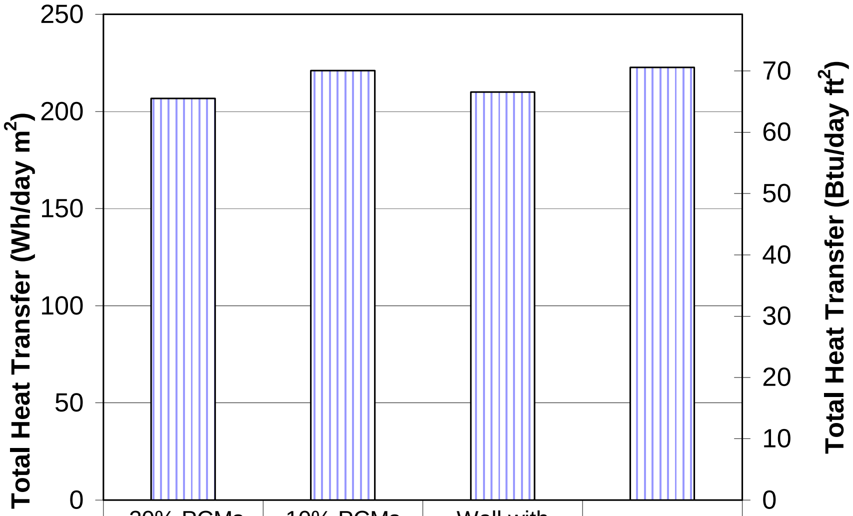


Figure 4.6.4. Percentages of peak heat flux reduction of walls (Series 2, Test 3)

From the data, it was observed that the 20% PCM shield wall had a reduced peak heat flux of approximately 9.60%. The 10% PCMs shield wall had a reduced peak heat flux of approximately 4.60%. The wall outfitted with only the cardboard had its peak heat flux reduced by about 7%. This means that at Series 2 location for the temperature range of 25ºC - 65ºC (77ºF - 149 ºF) the wall outfitted with only the cardboard could decrease its peak heat flux more than the wall outfitted with 10% PCM shield. This concludes that the 10% PCM shield wall was not able to decrease heat flux. The total heat transfer for each wall over a 24-hour period is shown in Figure 4.6.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	206.63	221.07	209.86	222.62
Total Heat Transfer for 24 Hours (Btu/hr ft2)	65.50	70.08	66.52	70.57

Figure 4.6.5. Total heat transfer for each wall over 24 hours period (Series 2, Test 3)

In this period of time the wall outfitted with the 20% PCMs shield wall transferred about 206 W/m^2 (65.50 Btu/hr.ft^2) of total heat. The wall outfitted with the 10% PCMs shield wall transferred about 221.07 W/m^2 (70.08 Btu/hr ft^2) of total heat.

In summary, it was observed that PCM-enhanced thermal shields, when integrated in walls at Series 2 location (PCM thermal shields were located in between two insulation layers, which were located in the middle section of the wall cavity) would tend to produce lower heat flux reductions at lower maximum surface temperature, which would decrease with increasing interior surface temperature.

Test Series 3: PCMs Shield Placed Towards the Interior side of the wall cavity.

Similar to first and second test series, a three day test was performed in the third test series. In this test series PCM thermal shields were located towards the interior side of the wall cavity. Figure 4.7.0 shows the PCM shield placement inside the wall cavity for the third test series.

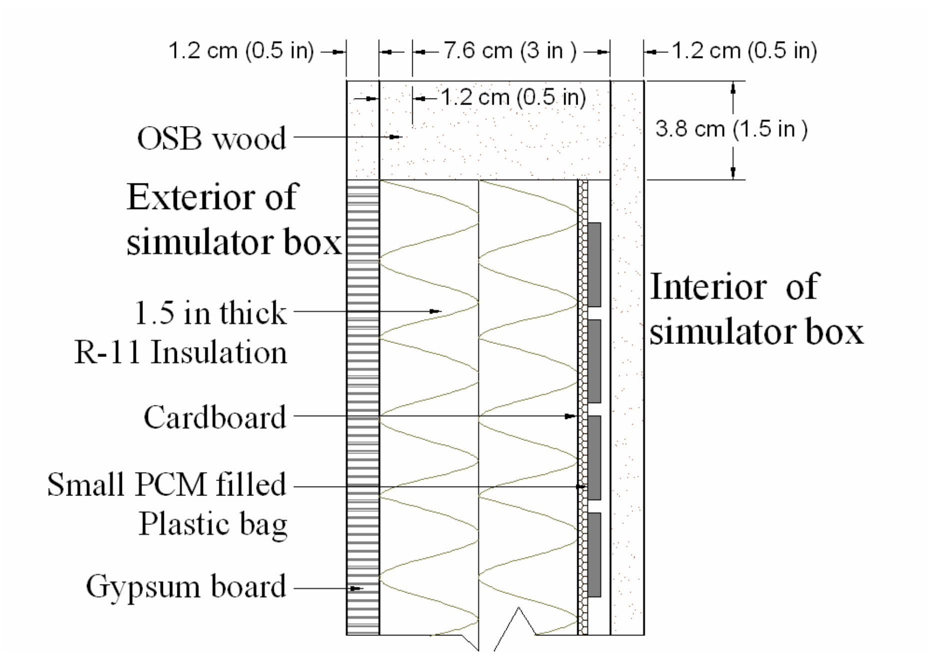


Figure 4.7.0. PCM arrangement inside the wall cavity for the third series of tests

Three individual tests in this test series were set into three different temperature ranges. The results of three individual tests in this test series are shown in Tables 4.3 a, b, and c.

Table 4.3.a. Peak Heat Fluxes for Test Series 3

			Peak Heat Flux							
Test no.	Max Temperature		Control Wall		Cardboard Wall		10% PCM Shield Wall		20% PCM shield Wall	
	˚C	˚F	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2	W/m^2	Btu/hr ft^2
4.7 Test No. 1	52	125	12.89	4.06	12.54	3.97	12.82	4.00	11.75	3.72
4.8 Test No. 2	60	140	15..02	4.82	14.58	4.62	14.90	4.72	13.69	4.34
4.9 Test No. 3	65	149	22.12	7.01	20.94	6.64	21.14	6.70	19.84	6.29

Table 4.3.b. Percent Peak Heat Flux Reductions for Test Series 3

			% Peak Heat Flux Reduction		
Test no.	Max Temperature		Cardboard Wall	10% PCM Shield Wall	20% PCM Shield Wall
	˚C	˚F	%	%	%
4.7 Test No. 1	52	125	2.30	0.20	8.50
4.8 Test No. 2	60	140	4.10	2.00	10.00
4.9 Test No. 3	65	149	6.40	5.70	11.10

Table 4.3.c. Total Heat Transfer for Test Series 3

			Total Heat Transfer							
Test no.	Max Temperature		Control Wall		Cardboard Wall		10% PCM Shield Wall		20% PCM Shield Wall	
	˚C	˚F	Wh/day m^2	Btu/day ft^2	Wh/day m^2	Btu/day ft^2	Wh/daym^2	Btu/day ft^2	Wh/daym^2	Btu/day ft^2
4.7 Test No. 1	52	125	127.46	40.40	123.20	39.05	131.43	41.66	119.03	37.73
4.8 Test No. 2	60	140	153.35	48.61	147.07	46.62	154.95	49.12	143.10	45.36
4.9 Test No. 3	65	149	227.36	72.07	216.72	68.70	228.44	72.42	211.66	67.10

4.7 Test No. 1

Similar to the first tests in Series 1 and 2, the first test of this series was performed at a temperature range of 25ºC to 52ºC (77ºF to 125ºF). This means the maximum temperature of the walls was approximately 52ºC (125ºF) while the average temperature of the walls was approximately 40°C (104°F). The Average surface temperature profiles of all the walls are shown in Figure 4.7.1. The graph also includes four air temperatures as indicated.

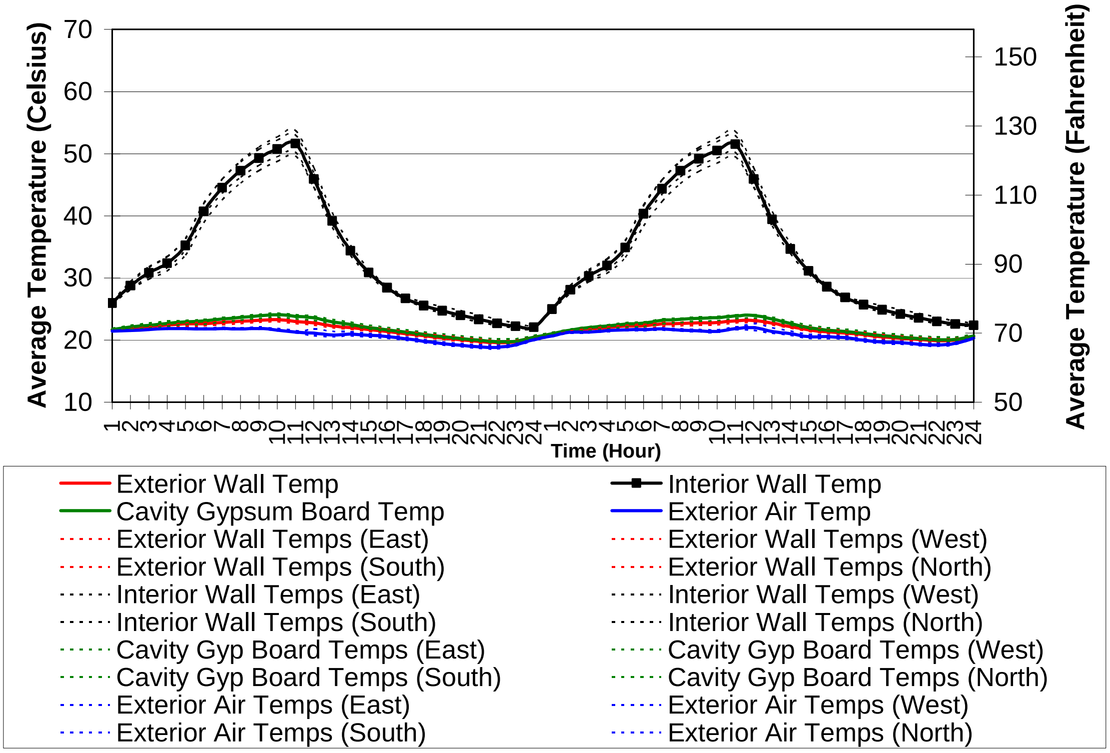


Figure 4.7.1. The average surface temperature profiles of all the walls (Series 3, Test 1)

Similar to the tests in Series 2, the interior surface temperatures were higher than the rest of the interior and exterior surface temperatures in each wall. The average hourly wall heat fluxes over 24-hour test period are shown in Figure 4.7.2.

