Using Hydrated Salt Phase Change Materials for Residential Air Conditioning Peak Demand Reduction and Energy Conservation in Coastal and Transitional Climates in the State of California

By

Kyoung Ok Lee

M.Eng., Chung-Ang University, Korea, Rep. of, 2003
B.Eng., Chung-Ang University, Korea, Rep. of, 2001

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Mario A. Medina, Ph.D., P.E., Chairperson

____
Thomas E. Glavinich, D.E., P.E., Member

____
C. Bryan Young, Ph.D., P.E., Member

Date Defended: ________________________

The Thesis Committee for Kyoung Ok Lee

certifies that this is the approved version of the following thesis:

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Mario A. Medina, Ph.D., P.E., Chairperson

Date approved: ________________________

ABSTRACT

The recent rapid economic and population growth in the State of California have led to a significant increase in air conditioning use, especially in areas of the State with coastal and transitional climates. This fact makes that the electric peak demand be dominated by air conditioning use of residential buildings in the summer time. This extra peak demand caused by the use of air conditioning equipment lasts only a few days out of the year. As a result, unavoidable power outages have occurred when electric supply could not keep up with such electric demand.

This thesis proposed a possible solution to this problem by using building thermal mass via phase change materials to reduce peak air conditioning demand loads. This proposed solution was tested via a new wall called Phase Change Frame Wall (PCFW). The PCFW is a typical residential frame wall in which Phase Change Materials (PCMs) were integrated to add thermal mass. The thermal performance of the PCFWs was first evaluated, experimentally, in two test houses, built for this purpose, located in Lawrence, KS and then via computer simulations of residential buildings located in coastal and transitional climates in California.

In this thesis, a hydrated salt PCM was used, which was added in concentrations of 10% and 20% by weight of the interior sheathing of the walls. Based on the experimental results, under Lawrence, KS weather, the PCFWs at 10% and 20% of PCM concentrations reduced the peak heat transfer rates by 27.0% and 27.3%, on average, of all four walls, respectively.

Simulated results using California climate data indicated that PCFWs would reduce peak heat transfer rates by 8% and 19% at 10% PCM concentration and 12.2% and 27% at 20% PCM concentration for the coastal and transitional climates, respectively. Furthermore, the PCFWs, at 10% PCM concentration, would reduce the space cooling load and the annual energy consumption by 10.4% and 7.2%, on average in both climates, respectively.

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Kyoung Ok Lee

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CHAPTER I

INTRODUCTION

The ongoing California electricity crisis (i.e., large-scale brownouts, shortages of electricity, and trans-state pipeline shutdowns) coupled with the rapid growth in the use of summer air conditioning, especially in the coastal and transitional climates of the State has prompted the adoption of technologies and programs aimed at maximizing electric energy efficiency in all sectors affected by these climates, especially the building sector. Coastal climates refer to climates in marine-dominated coastal locations and transitional climates refer to intermediate climates in locations between coastal areas and inland areas of the Central Valley or semi-deserts.

There are two important factors influencing electricity use in California. One is economics and population growth and the other is hot weather. As expected, electricity use increased as economic activity and population, both increased. The hot weather also caused an increase in electricity demand for air conditioning. California electricity peak demand generally fluctuates with summer temperature variations, where the air conditioning load contributes in large portion (CEC, 2002).

Electricity usage in California is divided into residential, commercial, and industrial sectors. The electric demands by the residential, commercial and industrial sectors in California were 34.6%, 37.5% and 17.4%, respectively. The remaining demand of 10.5% was contributed by other sectors, such as the agricultural (4.5%), electric vehicles (0.2%), and "other" (5.8%). Air conditioning became a common practice in residential buildings in coastal and transitional climates where air conditioning is typically required only a few days of the year. The air conditioning load these climates typically last between 3 to 5 days per year; however, these have nearly as much impact on peak demand as the air conditioning load in hot climates. As a result, residential air conditioning that is characterized by sharp peaks accounts for about 45% of residential peak demand but only 7% of residential annual load (DEG, 2004).

The State of California makes efforts so that power systems have enough capacity to serve the entire demand. However, it is costly to build an electric generation and transmission system to supply a peak demand that lasts only a few days each year. Instead, the power system is operated to accept some risks of outages (CEC, 2002). Therefore, the inevitable power outages affect State industries (e.g., tourism, investing,), as well as residents' comfort.

For this reason, the research presented in this thesis was focused on a method to mitigate peak electric demand by reducing the residential air conditioning load in coastal and transitional climates in the State of California. This method relies on increasing thermal mass in residential buildings by adding phase change materials to their exterior walls.

The technology proposed and evaluated in this thesis is referred to as Phase Change Frame Wall (PCFW). A PCFW is a typical wall in which phase change materials (PCMs) have been incorporated via macroencapsulation to enhance the energy storage capabilities of building walls via the high latent heats of fusion of the

PCMs. The use of PCFWs is proposed to reduce the elevated on-peak demand from air conditioning. The results of the research presented in this thesis set in motion a new technology, which if refined, adopted and implemented, could significantly reduce electricity outages, improve power plant summer load factors, and make residential air conditioning a more cost-effective load to serve. Also, should this technology be adopted, it would represent another step in the United States' efforts to develop energy-efficient home designs that will help lower or eliminate compressor-based space conditioning and that would allow space comfort systems to achieve their intended efficiencies and operation life by reducing their current short-cycle operation.

The main goal of this research was to determine the feasibility of using phase change frame walls (PCFWs) for peak air conditioning demand reduction and energy conservation in California's coastal and transitional climates. Therefore, the results are expected to apply to buildings located in these climate zones, which are subjected to high electric demand and usage for short periods in summer.

The PCM used in this research was a hydrated salt PCM with melting and solidification points in the range of 28 °C ~ 30 °C (82.4 °F ~ 86 °F). The PCM was commercially-known as TH29 and was produced and distributed by PCM Energy P. Ltd., Mumbai, India. The arguments for using this type of PCM as opposed to the most commonly used paraffin PCM types were its non-flammability, its relatively low cost, its high latent heat of fusion, and its non-toxic nature. Arguments against using this PCM were its corrosiveness and its tendency to supercool. Supercooling is the process experienced by some substances when their molecules tend to not solidify (crystallize) even when its solidification temperature has been reached and surpassed in a cooling process. This creates an incongruent solidification process that leads to inefficiencies. PCM companies, including PCM Energy Ltd. use proprietary chemicals to avoid this unwanted effect.

1.1 Phase Change Materials (PCMs)

All materials transform from solid-to-liquid and from liquid-to-gas as their temperatures are progressively increased from absolute zero. Energy, in the form of heat, is absorbed from their surroundings as they transition from solid-to-liquid and from liquid-to-gas. Conversely, heat is released from every material during their transition from gas-to-liquid and from liquid-to-solid. The energy that is stored and released during the changes of state is called latent heat and for some substances, including PCMs, it occurs over a range of temperatures.

In addition, during the materials' transition from solid-to-liquid and from liquid-to-gas and their reversed transitions, the materials remain at nearly constant temperatures until the phase change process is complete. Phase change materials (PCMs) are ordinary substances, usually waxes, oils, and hydrated salts, that have been *engineered* to change phase in specific temperature ranges depending on the intended application. In addition, PCMs have noticeably higher latent heats of fusion. It is the phase change in specific temperature ranges and the relatively large latent heats of fusion what makes PCMs attractive for thermal storage systems.

In buildings, the integration of PCMs with appropriate melting and solidification points and sufficiently high latent heats of fusion result in a means of converting regular building enclosures, such as walls, roofs, and foundations into high thermal mass components. In buildings, high thermal mass creates inertia against indoor and wall temperature fluctuations and lowers the amount of heat transfer during daily peak times. This reduces electricity usage during peak times by time-shifting the heat transfer process to later times of the day (Solomon, 1979).