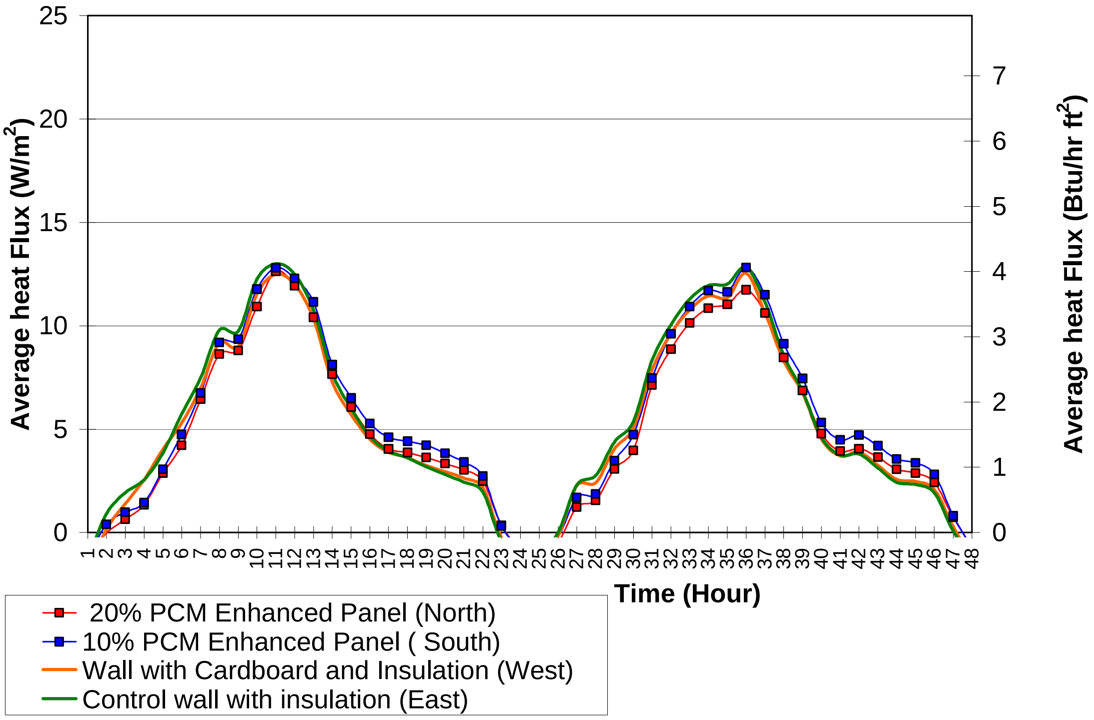


Figure 4.7.2. Average wall heat fluxes (Series 3, Test 1)

The graph shows that the control peak heat flux for the control wall was 12.89 W/m^2 (4.06 Btu/hr ft^2). The maximum peak heat flux for the wall outfitted with 10% PCM shield was 12.82 W/m^2 (4.00 Btu/hr ft^2) and the maximum heat flux for the wall outfitted with 20% PCM shield was 11.75 W/m^2 (3.72 Btu/hr ft^2). Table 4.3 shows the peak heat fluxes, reduction, and the total heat transferred across the wall for Test 1 in this series. The control wall outfitted with the cardboard and insulation seemed to have higher heat flux reduction than the wall outfitted with 10% PCM shield. Unlike the first tests in Series 1 and 2, in this test both walls outfitted with 10% and 20 % PCM shield respectively released almost the same amount of heat during the cool down period. Both walls had almost the same peaks. In this test series the PCM shields were placed towards the interior side of the wall cavity.

Each test in this research was actually performed four to six days in order to attain the most two consistent consecutive cycles to study. In order to collect the two most consistent data for this test, only third and fourth cycles were selected to study. While Test 1 in Series 3 was being performed, in the first two cycles, the PCM would not solidify completely. This happened because the PCM shields faced the interior of the simulation box, which was closer to the heat source and the other side of the PCM shields faced to the two layers of insulations inside the wall cavity. This prevented the heat from releasing to the exterior of the simulation box during the cool down period after the first two initial cycles in this test. As a result all melted PCMs stayed liquid after the first 24-hours cycle. Therefore, little heat flux was reduced by the walls outfitted with 10% and 20% PCM shield. Figure 4.7.3, the average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures.

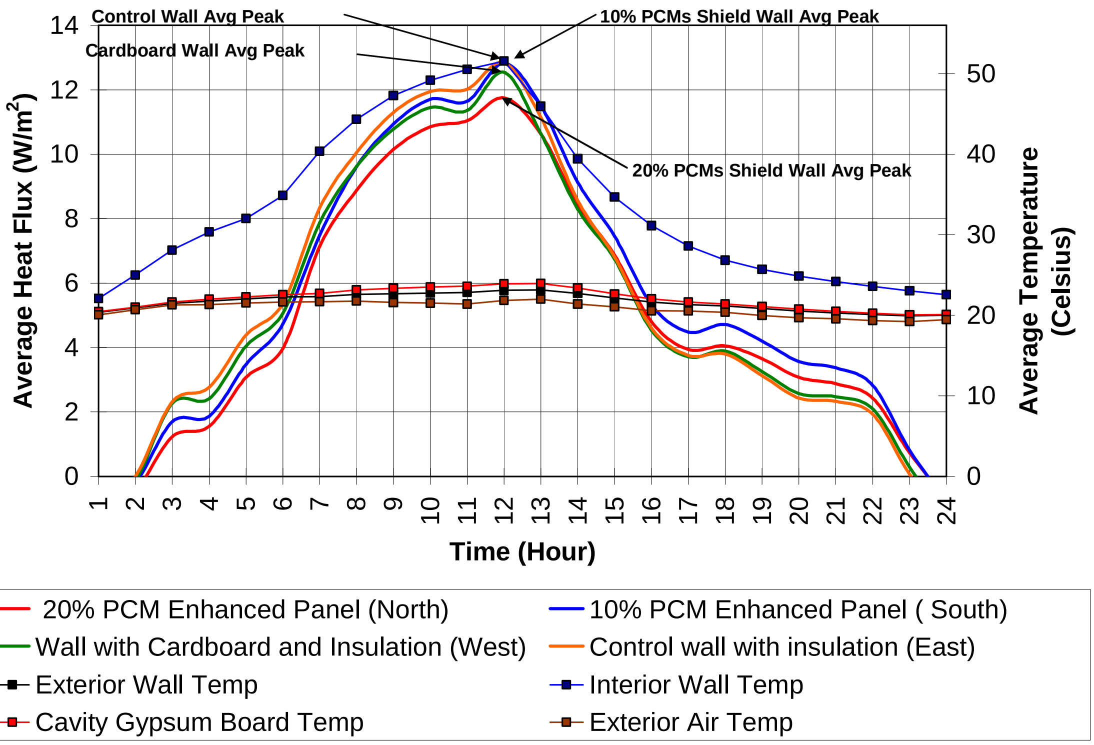


Figure 4.7.3. Average peak fluxes are indicated with their coincident interior and exterior wall temperatures (Series 3, Test 1)

In this test, there was no time delay in the peak heat fluxes for the 10%-PCM shield wall and for the 20%-PCM shield wall. These data confirm that after the first two initial cycles in this test, all the PCM was not able to change phase and complete its solid to liquid cycle during the heating period and vise versa during the cool down period. The percentages of peak heat transfer rate reductions are shown in Figure 4.7.4.

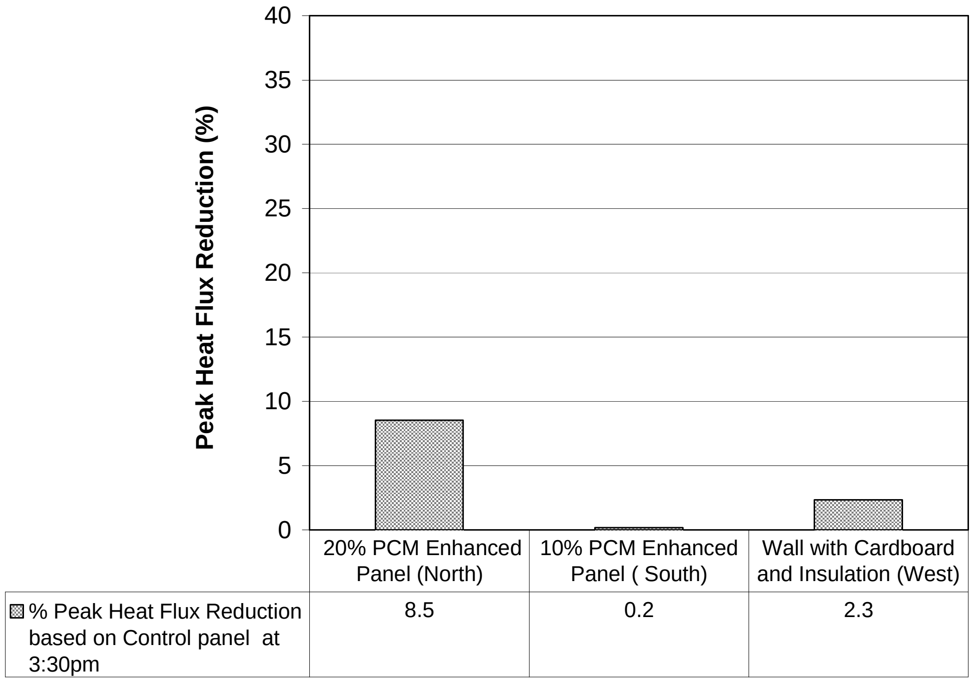
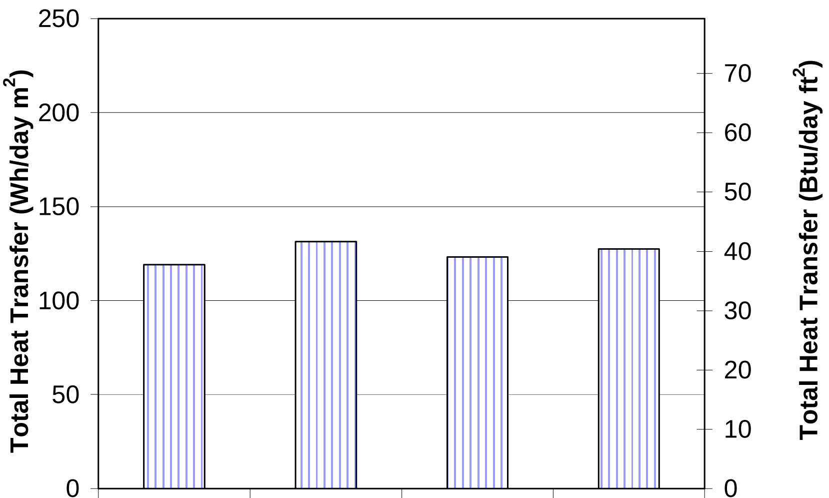


Figure 4.7.4. Percentages of peak heat flux reduction of walls (Series 3, Test 1)

According to the graph, the wall outfitted with 20% PCM shield reduced approximately 8.5% peak heat flux and the wall outfitted with 10% PCM shield reduced approximately 0.2% peak heat flux of the control wall. The control wall outfitted with cardboard and insulation had its peak heat flux reduced by about 2.3%. This means that at Series 3 location for the temperature range of 40ºC to 52ºC (104ºF to 125 ºF) the wall outfitted with only the cardboard could decrease its peak heat flux more than the wall outfitted with 10% PCM shield. This concludes that the both 10% and 20% PCM shield wall were not able to decrease heat flux as significantly as the first two tests of Series 1 and Series 2 location for lower temperature range. The total heat transfer for each wall over a 24-hour period is shown in Figure 4.7.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	119.03	131.43	123.20	127.46
Total Heat Transfer for 24 Hours (Btu/day ft2)	37.73	41.66	39.05	40.40

Figure 4.7.5. Total heat transfer for each wall over 24-hours period (Series 3, Test 1)

During this period the wall outfitted with the 20% PCM shielded transferred about 119.03 W/m^2 (37.73 Btu/hr ft^2) of total heat. The wall outfitted with the 10% PCM shield transferred about 131.43 W/m^2 (41.66 Btu/hr ft^2) of total heat. These reductions were not very significant compared to the control walls.

This test concluded that the PCM shield placement in this series for lower temperature range of 25 ºC to 52ºC (77ºF to 125 ºF) was not effective in terms of reducing peak heat flux and generating phase change process into the walls which were outfitted with PCM shield.

4.8 Test No. 2

Similarly to the second tests of Series 1 and Series 2 , second test of this series were performed in the temperature range of 25ºC to 60ºC (77ºF to 140 ºF). The average surface temperature profiles of all the walls are shown in Figure 4.8.1. The graph also includes four air temperatures as indicated.

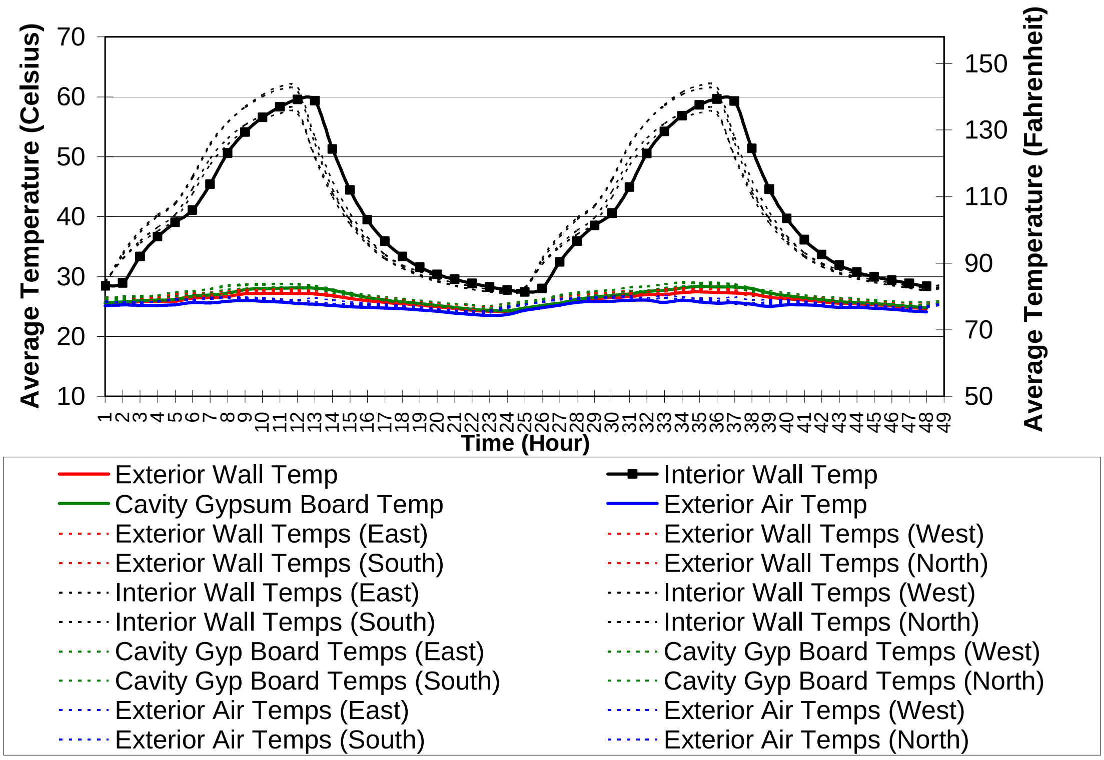


Figure 4.8.1. Average surface temperature profiles of all the walls (Series 3, Test 2)

Similar to the previous test the interior surface temperatures were higher than the rest of the surface temperatures in each wall. The average hourly wall heat fluxes over a 24-hour test period are shown in Figure 4.8.2.

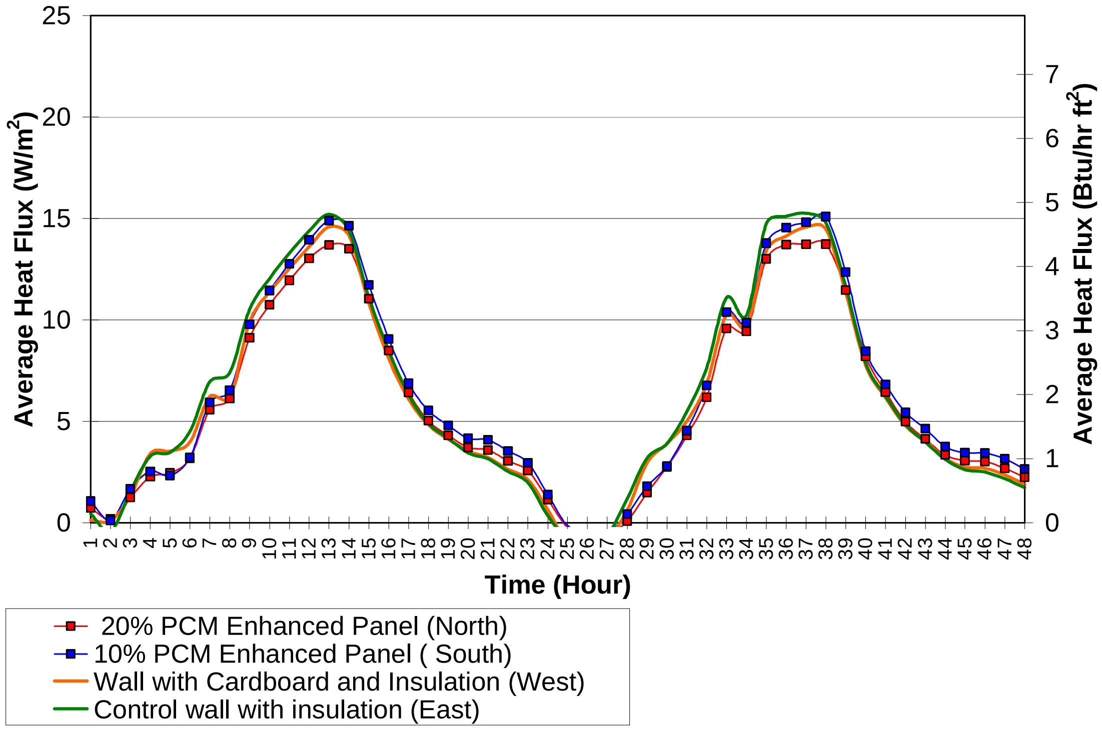


Figure 4.8.2. Average wall heat fluxes (Series 3, Test 2)

The control peak heat flux was 15.2 W/m^2 (4.83 Btu/hr ft^2). The maximum peak heat flux for the wall outfitted with the 10% PCM shield was 14.9 W/m^2 (4.72 Btu/hr ft^2) and the maximum peak heat flux for the wall outfitted with the 20% PCM shield was 13.69 W/m^2 (4.34 Btu/hr ft^2). Table 4.3 shows the peak heat fluxes, reduction, and the total heat transferred across each wall for Test 2 in this series. The control wall outfitted with cardboard and insulation seemed to have higher heat flux reduction than the wall outfitted with 10% PCM shield. Unlike the Test 1 in Series 3, the maximum peak heat flux of PCM-shield walls differed in this test because of the higher temperature range. In Figure 4.8.3, the average peaks heat fluxes are indicated with their coincident interior and exterior temperature profiles.

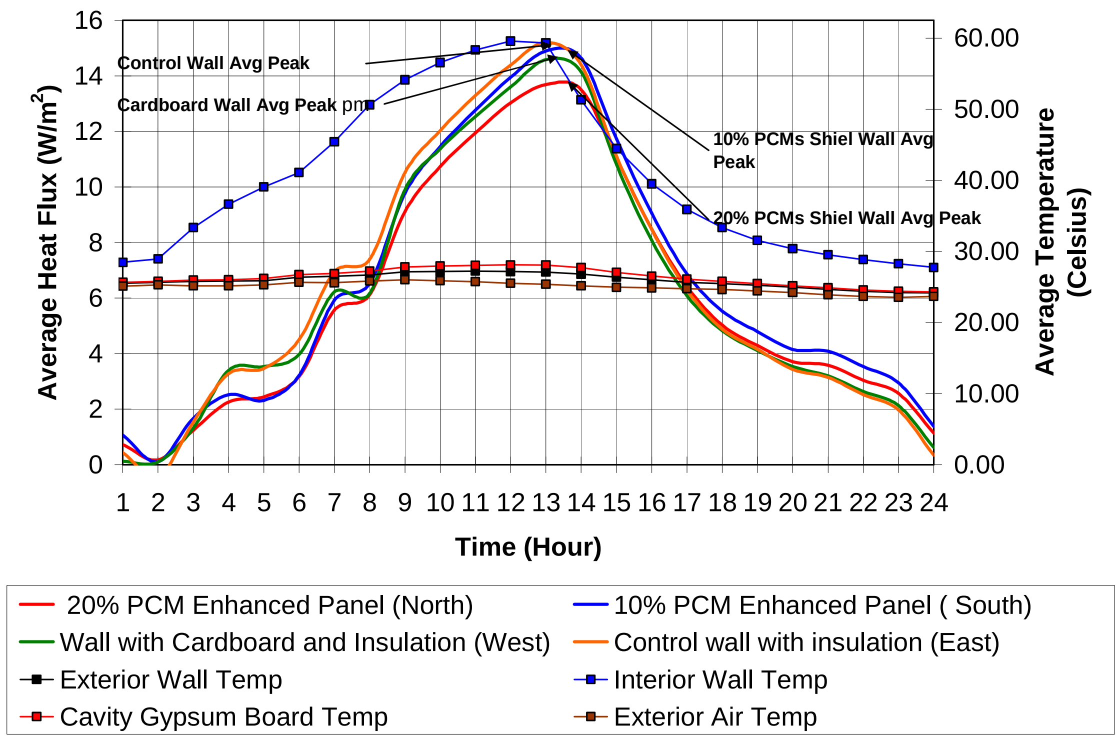
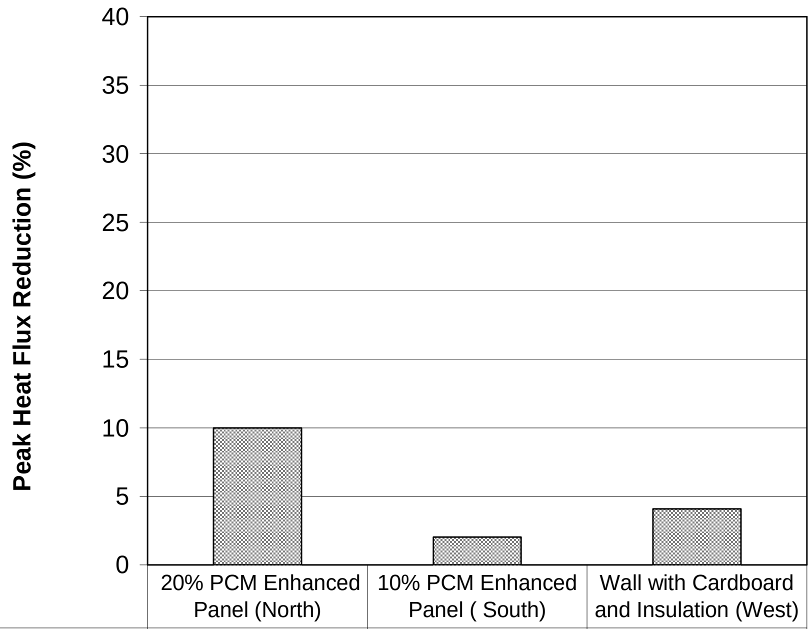