In general, the candidate PCMs must have the following characteristics to make them attractive for thermal heat storage. They must have (1) high latent heat of fusion, (2) phase change transition temperatures in the desirable range, (3) high thermal conductivity (to minimize thermal gradients), (4) high specific heat and density, (5) long term reliability during repeated cycling, (6) low volume change during phase transition, (7) low vapor pressure, (8) be nontoxic, and (9) exhibit little or no supercooling (Ghoneim et al., 1991).

The PCMs used in building applications can be both inorganic and organic materials. For building applications, the phase changes are predominantly of the solid-liquid transitions type, although solid-solid types are also used at higher operating temperatures in other applications (e.g., metallurgical and ceramic) (Hawes et al., 1993).

Inorganic PCMs

Salt hydrates, of which some are shown in Table 1.1, are among the inorganic PCMs that offer the potential for building or similar applications. These PCMs have some attractive properties such as high latent heat values, non-flammability, relatively low cost and their availability. On the other hand, hydrated salt PCMs also have some unwanted characteristics. They are corrosive, and therefore, are incompatible with several materials used in buildings, especially metals. For this reason, hydrated salts must be encapsulated using special containment methods that require support and space. They also have tendency to supercool. As stated above, supercooling leads to an incongruent solidification with internal molecular segregation. This affects the PCM cycle by not allowing all the stored heat to be released, which leads to a subsequent poor melting process. Proprietary chemicals, known as nucleating agents, are added to prevent supercooling. A common nucleating agent used with calcium chloride hexahydrate is strontium chloride hexahydrate because it is low price and because it meets other technological requirements, like desired melting temperature range (Feilchenfeld and Sarig, 1985).

Table 1.1. Hydrated Salt PCMs (typical values) (Source: Hawes et al., 1993)

PCM	Melting point °C (°F)	Heat of fusion J/g (Btu/lb_m)
$KF \cdot 4H_2O$ Potassium fluoride tetrahydrate	18.5 (65.3)	231 (99.3)
$CaCl_2 \cdot 6H_2O$ Calcium chloride hexahydrate	29.7 (85.5)	171 (73.5)
$Na_2SO_4 \cdot 10H_2O$ Sodium sulphate decahydrate	32.4 (90.3)	254 (109.2)
$Na_2HPO_4 \cdot 12H_2O$ Sodium orthophosphate dodecahydrate	35.0 (95.0)	281 (107.9)
$Zn(NO_3)_2 \cdot 6H_2$ Zinc nitrate hexahydrate	36.4 (97.5)	147 (63.2)

(shaded) Recommended for building applications.

Organic PCMs

Organic PCMs, some of which are shown in Table 1.2, have a number of characteristics that make them useful for building applications. These characteristics are: their constituents melt congruently and supercooling is not a significant problem. They are chemically stable and they comprise a broad choice of substances. They are compatible, with and suitable for, absorption in various building materials. However, organic PCMs also have some unsuitable properties. The most significant is their flammability. A few have odors, which may be objectionable, and in some, the volume change during phase transition can be appreciable (Hawes et al., 1993).

Table 1.2. Organic PCMs (typical values) (Source: Hawes et al., 1993)

PCM	Melting point °C (°F)	Heat of fusion J/g (Btu/lb_m)
$CH_3(CH_2)_{16}COO(CH_2)_3CH_3$ butyl stearate	19 (66.2)	140 (60.2)
$CH_3(CH_2)_{11}OH$ 1-dodecanol	26 (78.8)	200 (86.0)
$CH_3(CH_2)_{12}OH$ 1-tetradecanol	38 (100.4)	205 (88.1)
$CH_3(CH_2)_nCH_3$ paraffin	20~60 (68~140)	~200 (~86.0)
45% $CH_3(CH_2)_8COOH$ 55% $CH_3(CH_2)_{10}COOH$ 45/55 capric-lauric acid	21 (69.8)	143 (61.5)
$CH_3(CH_2)_{12}COOC_3H_7$ propyl palmitate	19 (66.2)	186 (80.0)

Recommended for building applications.

1.2 Phase Change Frame Walls (PCFWs)

The concept of the phase-change frame walls is an improvement from previous attempts made to integrate PCMs into frame walls. In the past, the attempts to enhance the energy efficiency of walls and ceilings by the application of thermal mass, using the heat storage available during the phase-change process, were met with mixed results (Salyer and Sircar, 1990). Various PCMs were utilized for this purpose, which were mostly introduced via an imbibing process into gypsum wallboards. These systems demonstrated many advantages in energy savings; however, four main problems limited their potential application. These were (1) durability of PCM-impregnated gypsum wallboards, (2) low water permeability of the walls, (3) low fire rating, and (4) issues of contact between PCM and people and/or PCM and wall coatings and/or wallpapers (Banu et al., 1998).

In the system proposed and evaluated in this thesis, a macrocapsule containment method (MCM) rather than an imbibing method (IM) was used. The MCM proved safer and more stable than the IM because PCMs were first encapsulated in pipes, which were then capped at both ends to prevent leakage. The pipes were assembled within the wall and held in place by light metal “ladder type” frames, which were then fastened to the structural support members of the walls (studs). No holes were drilled across the studs, which otherwise could have compromised the walls' structural properties. The MCM eliminated PCM dripping and contact issues, eliminated moisture transfer problems across the enclosure, and reduced the flammability of the wall. Preliminary fire tests indicated that the PCFWs passed wall fire tests (Miller, 2007). In addition, because the pipes were never completely filled with PCM, problems associated with PCM volume changes during the phase change process were eliminated.

CHAPTER II

LITERATURE REVIEW

In buildings, enclosure thermal storage is an important aspect of energy management and conservation. It is related to building thermal mass. In general, thermal storage is achieved by constructing massive structures, which is expensive and old-fashioned. The principle of thermal storage can be significantly assisted by the incorporation of latent heat storage in building components. This can be achieved by the use phase change materials (PCMs), which absorb and release heat much more effectively than conventional building materials. This is the case because conventional building materials store heat energy in a sensible rather than latent manner. Many experimental and simulation studies on the application of PCMs in building components appear in the technical literature (Tomlinson and Heberle, 1990; Salyer and Sircar, 1990., 1997; Hawes et al., 1993; Kissock et al., 1998; Kissock 2000; Zhang, 2004; Zhang et al., 2005; King, 2004; Medina et al., 2008; Zhu, 2005; Medina and Zhu, 2008; Evers, 2008; Evers et al., 2010; Fang, 2009; Fang and Medina, 2009; Reshmeen, 2009). The most relevant are summarized below.

Tomlinson and Heberle (1990) determined the thermal and economic performance of PCM-imbibed wallboards. In this research, two houses were used. One house had glazing in the south-facing wall while the other did not. Both houses were simulated with and without PCM-wallboards in a situation where both received the same amount of solar radiation over a period of time. The simulation program was a modified Transient Systems Simulation Program (TRNSYS). The simulations were performed using a Denver, CO weather file and with PCM concentrations in the wallboards from 0% up to 30% by weight of the wallboard. For example, the 30% indicated that an amount of PCM equivalent to 30% of the weight of the wallboard was absorbed and retained evenly in the wallboard. The simulation results showed that the PCM wallboards had a significant impact in reducing the amount of space heating energy in the house with glazing in its south side. The PCM wallboards had almost no impact in the reduction of space heating energy in the house with no glazing. Furthermore, an economic analysis showed that energy savings were related to the quantity of PCM uptake in the wallboard. An optimization analysis showed that the best performance was obtained when the PCM uptake was approximately 15%. The optimized PCM-wallboard produced a simple payback of less than five years.

Salyer and Sircar (1990, 1997) developed a cost-effective, environmentally-acceptable PCM as well as several PCM-incorporating-methods for building and other applications using concrete and plasterboard. The product of this research was a suitable low-cost alkyl hydrocarbon PCM, that is now commercially-produced from petroleum refining, that melts at approximately 25 °C (77 °F). The main constituent of this PCM is n-octadecane, $CH_3(CH_2)_{16}CH_3$. This PCM has been recommended for building applications when the goal is to reduce space heating and space cooling energy requirements. PCM containment methods to solve problems of PCM leakage, volume change in melting and solidification, heat transfer and flammability were developed. These included imbibing the PCM into porous materials (e.g., plasterboard), permeating the PCM into polymeric carriers (e.g., cross-linked pellets of high-density polyethylene), and absorbing the PCM into finely divided special silicas to form soft free-flowing dry powders.

In addition to space heating and cooling of buildings, additional applications of commercial interest were studied. They concluded that this PCM could be used for medical applications (e.g., medicine and chemical supplies storage), service applications (e.g., tableware and insulated food carriers), textiles, aerospace (e.g., thermal protection of flight data and cockpit voice recorders), civil engineering (e.g., for the prevention of overnight freezing of bridge decks), and agricultural (e.g., for the prevention of overnight freezing of citrus tree trunks).

At the Centre for Building Studies (CBS) of Concordia University in Montreal, a number of studies related to building energy-storage materials were conducted. This research showed the potential of producing functional and effective building elements that could significantly affect energy savings (Hawes et al., 1993). The research focused on the combination of several building materials with several PCMs. Similar to Salyer and Sircar (1990, 1997) the most promising results dealt with organic PCM-imbibed concrete blocks and gypsum wallboards. Of these, Butyl stearate and paraffin appeared to be the most effective PCMs. Fire and fume generation characteristics, however, were yet to be established at an appropriate fire testing facility.

According to Hawes et al. (1993), in the case of gypsum–PCM combinations, wallboard could absorb PCMs in amounts of up to about 50% of its own weight;

however, a 25% ~ 30% uptake showed the most satisfactory performance. In concrete-PCM combinations, PCM uptakes of up to 20% by weight could be realized depending on the types of blocks used. That is, in denser types of concrete blocks, the absorbed percentages were usually 5%. This was eventually set as a minimum proportion since this provided some degree of latent thermal storage.

In manufacturing considerations, direct incorporation (i.e., mixing and blending during the manufacturing process) appeared to be the most practical and economical procedure for incorporating PCMs into wallboards. It was concluded that the energy-storing capacity of wallboards for an average house would provide approximately 0.48 MJ/m^2 (169.0 Btu/ft^2) of energy storage while the storage capacity of a house constructed of PCM concrete blocks would be about 1.92 MJ/m^2 (42.2 Btu/ft^2) (Hawes et al., 1993).

In 1998, an experimental and simulation study of the thermal performance of phase-change wallboard in simple structures was conducted at the University of Dayton (Kissock et al., 1998 and Kissock, 2000). Two test cells with dimensions of 1.22 m (4 ft) x 1.22 m (4 ft) x 0.61 m (2 ft) were constructed of common light-frame construction materials. One wall of each test cell faced south and consisted of a transparent acrylic sheet that allowed solar radiation to penetrate the cell. In the control cell, conventional wallboard was installed and in the test cell, wallboard imbibed to 29% by weight. The PCM used was K18, which was a paraffin-based PCM, consisting mostly of octadecane, with an average melting temperature of about

25.6 °C (78.1 °F). Results showed that, on average, peak temperatures in the PCM test cell were up to 10 °C (18 °F) lower than in the control test cell during sunny days.

The research was extended to develop a simulation model predicting interior air and wall temperatures to investigate the thermal performance of other phase-change building components in temperature-controlled buildings. The simulation used an explicit finite-difference method, which was modified to account for the latent heat storage properties of PCMs. In addition, peak and annual thermal loads were simulated through concrete sandwich walls, steel roofs, gypsum wallboard, light-frame residential housing and mobile homes, both with and without the addition of K18, for annual typical meteorological data of Dayton, Ohio.

The addition of 10% K18 to the concrete in concrete-sandwich walls reduced the peak and annual cooling loads through the wall by 19% and 13%, respectively. The addition of PCM to low-mass steel roofs reduced the peak and annual cooling loads through the roof by 30% and 14%, respectively. The addition of PCM to gypsum wallboard in frame walls reduced the peak and annual cooling loads through the walls by 16% and 9%, respectively. In summary, the application of PCMs in each building component was shown to dramatically influence its thermal performance.

The use of phase-change wallboard in the frame house did not significantly decrease overall space conditioning loads, except in the case where night flushing was used. A night flushing is a fan operating scenario that increases outside air ventilation from 0.25 air changes per hour during the day to 4 air changes per hour during the night if the outside air temperature is lower than the indoor set-point temperature. A night flushing cools interior walls and furniture during the night to reduce cooling loads during the day. In this case, the annual cooling load was reduced by 17%. The use of phase-change wallboard in a mobile home reduced the annual space-cooling load by 18% with standard air-conditioning and 27% with night flushing. In an unconditioned mobile home, phase-change wallboard increased the time that interior temperatures remained within a comfortable range by 41%.

Since 2000, research at the University of Kansas has been conducted to evaluate the thermal performance of building walls enhanced with PCMs (Zhang, 2004; Zhang et al., 2005; King, 2004; Medina et al., 2008; Zhu, 2005; Medina and Zhu, 2008; Evers, 2008; Evers et al., 2010; Fang, 2009; Fang and Medina, 2009 and Reshmeen, 2009). The purposes of these investigations were to assess peak air conditioning demand reductions, thermal load shifting, and energy savings.

Zhang (2004) and Zhang et al. (2005) developed an experimental set up to evaluate the thermal performance of phase change frame walls (PCFWs) using n-Octadecane as the PCM. Two wood framed 1.83 m × 1.83 m × 1.22 m (6 ft × 6 ft × 4 ft) test houses were constructed, one house was used as a control house and the other as an experimental house. Monitoring systems were installed to measure and collect space cooling loads, wall heat fluxes, air and surface temperatures, and air relative humidity. The test houses were equipped with space heating and cooling systems. During the tests, the indoor air temperatures of both houses were well controlled and maintained almost identical to less than 1.5 °C (2.7 °F) difference. In the winter, the average indoor air temperatures were about 19 °C ± 1 °C (66.2 °F ± 1.8 °F) and 21.5

°C ± 0.5 °C (70.7 °F ± 0.9 °F) for summer. The PCM was encapsulated in copper pipes arranged horizontally in the stud walls and placed next to the interior plywood wallboard. A highly crystalline, n-paraffin based PCM, commercially known as RT-25 was used. This PCM had a melting and solidification points in the range of 20 °C ~ 30 °C (68 °F to 86 °F). In winter, 10% concentration of PCM was applied. In the summer, 10% and 20% concentrations of PCM were applied. The concentration was based on the weight of interior sheathing. This was done to be able to compare these results to those in which the wallboards had been imbibed. The results for the summer season showed that the average peak heat flux through the walls decreased by as much as 21% when 10% PCM was applied and 15% for a PCM concentration of 20%. A one to two hours peak heat transfer rate delay was observed in the data for the south-facing wall for both the 10% and 20% PCM concentrations.

King (2004) and Medina et al. (2008) tested the different type of wall, which was called Phase Change Material - Structural Insulated Panel (PCM-SIP). Structural Insulated Panels (SIPs) are composite walls made from three layers, two of which are oriented strand board, which sandwich a layer of expanded polystyrene (EPS). These panels are predicted to gain popularity in the construction market because of their energy efficiency and ease of construction. The purpose of this research was to show the enhanced thermal performance of the panels when PCMs were integrated into the SIPs. Experimental measurements were conducted using the same two identical test houses used by Zhang (2004) and Medina et al. (2008). A similar highly crystalline, n-paraffin based PCM, commercially known as RT-26 was used. This PCM had a melting point of 26 °C (78 °F). Summer results showed that when 10% PCM was applied, the peak heat fluxes across the walls decreased by an average of 37% and 20% for the south-facing and west-facing walls, respectively. When 20% PCM was applied, the peak heat fluxes through the walls decreased by an average of 62% and 60% for the south-facing and west-facing walls, respectively. In addition, the PCM-SIP wall showed more constant surface temperatures when compared to the standard SIP wall, which showed larger temperature fluctuations. More constant surface temperatures translate to occupant comfort.