Figure 4.8.3. Average peak heat fluxes are indicated with their coincident interior and exterior wall temperatures (Series 3, Test 2)

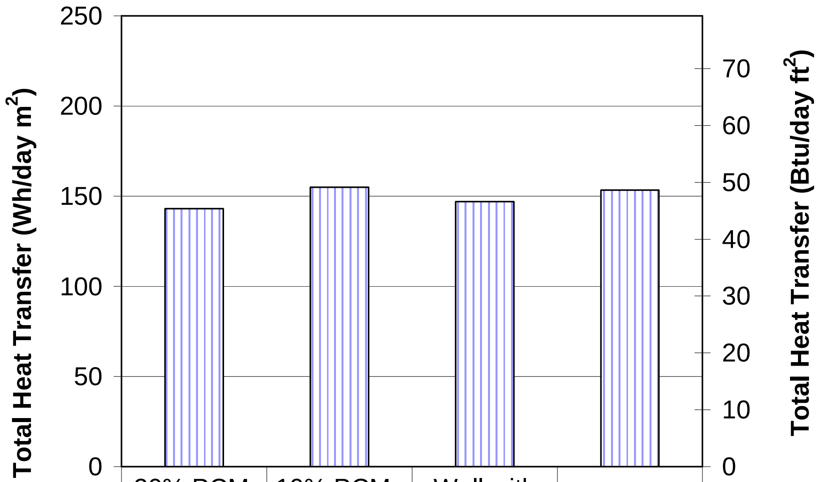
The figure shows how the PCM-shield walls performed as a function of their change of temperatures over time. The 10% PCM-Shielded wall seemed to have delayed its peak about 15 minutes and the 20% PCM-shielded wall delayed its peak approximately 35 minutes towards the cooling down period. The reason of this delay is the higher temperature range used in this test compared to Test 1 in this Series 3 location, where it was observed that there is not delay in peak heat flux for PCM-shield wall. During the heating period some heat energy was used to melt the PCMs, which resulted in an interruption in the motion of the heat across the wall from the hotter side to the colder side of the wall during the heating period. Thus the delay occurred in this test. The percentages of peak heat flux reductions are shown in Figure 4.8.4.



	20% PCM Enhanced Panel (North)	10% PCM Enhanced Panel (South)	Wall with Cardboard and Insulation (West)
Peak Heat Flux Reduction (%) based on Control Wall	10.0	2.0	4.1

Figure 4.8.4. Percentage of peak heat flux reduction of walls (Series 3, Test 2)

According to the data the wall with the 20% PCM shield reduced peak heat flux approximately 10% and the wall with the 10% PCM Shield reduced peak heat flux approximately 2%. The wall outfitted with the cardboard only had a higher peak heat flux reduction that the wall with the 10% PCM shield, which is about 4.1%. This means that at Series 3 location for the temperature range of 25ºC to 60ºC (77ºF to 140 ºF) the wall outfitted with only the cardboard could decrease its peak heat flux more than the wall outfitted with 10% PCM shield. This concludes that the both 10% and 20% PCM shield wall were not able to decrease heat flux as significantly as the second two tests of Series 1 and Series 2 location at this temperature range. The total heat transfer for each wall over a 24-hour period is shown in Figure 4.8.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	143.10	154.95	147.07	153.35
Total Heat Transfer for 24 Hours (Btu/day ft2)	45.36	49.12	46.62	48.61

Figure 4.8.5. The total heat transfer for each wall over a 24-hours period (Series 3, Test 2)

In this period of time the wall outfitted with the 20% PCM shield transferred about 143.10 W/m^2 (45.36 Btu/hr ft^2) of total heat. The wall outfitted with the 10% PCM shield transferred about 154.95 W/m^2 (49.12Btu/hr ft^2) of total heat. These reductions are not very significant compared to the control walls.

This test concluded that the PCM shield placement in this series for lower temperature range of 25 ºC to 60ºC (77 ºF to 140 ºF) is not very effective in terms of reducing peak heat flux and generating phase change process into the walls which were outfitted with PCM shield.

4.9 Test No. 3

The last test of this series was performed exactly in the same manner like the third tests of Series 1 and Series 2 in temperature range of 40 ºC to 65ºC (104ºF to 149 ºF), except the placements of the PCM shield.

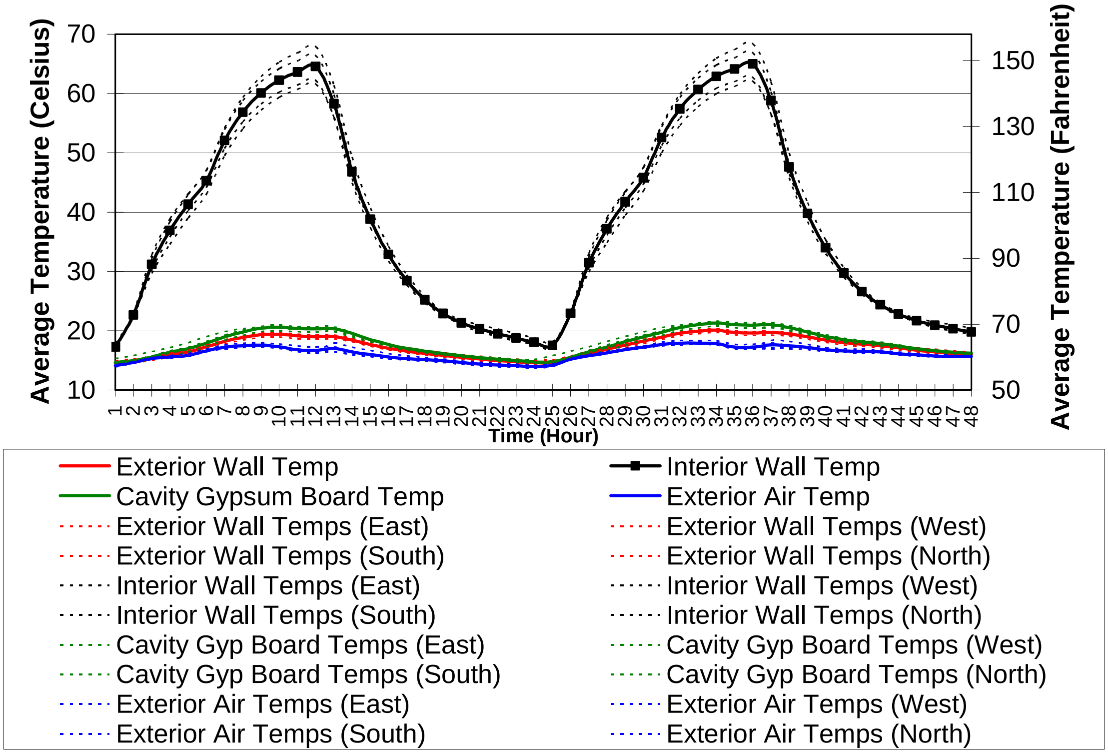


Figure 4.9.1. Average surface temperature profiles of all the walls (Series 3, Test 3)

Similar to the previous test the interior surface temperatures were higher than the rest of the surface temperatures in each wall. The average hourly wall heat fluxes were graphed over a 24-hour test period in Figure 4.9.2.

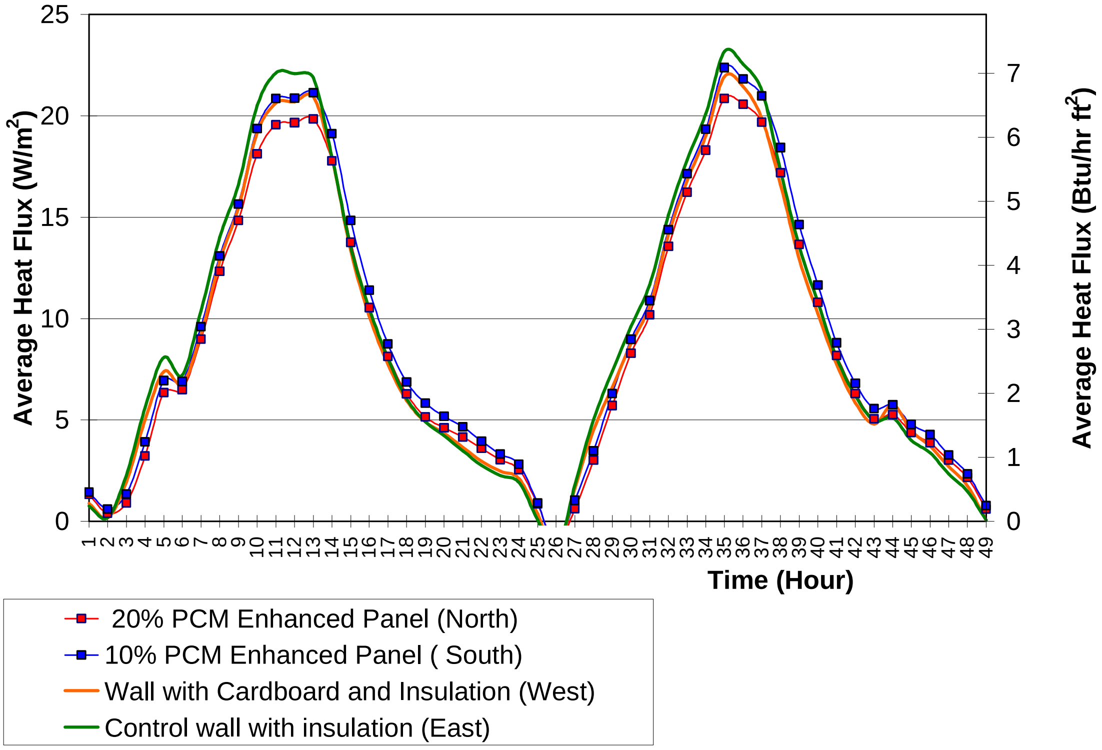


Figure 4.9.2. Average peak heat fluxes of walls (Series 3, Test 3)