Zhu (2005) and Medina and Zhu (2008) presented an advanced design of the previously developed integrated Phase Change Material - Structural Insulated Panel (PCM-SIP) developed by King (2004) and Medina et al. (2008). A dynamic wall simulator was designed and built to conduct well-controlled laboratory experiments. All the previous studies at the University of Kansas were performed under full weather conditions. The dynamic wall simulator was shaped as a cubic, which had equally sized removable panels of dimensions 1.2 m (4 ft) x 1.2 m (4 ft). The simulator was equipped with sensors and monitoring systems to measure thermal performances such as temperatures and heat fluxes. An n-Octadecane based PCM with melting point of 25 °C (77 °F) was selected. The PCM-SIPs were fitted with a PCM concentration of 15% based on the weight of one 1.11 cm (7/16 in.) nominal OSB boards. Experiments were conducted through a comparative heat transfer examination of SIPs with and without PCMs. Parameters, such as foam core material of the SIP (i.e., molded expanded polystyrene (EPS) vs. urethane), material of the

PCM holding containers (i.e., copper vs. PVC encapsulating pipes) and configuration of the encapsulating pipes (i.e., vertical vs. horizontal) were evaluated. The results showed that the PCM had more influence over SIPs with EPS core than those with urethane core. Also, the horizontal pipe configuration produced higher heat flux reductions than the vertical pipe configuration. PVC pipes as a PCM holding container were not as efficient as copper pipes.

Evers (2008) and Evers et al. (2010) evaluated the thermal performance of frame walls insulated with *"PCM-enhanced cellulose insulation."* PCM-enhanced cellulose insulation referred to the addition of PCM to cellulose insulation. Paraffin-based, hydrated salt-based, and eutectic PCMs mixed with cellulose insulation were tested using the same dynamic wall simulator which was described in Zhu (2005) and Medina and Zhu (2008). The results on paraffin-based PCMs (commercially-known as RT27) showed that the reductions of peak heat transfer rate with 10% RT27, 20% RT27 and 40% PX27 (powdered paraffin-based PCM) were 5.7%, 9.2%, and 9.3%, respectively. The hydrated salt PCMs TH29 and TH24 and eutectic PCM SP25 did not reduce heat transfer rates compared to the walls with cellulose insulation only.

Fang (2009) and Fang and Medina (2009) studied the thermal behavior of PCMs using DSC (Differential Scanning Calorimeter) tests on pure PCMs, mixture of PCM with cellulose insulation, and *"aged"* PCM samples (i.e., PCMs exposed to ambient air, room temperature, and high temperature conditions). When PCMs were exposed to air, hydrated salt-based PCMs absorbed moisture at about 50% of their weight and lost their heat storage capacity in about eight days of tests and paraffin-based PCMs lost their mass via oxidation. Based on these test results, both of hydrated salt-based PCMs and paraffin-based PCMs could not be mixed directly with insulation.

The *"layer method"* as a new method of incorporating PCMs into the walls was proposed and a numerical model for a paraffin-based PCM in partially-melted processes was developed. The layer method is now known as PCM sheet encapsulation method. That is, small and thin PCMs packets are arranged in sheets similar to reflective bubble wrap sheets. The experimental studies showed that PCM would start to change its phase from partially-melted state when the PCM was integrated into the walls. Not accounting for this fact would lead to incorrect calculations on heat absorption or release in PCM-based systems. From the simulation results, the PCM-enhanced wall using the layer method performed best in reducing peak space cooling load when a PCM layer was 7 mm (0.28 in) thick and was located at 3/16 L from the wallboard, where L was the thickness of the wall cavity.

Reshmeen (2009) performed wall PCM tests in the dynamic wall simulator at the University of Kansas. The layer method was by the referred to as *"PCM-enhanced thermal shield."* The PCM-enhanced thermal shield was tested in two PCM concentrations (10% and 20%), three locations into the wall cavity (next to the wallboard, middle of the wall cavity and next to plywood, i.e., closer to the heating source) at three maximum plywood wall surface temperature ranges (low to high: 52 °C (125 °F), 60 °C (140 °F) and 65 °C (149 °F)). The best results in peak heat transfer rate reduction were achieved when the PCM shield was located next to the wallboard at 20% PCM concentration. The PCM shield reduced peak heat transfer rates by 20.4%, 25.0% and 23.8%, for each maximum wall surface temperature of 52 °C (125 °F), 60 °C (140 °F) and 65 °C (149 °F), respectively.

CHAPTER III

EXPERIMENTAL SET-UP

3.1 Test Houses

In 2000, two 1.83 m × 1.83 m × 1.22 m (6 ft × 6 ft × 4 ft) identical test houses (Figure 3.1 and Figure 3.2) were constructed in the West Campus of the University of Kansas, in Lawrence. The test houses were built using conventional residential construction with scaled down heating and cooling systems. The houses were in an open space where no shade from trees, buildings, or other obstructions existed.

The roof was a built-up roof with gray asphalt shingles, 6.8 kg (15 lb) felt, and 1.27 cm (1/2 in.) plywood sheathing. The wall assemblies were 1.11 cm (7/16 in.) plywood siding, 5.08 cm × 10.16 cm (2 in. × 4 in.) studs, and 1.27 cm (1/2 in.) plywood board. Fiberglass with a resistance of 1.94 $m^2 \cdot K/W$ (R-11) was used for both the ceiling and the walls. In each test house, a window with an area of 0.32 m^2 (3.4 ft^2) was placed in the south-facing walls. Fan coil units were installed inside each house next to the east-facing walls. Figure 3.3 and Figure 3.4 show the details of test houses constructions.

Figure 3.1. Test Houses - Front (South) View

Figure 3.2. Test Houses - Back (North) and East Views

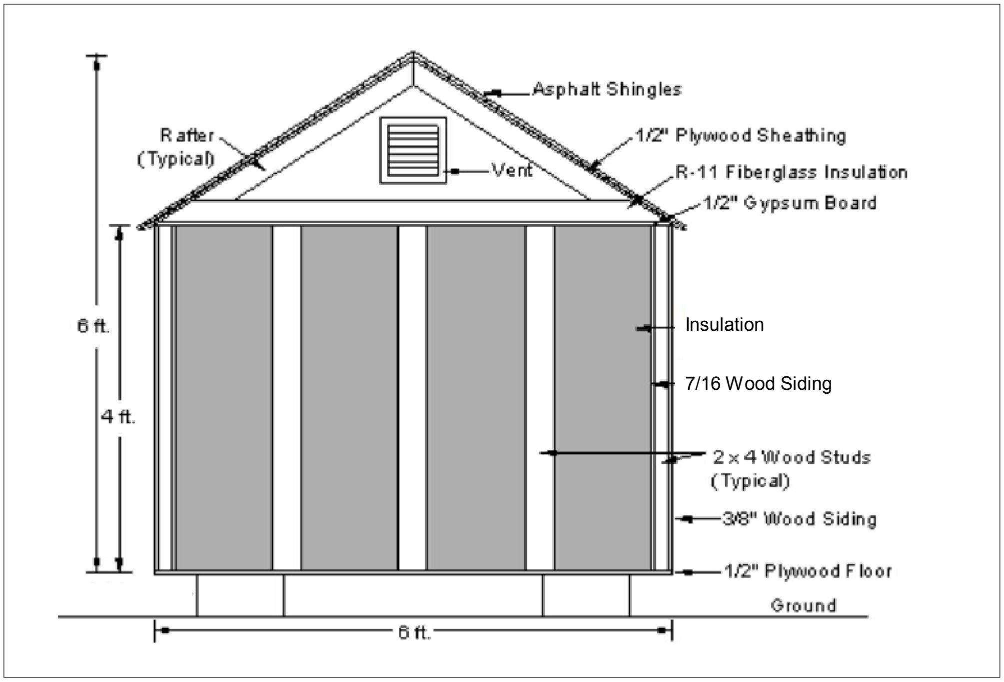

Figure 3.3. Test House Schematic

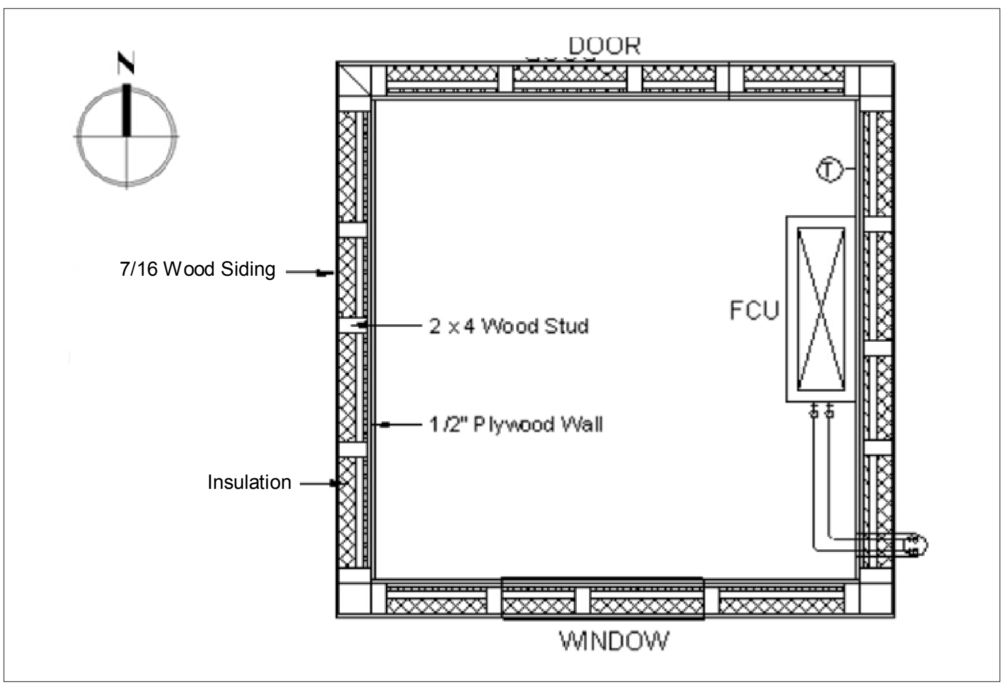

Figure 3.4. Test House - Top Section

3.2 Heating and Cooling Systems

For the space heating system, 1.5 kW electric resistance heaters were used, which were controlled by integrated thermostats and monitored using watt-hour counters. For the cooling system, even the smallest conventional window air conditioner was too large for the houses' space cooling load of 0.56 kW (0.16 tons). In addition, with conventional air conditioners the uncertainty of each unit's coefficient of performance would have entered the mix of variables. Therefore, it was decided to develop a chilled water system as depicted in Figure 3.5.

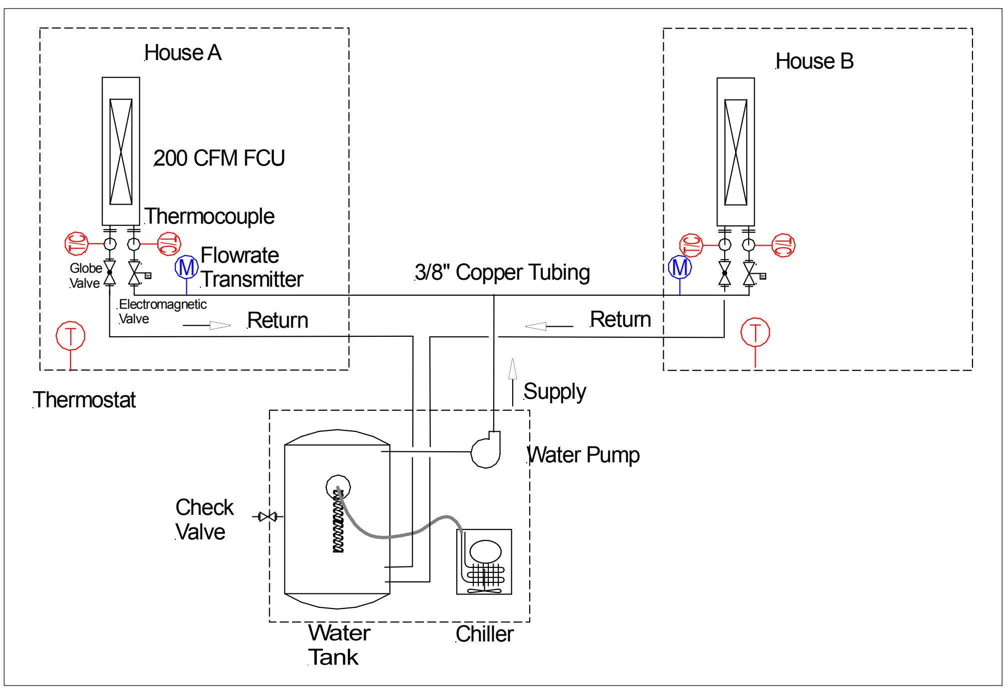

Figure 3.5. Cooling System (Source: Zhang, 2004)

The chilled water system included a water tank, a drop-in titanium coil water chiller, a temperature controller and a set of water pumps. The temperature controller was connected to the chiller to regulate the chilled water temperature in the tank, which was set at around 12.8 °C ± 2.8 °C (55 °F ± 5 °F). The chilled water was circulated from the 265 L (70 gal) insulated plastic tank to each fan-coil-unit (FCUs) inside each test house. The pumps and the electromagnetic valves were controlled by low voltage thermostats to maintain test houses' indoor air temperatures at approximately 21.5 °C ± 0.5 °C (70.7 °F ± 0.9 °F).

3.3 Data Acquisition System

An Agilent 34970A Data Acquisition Unit with 66 channels was used to collect data from thermocouples, heat flux sensors, relative humidity transducers, and from a weather station. The data were transferred to a computer for analysis and archiving.

3.3.1 Temperature Measurements

Type T thermocouples (T/Cs) were installed to measure indoor and outdoor air and wall surface temperatures. For air temperature measurements, the T/Cs was shielded with aluminum tape to minimize radiation exchange effects. For surface temperatures the T/Cs were covered and painted with a thin film of the same color and texture of the surface whose temperature it was measuring. Each wall was instrumented with nine T/Cs arranged in parallel grids. This arrangement gave a representative wall temperature, which was the average of the nine measured points.

The accuracy of the T/C was within ± 0.6 °C (± 1 °F) of the true value of the measurements.

3.3.2 Heat Flux Measurements

Flat Thermal Flux Meters (TFMs) with dimension of 10.16 cm × 10.16 cm × 0.24 cm (4 in. × 4 in. × 3/32 in.) were attached to the interior wall surfaces to measure heat fluxes through the walls. These were pressure mounted using screws. The accuracy was 1% in departure of reading over the repeatable range of the meter.

3.3.3 Relative Humidity Measurements

Relative Humidity (RH) was measured with Vaisala™ HMY60Y Humidity Transducers. Indoor air RH values were transmitted through DC current outputs in the form of 4mA to 20 mA signals. The RH values were calculated by

$$RH\ (\%) = (x - 4) \times 1.00 / (20 - 4) \times 100\%$$

Where, x was the reading of the current output (I) with units of mA.

3.3.4 Weather Station

A Campbell Scientific TM CM10 Tripod Weather Station was installed, which had wind speed sensor, a pyranometer, and temperature and relative humidity probes. Year-round outdoor weather conditions were measured such as outdoor air temperature, relative humidity, solar irradiation and wind speed.

3.4 Phase Change Material Type

In this research, a hydrated salt PCM was used with a macrocapsule containment method (MCM). The PCM was encapsulated in copper pipes mounted to the studs via light metal frames.

3.4.1 PCM Properties

The type of PCM used in this research was a hydrated salt PCM with melting and solidification temperatures in the range of 28.0 °C ~ 30.0 °C (82.4 °F ~ 86.0 °F). The PCM was commercially-known as TH29 and was produced by PCM Energy P. Ltd., Mumbai, India. The main component of TH29 was calcium chloride hexahydrate. The properties of TH29 are listed in Table 3.1.