The data show that the control peak heat flux was 22.12 W/m^2 (7.01 Btu/hr ft^2). The maximum peak heat flux was for the wall outfitted with the 10% PCM shield was 21.14 W/m^2 (6.7 Btu/hr ft^2) and the maximum peak heat flux for the wall outfitted with the 20% PCM shield was 19.84 W/m^2 (6.29 Btu/hr ft^2). Table 4.3 shows the heat fluxes, reduction and total heat transferred across each wall for this Test 3. The control wall outfitted with the cardboard and insulation seemed to have higher heat flux reduction than the wall outfitted with 10% PCM shield in the second cycle. Unlike the third tests in Series 1 and 2, in this test both walls outfitted with 10% and 20 % PCM shield respectively released almost the same amount of heat during the cool down period. However, because of the higher temperature range of 25 ºC to 65ºC (77 ºF to 149 ºF), the peak heat fluxes of both PCM-shielded walls differed compared to the other two previous tests in this series. In Figure 4.9.3, the average peak heat flux peaks are indicated with their coincident interior and exterior temperature profiles.

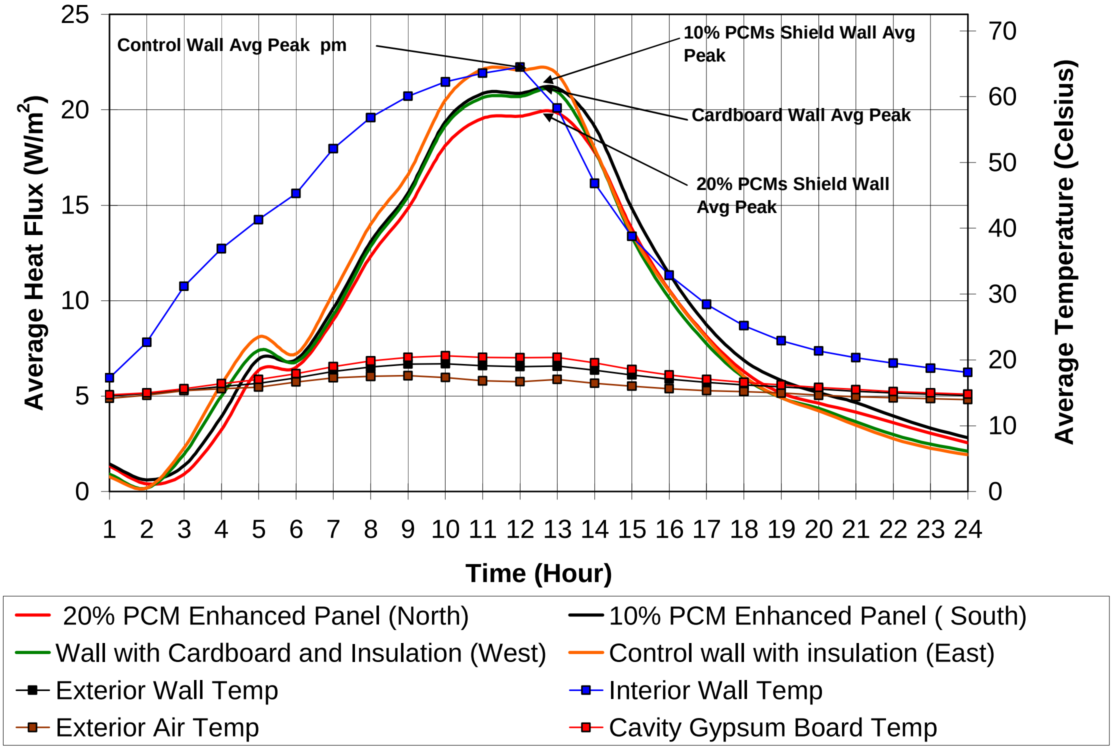
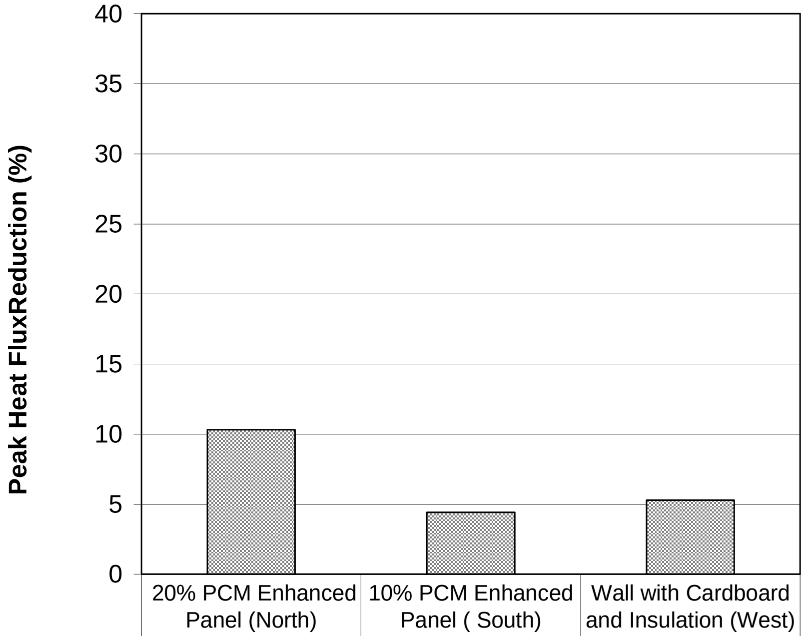


Figure 4.9.3. Average peaks of heat fluxes are indicated with their coincident interior and exterior wall temperatures (Series 3, Test 3)

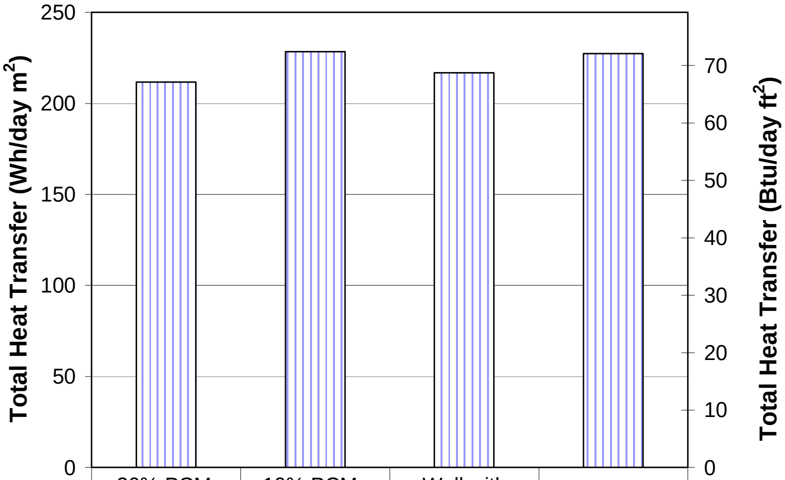
The figure shows how the PCM-shielded walls performed as a function of their change of temperatures over time. The 10% PCM Shielded wall seemed to have delayed its peak about 5 minutes and the 20% PCM shielded wall delayed its peak approximately 10 minutes towards the cooling down period. The percentages of peak heat flux reductions are shown in Figure 4.9.4.



	20% PCM Enhanced Panel (North)	10% PCM Enhanced Panel (South)	Wall with Cardboard and Insulation (West)
Peak Heat Flux Reduction (%) based on Control Wall	10.3	4.4	5.3

Figure 4.9.4. Percentages of peak heat flux reduction of walls (Series 3, Test 3)

From the data, it was observed that the 20% PCM-shielded wall had reduce approximately 10.30% of its peak heat flux and 10% PCM-shielded wall reduced approximately 4.40% of its peak heat flux. The wall outfitted with only cardboard and insulation reduced peak heat flux about 5.30%. This means that at Series 3 location for the temperature range of 25ºC to 65ºC (77ºF to 149 ºF) the wall outfitted with only the cardboard could decrease its peak heat flux more than the wall outfitted with 10% PCM shield. The total heat transfer for each wall over a 24-hour period is shown in Figure 4.9.5.



	20% PCMs Sheild wall (North)	10% PCMs Sheild wall (South)	Wall with Cardboard (West)	Control wall (East)
Total Heat Transfer for 24 Hours (Wh/day m2)	211.66	228.44	216.72	227.36
Total Heat Transfer for 24 Hours (Btu/day ft2)	67.10	72.42	68.70	72.07

Figure 4.9.5. Total heat transfer for each wall over 24-hours period (Series 3, Test 3)

In this period of time the wall outfitted with the 20% PCM shield transferred about 211.66 W/m^2 (67.10 Btu/hr ft^2) of total heat. The wall outfitted with the 10% PCM shield transferred about 228.44 W/m^2 (72.42 Btu/hr ft^2) of total heat.

In summary, it was observed that PCM-enhanced thermal shields, when integrated in walls at Series 3 location (PCM thermal shields were located towards the interior side of the wall cavity) would tend to produce lower heat flux reduction at lower maximum surface temperature, which would decrease with increasing interior surface temperature.

4.10 Performance of PCM Shields in Various Locations

The performance of the PCM shields in three different locations inside of the wall cavity were discussed in this section. The three locations were:

S 1: Series 1: Next to the wallboard

S 2: Series 2: In the middle of the wall cavity between two insulation layers

S 3: Series 3: Next to the siding, closer to the heat sources in the interior of the dynamic wall simulator.

***For the range from 40ºC (104ºF) average to 52ºC (125ºF) maximum interior surface temperature*:**

In the range of 25ºC to 52ºC (77ºF to 125ºF) the wall outfitted with the 10% PCM shield had its peak heat fluxes reduced less than the wall outfitted with the 20% PCM shield for all locations within the wall cavity. The percent peak heat flux reductions produced by the PCM shields at the various locations are shown in Figure 4.10.1.