Table 3.1. Properties of the PCM Used in the PCFWs
(Source: PCM Energy P. Ltd. Mumbai, India)

Property	Value
Appearance	Translucent
Base Material	Inorganic Salts
Phase Change Temperature	28.0 ~ 30.0 °C (82.4 ~ 86.0 °F)
Subcooling	2.0 °C (3.6 °F) Max
Specific Gravity	1.48 ~ 1.50
Maximum Operating Temp	100.0 °C (212 °F)
Latent Heat	175.0 ~ 188.0 J/g (75.2 ~ 80.8 Btu/lb_m)
Specific Heat	2.0 J/g °C (0.5 Btu/lb_m °F)
Thermal Conductivity	1.0 W/m °C (0.6 Btu/hr ft °F)
Congruent Melting	Yes
Flammable	No
Thermal Stability	>10000 Cycles

3.4.2 Containment of PCM and Arrangement of PCM Pipes

In this research, a macrocapsule containment method (MCM) rather than an imbibing method (IM) was used. In the IM, the PCM was infused into the gypsum board. The MCM is safer and more stable than the IM because PCMs are first encapsulated in pipes, which are then capped at both ends to prevent leakage. The MCM eliminates PCM dripping (if any) and contact issues, eliminates moisture transfer problem across the envelope, and reduces the flammability of the wall. Preliminary fire tests indicated that the PCFWs passed wall fire tests (Miller, G., 2007). In addition, because the pipes were never completely filled with PCM, problems associated with PCM volume changes during the phase change process were eliminated.

The PCM was encapsulated in 2.54 cm (1 in.) diameter thin-walled cylindrical copper pipes 38.1 cm (15 in.) in length. The pipes were closed with sealed caps at both ends to prevent leakage. The pipes were placed horizontally and were attached to the studs via a light metal "ladder type" frame. This arrangement is shown in Figure 3.6. The PCM-filled pipes were assembled within the wall and held in place by light metal "ladder type" frames, which were then fastened to the studs. Thus, no holes were drilled across the studs, which otherwise could have reduced their structural properties.

Two sets of PCFWs were fabricated, one set contained enough PCM to amount to a PCM concentration of 10% and one set contained twice as much PCM to produce a 20% PCM concentration. The percent concentrations of PCM were based on the mass of the indoor wallboard. For example, if the wallboard of one wall had a mass of 45.36 kg (100 lb), to make a PCFW at 10% PCM concentration, it required an amount of PCM inside all the pipes of the PCFW equivalent to 4.54 kg (10 lb). The concentrations were achieved by varying the number of pipes placed in each wall.

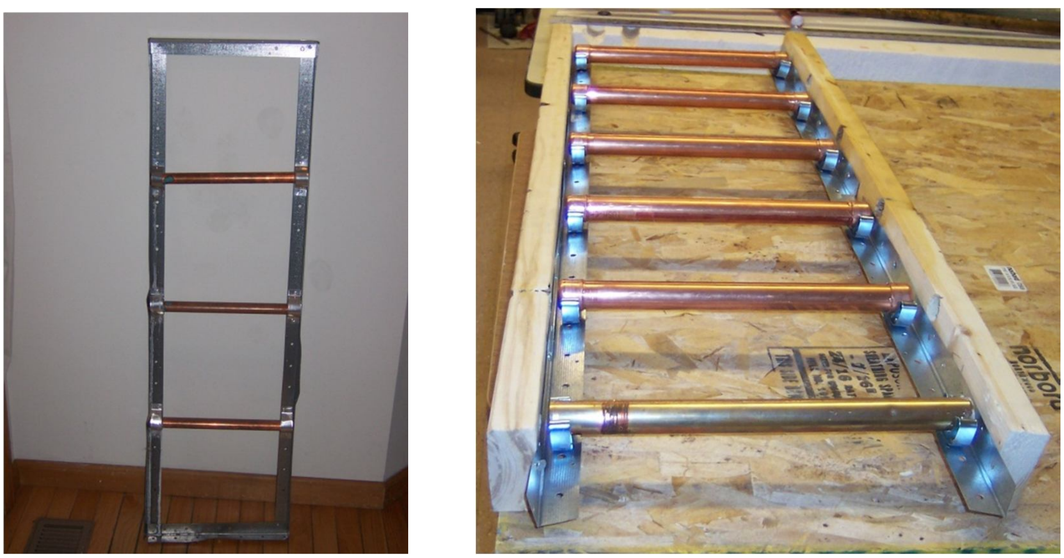

Figure 3.6. Light Metal "Ladder Type" Frame Holding PCM Pipes for PCFWs (Photo courtesy of Building Thermal and Material Science Laboratory)

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Pre-retrofit Thermal Performance Verification of the Test Houses

It was necessary to perform calibration tests before any retrofit. For this, the thermal performances of the two houses were compared and recorded as reference. Indoor air temperatures, average wall temperatures, and surface heat fluxes were measured and compared to verify their similarity.

4.1.1 Indoor Air Temperatures

During the calibration period, the indoor air temperatures of the test houses were controlled to the high precision of 0.05 °C (0.1 °F) difference between both test houses. That is, the control house was kept at an average indoor air temperature of 24.17 °C (75.5 °F), while the soon-to-be-retrofit house was kept at an average temperature of 24.22 °C (75.6 °F). This level of temperature control would make the result significantly accurate. Figure 4.1 and Figures 4.2 (a), (b) show the level of precision to which the indoor air temperatures and outside surface temperatures were controlled. In Figure 4.1, and all subsequent figures used for comparison purposes, the darker solid lines represented data from the test house that was always kept as the control house. The lighter solid lines with the symbols (dots) represented the data of the house that was always used as the retrofit house. That is, the house with the Phase Change Frame Walls.

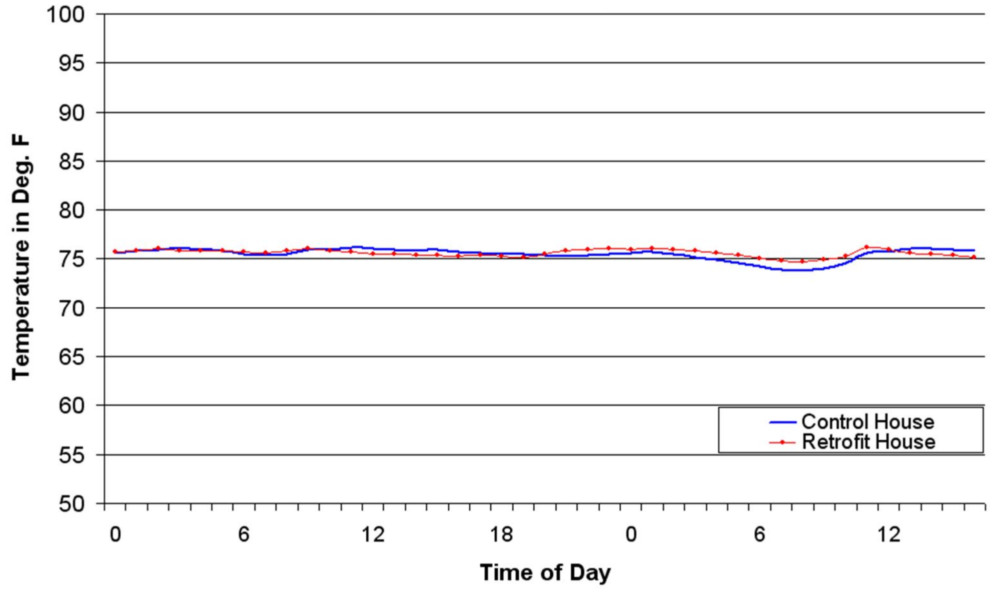

Figure 4.1. Indoor Air Temperatures during Pre-retrofit Tests

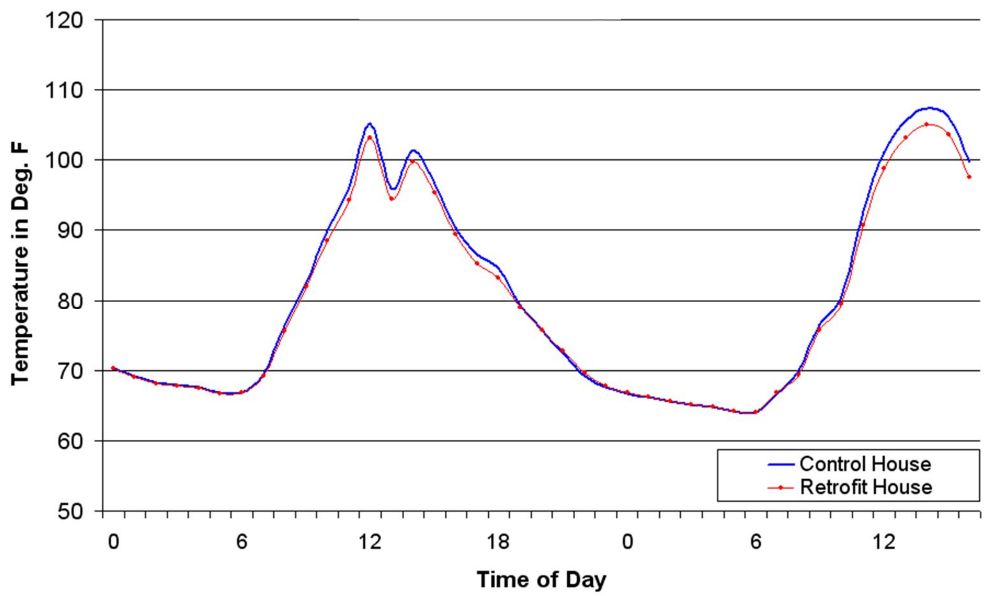

Figure 4.2 (a). Outside Surface Temperatures of the South Walls during Pre-retrofit Tests

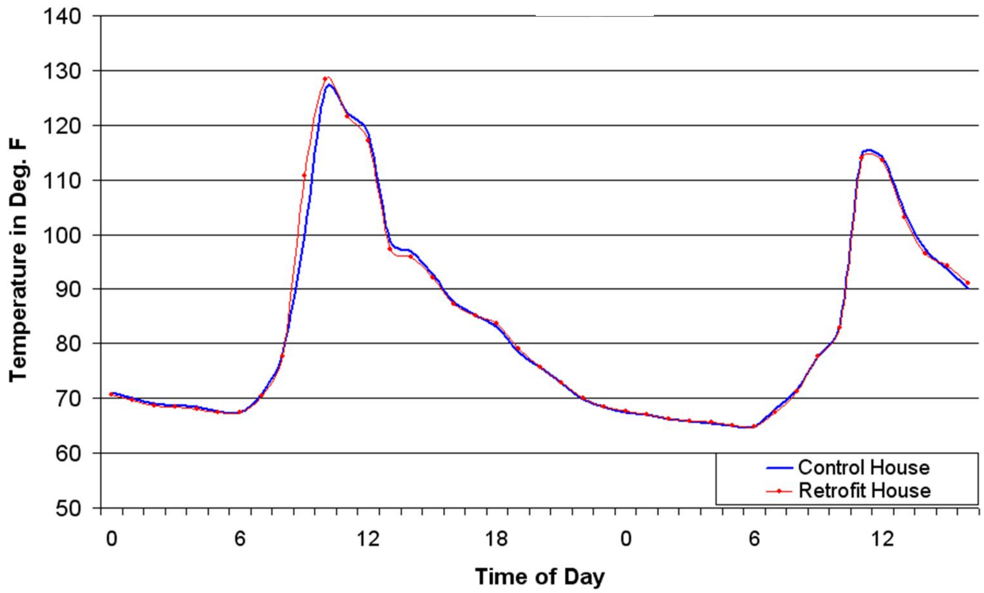

Figure 4.2 (b). Outside Surface Temperatures of the East Walls during Pre-retrofit Tests

4.1.2 Heat Transfer Rates Across the Walls

Figures 4.3. (a), (b), (c), and (d) show the heat transfer rate comparisons for the north, south, east and west walls, respectively. From the trend shown in these figures, it was concluded that the thermal responses of both test houses were nearly identical. In addition, the high level of control exercised during the experiments can be observed. The average difference in peak heat transfer rate for the north, south, east, and west walls were approximately 4.5%, 3.5%, 3.8%, and 0.5%, respectively.

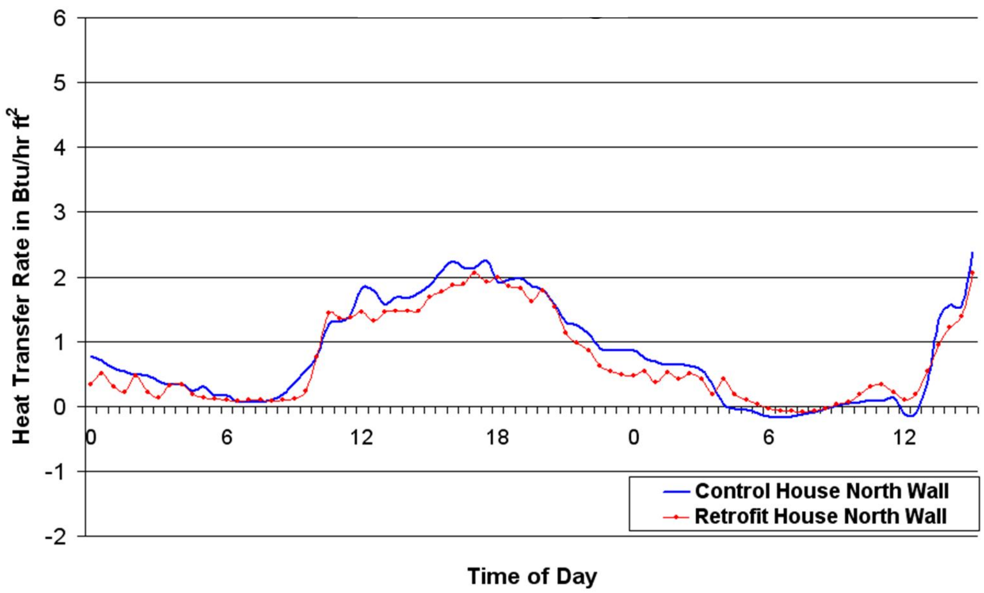

Figure 4.3 (a). Wall Heat Transfer Rates Across the North Walls during Pre-retrofit Testing

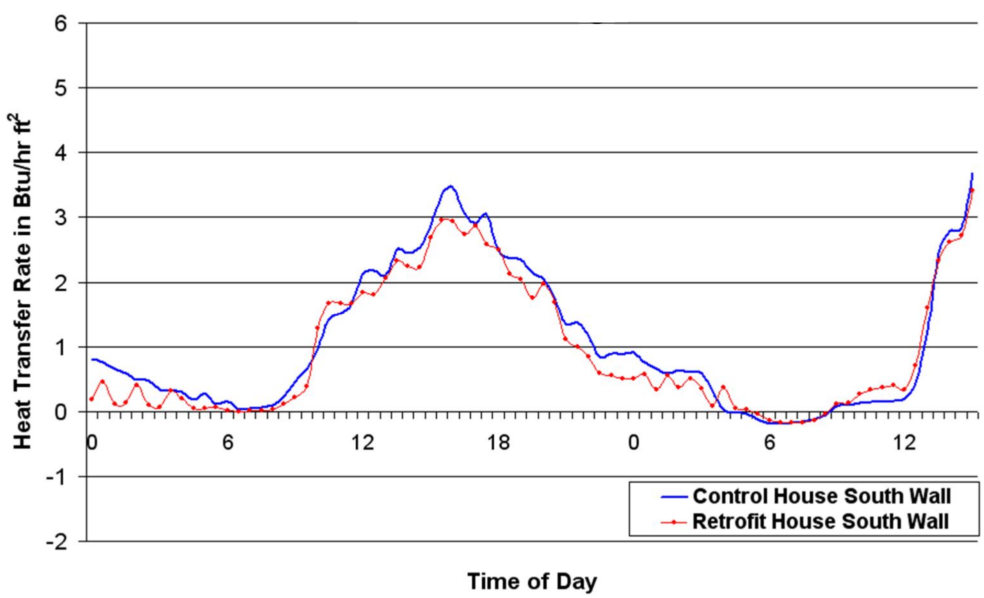

Figure 4.3 (b). Wall Heat Transfer Rates Across the South Walls during Pre-retrofit Testing