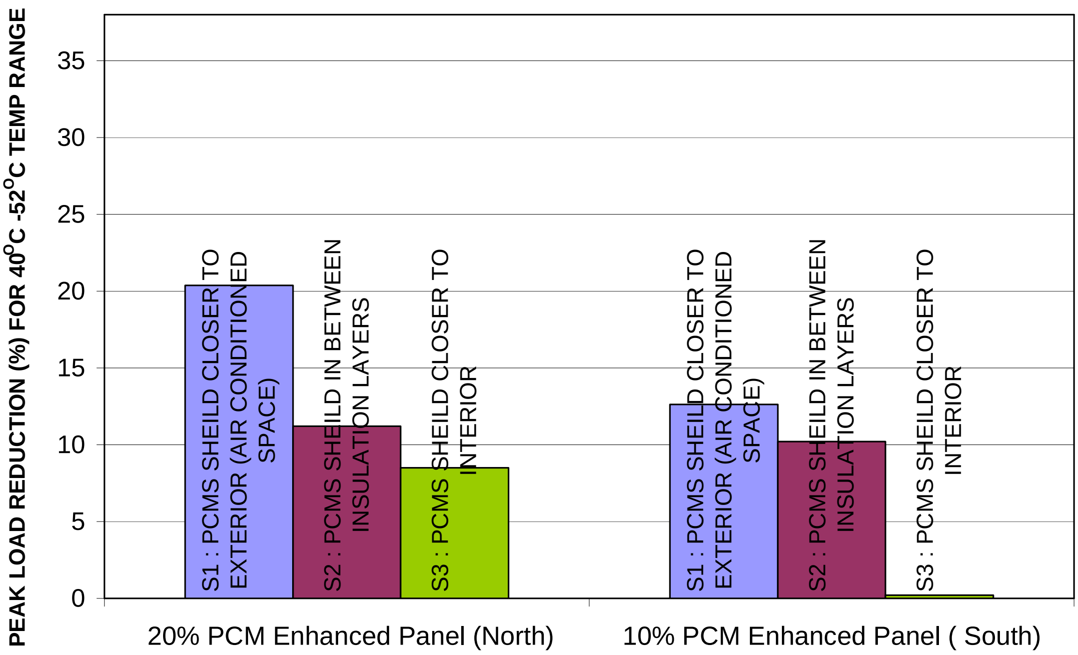


Figure 4.10.1. Peak heat flux reduction produced by the PCM shield walls at various locations inside the wall cavity for a temperature range of 40ºC to 52ºC (104ºF to 125ºF)

The graph shows that when the PCM shields were located next to the wallboard their thermal performance was better in terms of reducing the peak heat flux across the walls for both the 10% and 20% PCM shields. The following Figure 4.10.2 shows the heat fluxes for walls outfitted with 10% PCM shields at various locations for a temperature range of 25ºC to 52ºC (77ºF to 125ºF).

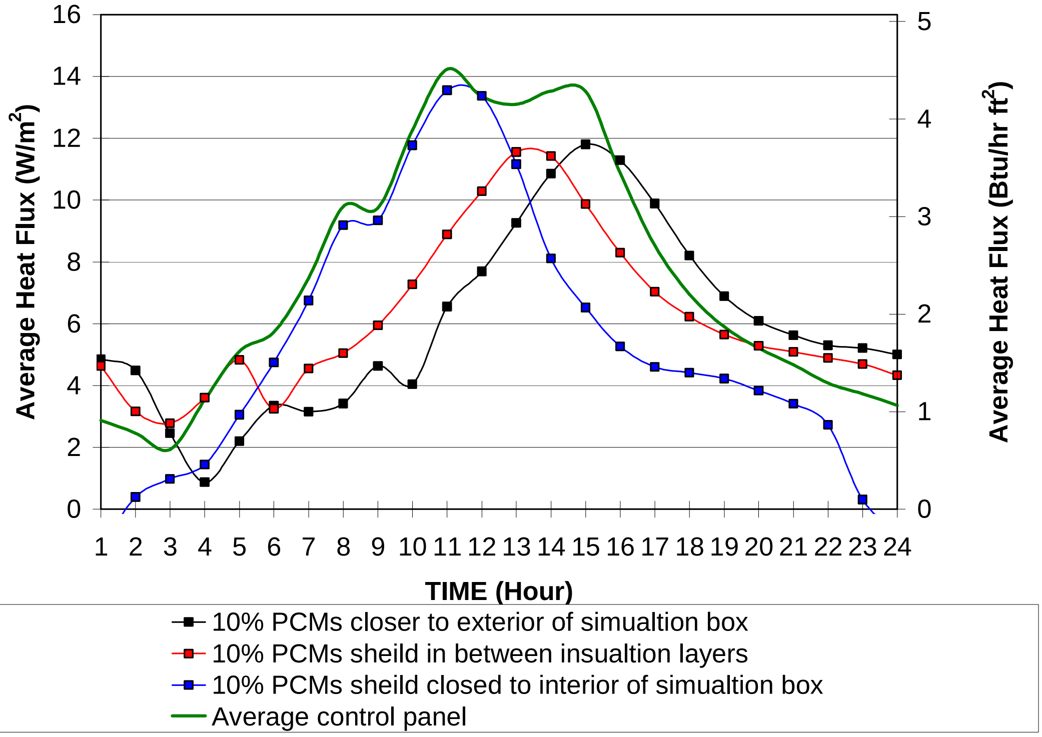


Figure 4.10.2. Heat fluxes for walls outfitted with 10% PCM shields at various locations for a temperature range of 40ºC to 52ºC (104ºF - 125ºF).

The figure shows the heat fluxes for walls outfitted with PCM shields with a concentration of 10%. The data indicate that for a temperature range of 25 ºC to 52 ºC (77 ºF to 125 ºF) the performance of the PCM shield was better when it was located next to the wallboard, that is, closer to the conditioned space. At this location, the PCM was able to change phase in both directions, that is, melt and solidify. The melting was produced by the heat traveling to the outside of the simulator. The solidification was enhanced by the location, near the conditioned space, which helped the shields release the heat rapidly during the cooling down period. On the other hand, when the PCM shields were placed in the middle of the wall cavity, in between of the insulation layers, and in close proximity to the interior of the simulator, their performance was not as effective. When the shields were placed in between the insulation layers, PCMs would melt rapidly, thus not taking advantage of a timely absorption of heat. At this location, it also slowed down the heat transfer process from the PCM during the cool down period, thus losing the ability to of the PCM to solidify. That is, the insulation layers prevented the heat to be released from the PCM shields. Similarly, in location S 3, when the shields were placed in close proximity to the heating source, the PCMs melted rapidly and then were not allowed to solidify because the insulation layers prevented the heat transfer towards the exterior sides of walls. Therefore, the peak heat fluxes of the walls outfitted with the PCM shields in these locations did not experience much of a heat transfer delay as much as was the case for when the shields were located next to the wallboard. The following figure 4.10.2 shows the heat fluxes for walls outfitted with 20% PCM shields at various locations for a temperature range of 25 ºC to 52 ºC (77 ºF to 125 ºF).

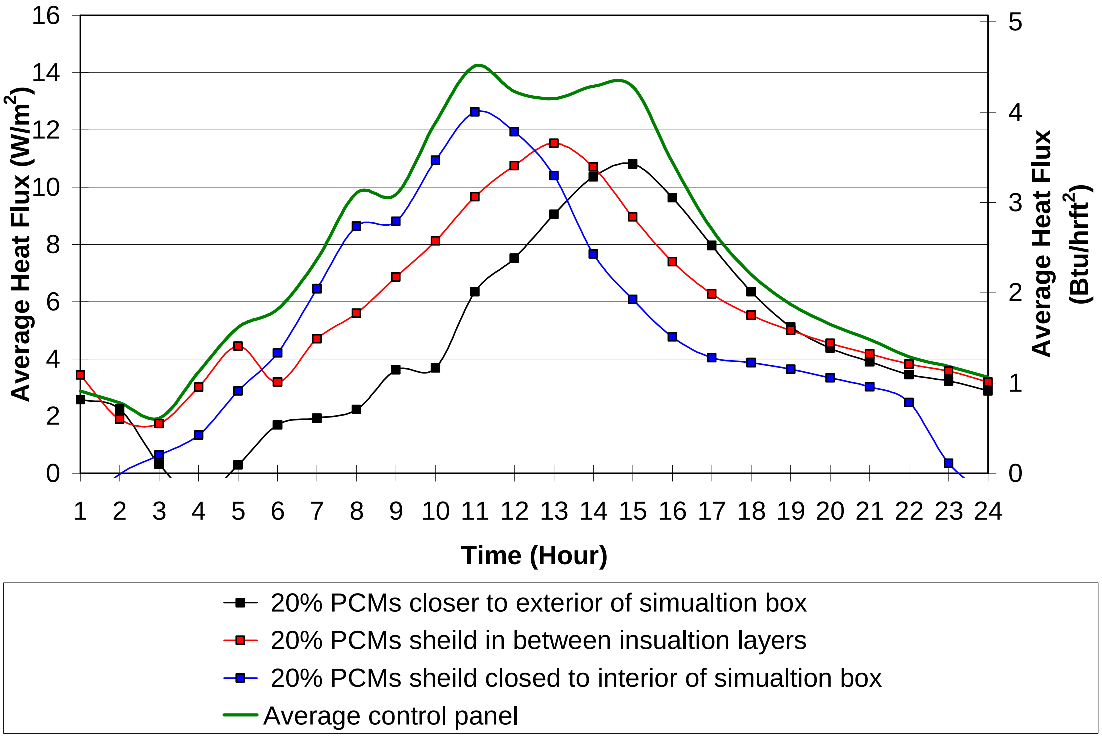


Figure 4.10.3. Heat fluxes for walls outfitted with 20% PCM shields at various locations for a temperature range of 40°C to 52°C (104°F to 125°F).

Similar to the 10% PCM shield wall, the 20% PCM shield wall performed most efficiently at the location closer to the wallboard for the temperature range of 25°C to 52°C (77°F to 125°F). The wall outfitted with the 20% PCM shield had its peak heat fluxes reduced higher than the wall outfitted with the 10% PCM shield for all locations within the wall cavity. This is simply because the higher concentrated PCM shielded walls performed comparatively better than the PCM shield with lower PCM concentration. With high concentration of PCMs, PCM shields were able to absorb higher amount of heat to generate phase change. Therefore, the peak heat flux reduced in 20% PCM shielded walls.

***For the range from 40ºC (104ºF) average to 60ºC (140ºF) maximum interior surface temperature*:**

In the range of 25ºC to 60ºC (77ºF to 140ºF) the wall outfitted with the 10% PCM shield had its peak heat fluxes reduced less than the wall outfitted with the 20% PCM shield for all locations within wall cavity. The percent peak heat flux reductions produced by the PCM shield at the various locations are shown in Figure 4.10.4.

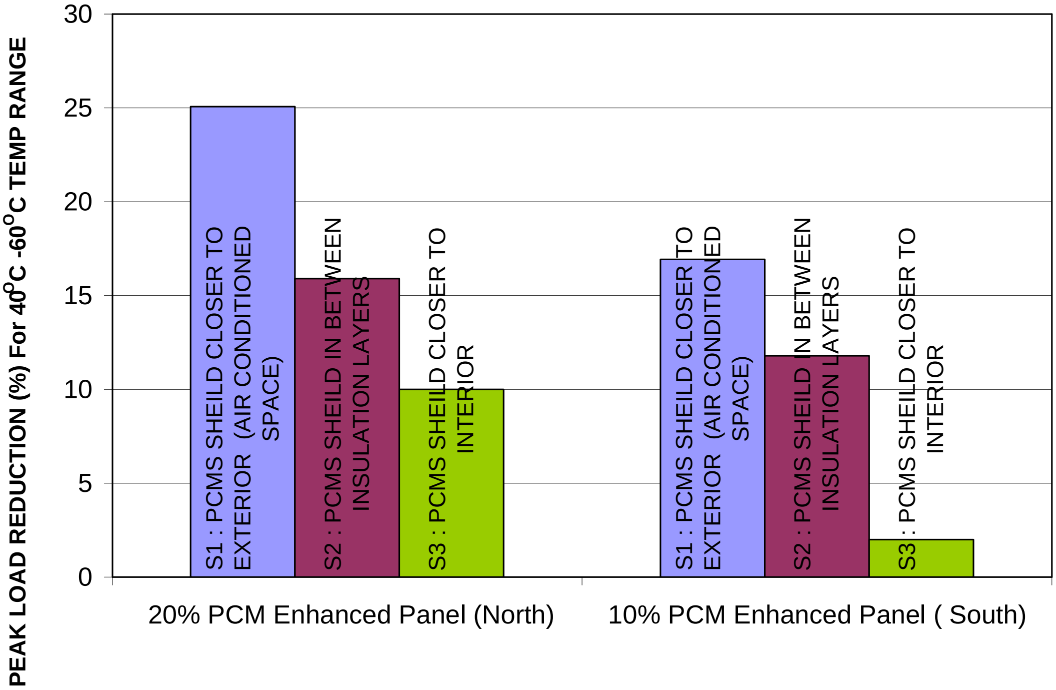


Figure 4.10.4. Peak heat flux reduction produced by the PCM shields wall at various locations inside the wall cavity for a temperature range of 40ºC to 60ºC (104ºF to 140ºF)

The graph shows that when the PCM shields were located next to the wallboard their thermal performance was better in terms of reducing the peak heat flux across the walls for both the 10% and 20% PCM shields. The following Figure 4.10.5 shows the heat fluxes for walls outfitted with 10% PCM shields at various locations for a temperature range of 25ºC to 60ºC (77ºF to 140ºF).

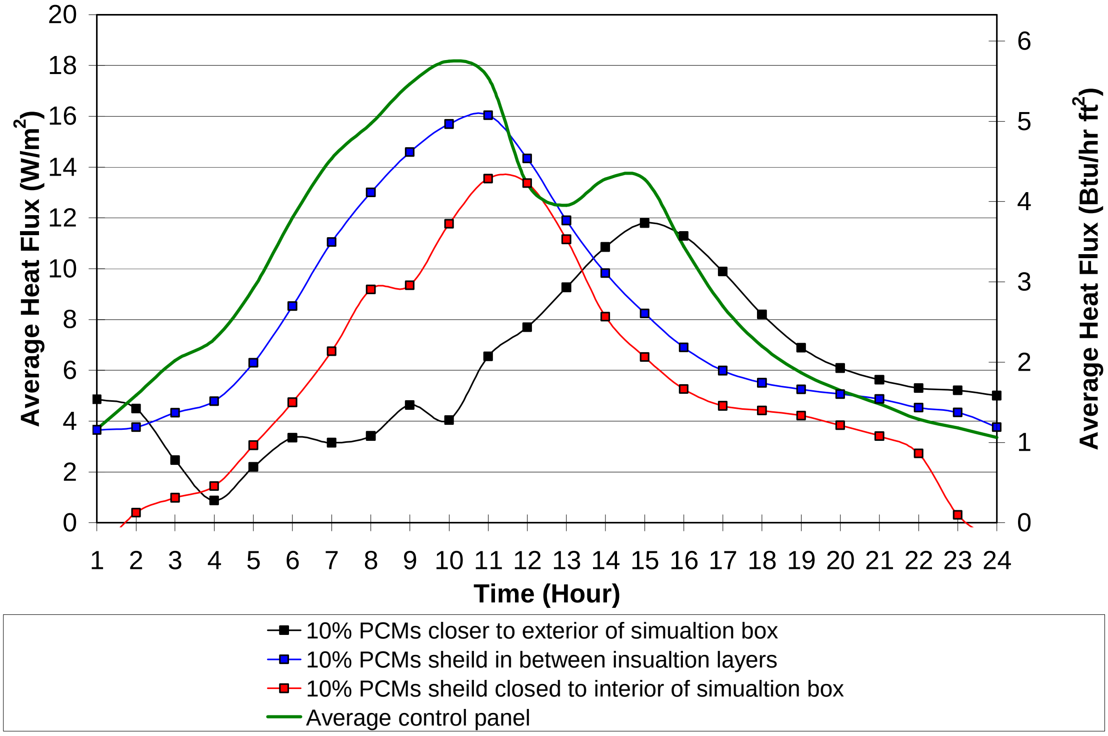


Figure 4.10.5. Heat fluxes for walls outfitted with 10% PCM shields at various locations for a temperature range of 40ºC to 60ºC (104ºF to 140ºF).

The figure shows the heat fluxes for walls outfitted with PCM shields with a concentration of 10%. Similar to the previous temperature range this data indicate that the performance of the PCM shield was better when it was located next to the wallboard for same reasons at temperature range of 25ºC to 60ºC (77ºF to 140ºF). The following figure 4.10.6 shows the heat fluxes for walls outfitted with 20% PCM shields at various locations for a temperature range of 25ºC to 60ºC (77ºF to 140ºF).

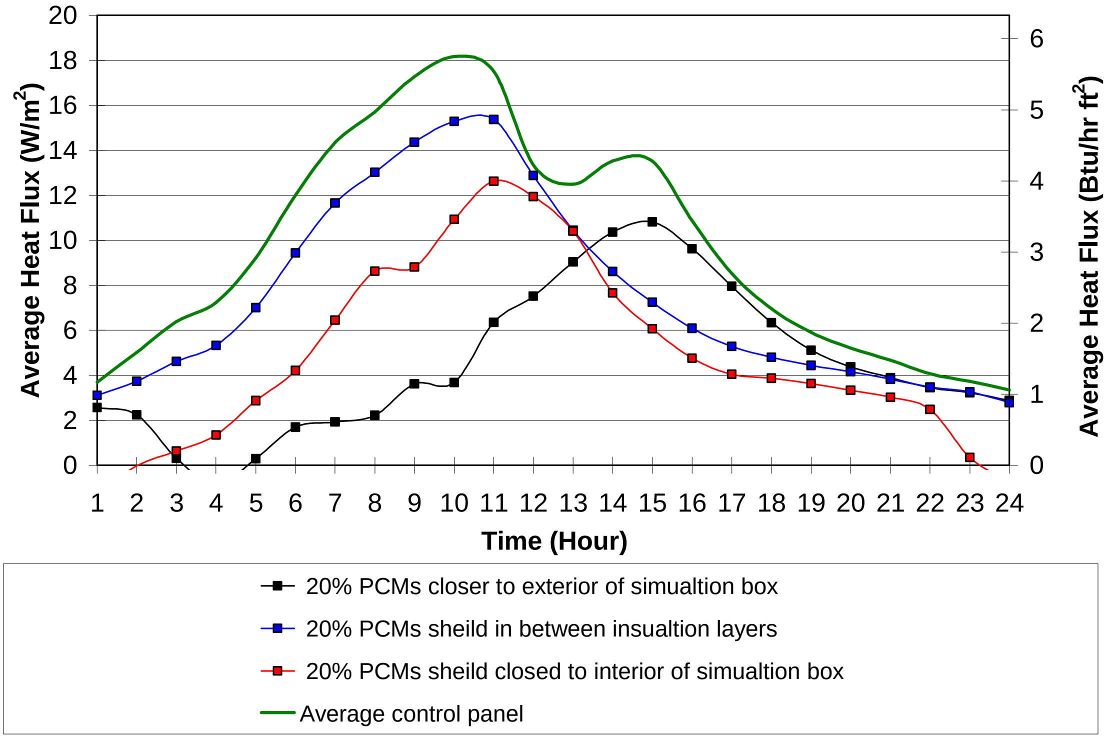


Figure 4.10.6. Heat fluxes for walls outfitted with 20% PCM shields at various locations for a temperature range of 40ºC to 60ºC (104ºF to 140ºF).

Similar to the 10% PCM shield wall, the 20% PCM shield wall performed most efficiently at the location closer to the wallboard for the temperature range of 25ºC to 60ºC (77ºF to 140ºF) for same previous reasons.

For 40ºC (104ºF) average to 65ºC (149ºF) maximum temperature range:

In the range of 40ºC to 65ºC (104ºF to 149ºF) the wall outfitted with the 10% PCM shield had its peak heat fluxes reduced less than the wall outfitted with the 20% PCM shield for all locations within the wall cavity. The percent peak heat flux reductions produced by the PCM shields at the various locations are shown in Figure 4.10.7.

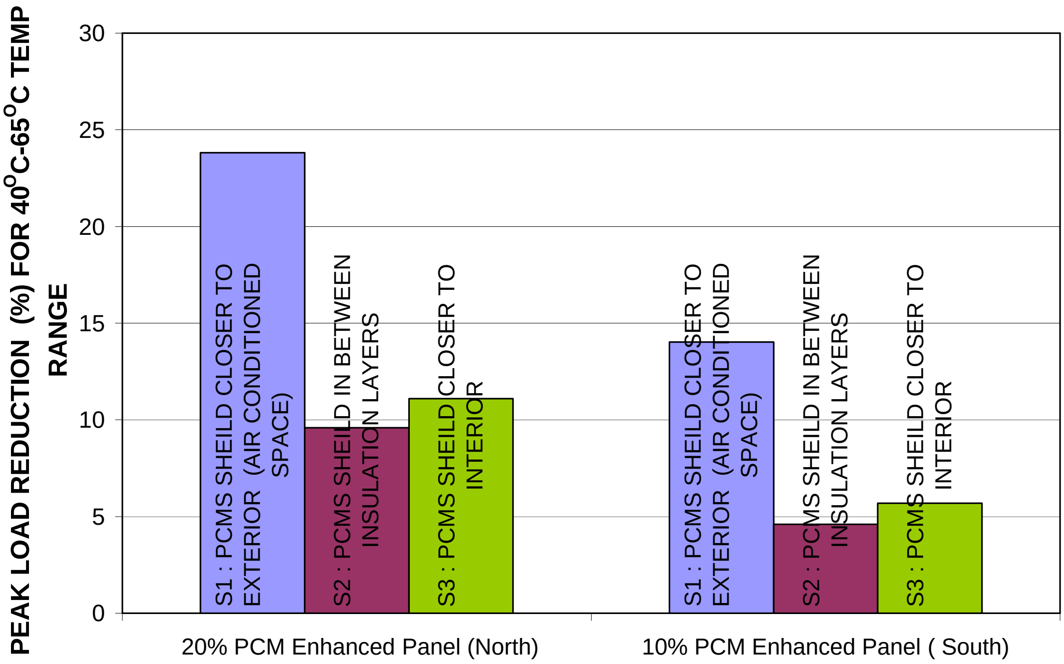


Figure 4.10.7. Peak heat flux reduction produced by the PCM shields wall at various locations inside the wall cavity for a temperature range of 40ºC to 65ºC (104ºF to 149ºF)

The graph shows that when the PCM shields were located next to the wallboard their thermal performance was better in terms of reducing the peak heat flux across the walls for both the 10% and 20% PCM shields. The following Figure 4.10.8 shows the heat fluxes for walls outfitted with 10% PCM shields at various locations for a temperature range of 25ºC to 65ºC (177ºF to 149ºF).

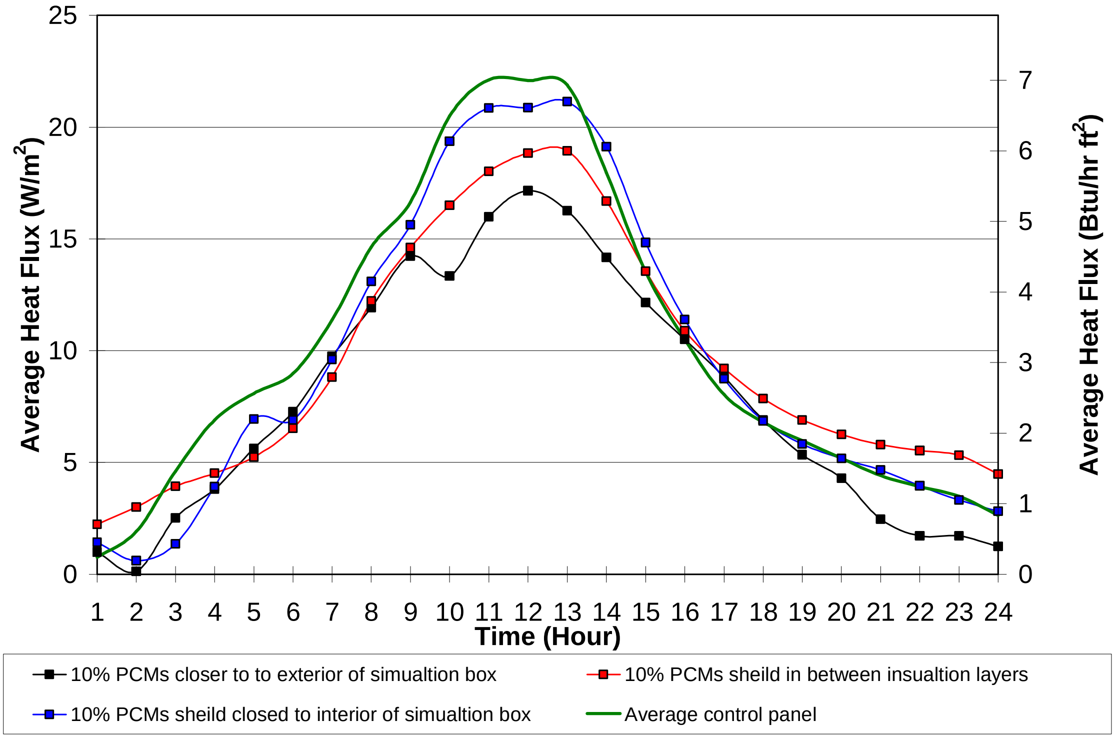


Figure 4.10.8. Heat fluxes for walls outfitted with 10% PCM shields at various locations for a temperature range of 40ºC to 65ºC (104ºF to 149ºF).

The figure shows the heat fluxes for walls outfitted with PCM shields with a concentration of 10%. Similar to the previous temperature range this data indicate that the performance of the PCM shield was better when it was located next to the wallboard for same reasons at temperature range of 25ºC to 65ºC (77ºF to 149ºF). The following Figure 4.10.9 shows the heat fluxes for walls outfitted with 20% PCM shields at various locations for a temperature range of 25ºC to 65ºC (77ºF to 149ºF).

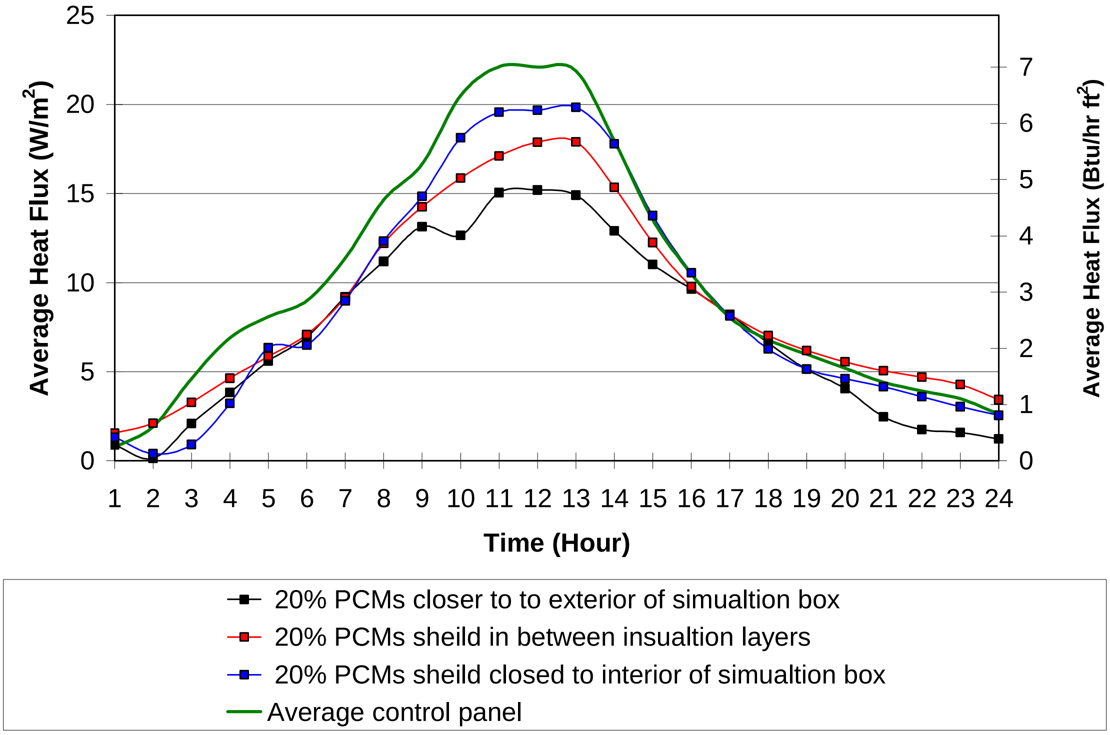


Figure 4.10.9. Heat fluxes for walls outfitted with 20% PCM shields at various locations for a temperature range of 40ºC to 65ºC (104ºF to 149ºF).

Similar to the 10% PCM shield wall, the 20% PCM shield wall performed most efficiently at the location closer to the wallboard for the temperature range of 40ºC to 60ºC (104ºF to 140ºF).

CHAPTER V

Conclusions and Recommendations

5.1 Conclusions

It was proposed to develop a PCM-enhanced thermal shield for residential walls. The shields were to be evaluated for concentration and location. A dynamic wall simulator was used for the evaluations. Two PCM concentrations were used, which were 10% and 20%. These concentrations were based on the weight of the wallboard. Three locations were evaluated. These were, next to the wallboard (S 1), middle of the wall cavity (S 2), and the innermost location of the simulator closer to the heating source (S 3).

The four walls of the simulator were used as follows: one wall was left as a control, one was used to carry the 10%-shield, one carried the 20%-shield, and one carried insulation layers and a replica of the board that was used to hold the PCM in place in the shield. The tests consisted of a heating period and of a cooling down period. This represented one cycle. Each testing period was composed of several cycles.

It was concluded from the results that the optimum placement of PCMs shields inside the wall cavity was the S 1 location. That means PCM thermal shield has large peak load reduction when they are placed further away from the heat source inside of the wall cavity. PCM thermal shield was less effective in high temperature range. 20% PCM thermal shields were more effective than 10% PCM thermal shields. The reason is that the wall outfitted with the 20% PCM shield reduced peak heat fluxes more than the wall outfitted with the 10% PCM shield for all locations within the wall cavity.

In the S 1 location the walls outfitted with both the 10% PCM and the 20% PCM shields, produced the highest reduction in peak heat flux across the wall and also produced the longest time shift among all. For the S 1 location, the 10% and 20% PCM shielded walls reduced peak heat fluxes by approximately 12.64% and 20.37%, respectively, when the maximum surface temperature of the wall closest to the heating sources was 52ºC (125ºF). The percent peak heat flux reductions for the walls outfitted with the 10% PCM and 20% PCM shield were 16.94% and 25.04%, respectively, when the temperature was 60ºC (140ºF), and the peak heat flux reductions were 14.02% and 23.82% for the 10% shield and 20% shield, respectively, when the maximum temperature was 65ºC (149ºF) compared to the control wall.

Comparatively, in the S 2 location the peak reduction of the PCM shielded walls for all temperature ranges (low to high) were not as high as those in the S 1 location. In the S 2 location, the 10% and 20% PCM shields reduced the peak heat flux by approximately 10.2% and 11.2%, respectively, when the maximum temperature was 52ºC (125ºF); 11.8% and 15.9%, respectively, when the maximum temperature was 60ºC (140ºF); and 4.6% and 9.6%, respectively, when the maximum temperature was 65ºC (149ºF).

In the S 3 location, which proved to be the least optimum location, the 10% and 20% PCM shields reduced the peak heat flux by approximately 0.20% and 8.50%, respectively, when the maximum temperature was 52ºC (125ºF); 2.00% and 10.00%, respectively, when the maximum temperature was 60ºC (140ºF); and 5.70% and 11.10% respectively when the maximum temperature was 65ºC (149ºF). It seemed like at higher temperature the wall outfitted with the 20% PCM shield performed better than the wall outfitted with the 10% PCM shield in terms of reducing peak heat flux. The reason was that at higher temperature higher concentration PCM shield was able to absorb more heat to generate phase change during the heating period.

Therefore, the wall outfitted with the 20% PCM shield performed comparatively better when the maximum temperature was higher, that is 65ºC (149ºF) at this location.

5.2 Recommendations

There are several recommendations for future researches for this field:

- It is recommended to incorporate a source of ventilation inside of the dynamic simulator during the cooling down period. In this way the simulation process would replicate a conventional building wall under full weather conditions more realistically.
- For organic phase change materials, it is highly recommended to use any type of fire retardant formulation with the PCMs shield system in order to reduce any kind of fire hazard.

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