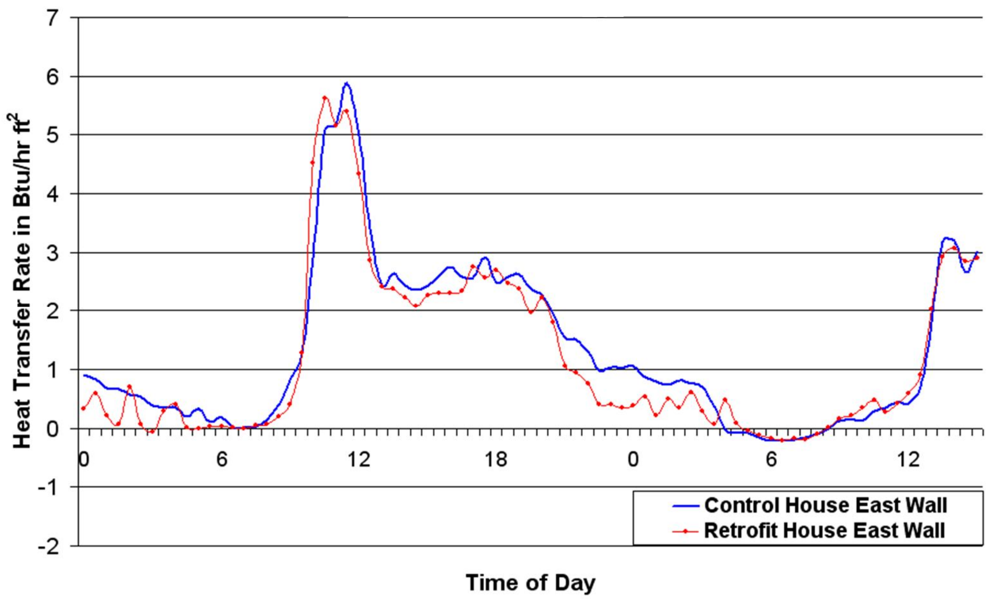

Figure 4.3 (c). Wall Heat Transfer Rates Across the East Walls during Pre-retrofit Testing

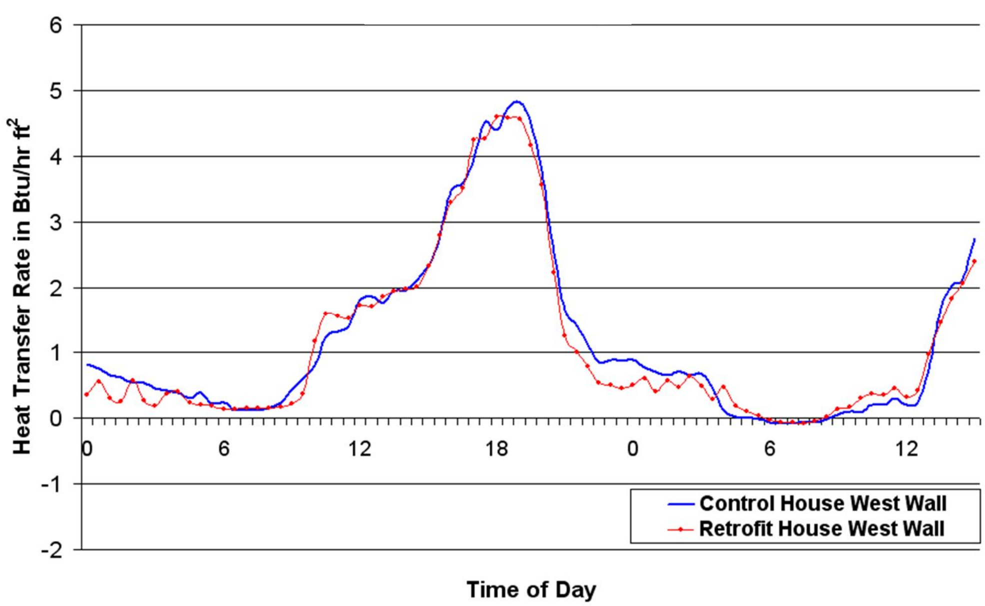

Figure 4.3 (d). Wall Heat Transfer Rates Across the West Walls during Pre-retrofit Testing

4.2 Performance of PCFWs at 10% PCM Concentration

The performance of PCFWs at 10% PCM concentration was evaluated by measuring and analyzing the heat transfer rates across the walls, indoor air temperatures, interior wall surface temperatures and indoor air relative humidities.

4.2.1 Heat Transfer Rates Across the Walls

The average reductions in peak heat transfer rates when using the PCFW in the north, south, east, and west walls were 33.7%, 25.6%, 24.3%, and 24.6%, respectively. Figures 4.4 (a), (b), (c), (d) show the comparisons in heat transfer rates in the north, south, east and west walls, respectively, and Table 4.1 summarizes the reductions in peak heat transfer rate in each of the walls. Percent reductions of peak heat transfer rates were calculated using Equation 1:

$$Percent\ \mathrm{Re}duction(\%) = \frac{(PHTR\ for\ Std\ Wall - PHTR\ for\ PCFW)}{PHTR\ for\ Std\ Wall} \times 100 \qquad \text{(Eq. 1)}$$

Where *PHTR* was the peak heat transfer rate.

Table 4.1. Peak Heat Transfer Rate Reductions Produced by the PCFWs at 10% PCM Concentration

Wall Orientation	Peak Heat Transfer Rate Reduction (%)
North	33.7
South	25.6
East	24.3
West	24.6
Average	27.1

In terms of load shifting to off-peaks times, it was found that the shift was approximately one hour. A longer time shift had been expected. However, this could be explained by the melting and solidification temperatures of TH29 as being higher than those of the paraffin PCMs, which were the ones used in previous research.

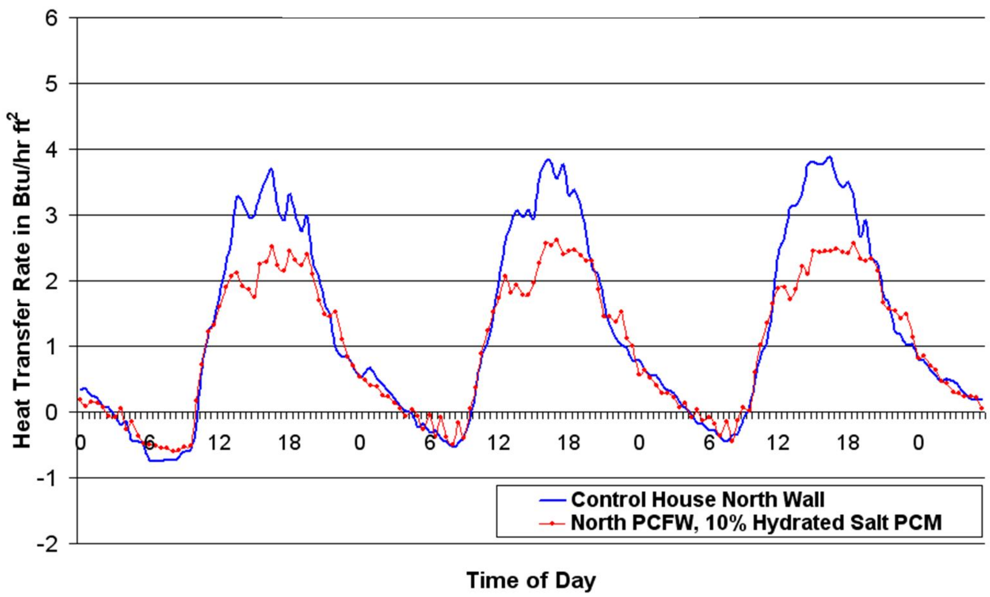

Figure 4.4 (a). Wall Heat Transfer Rates Across the North Walls at 10% PCM Concentration

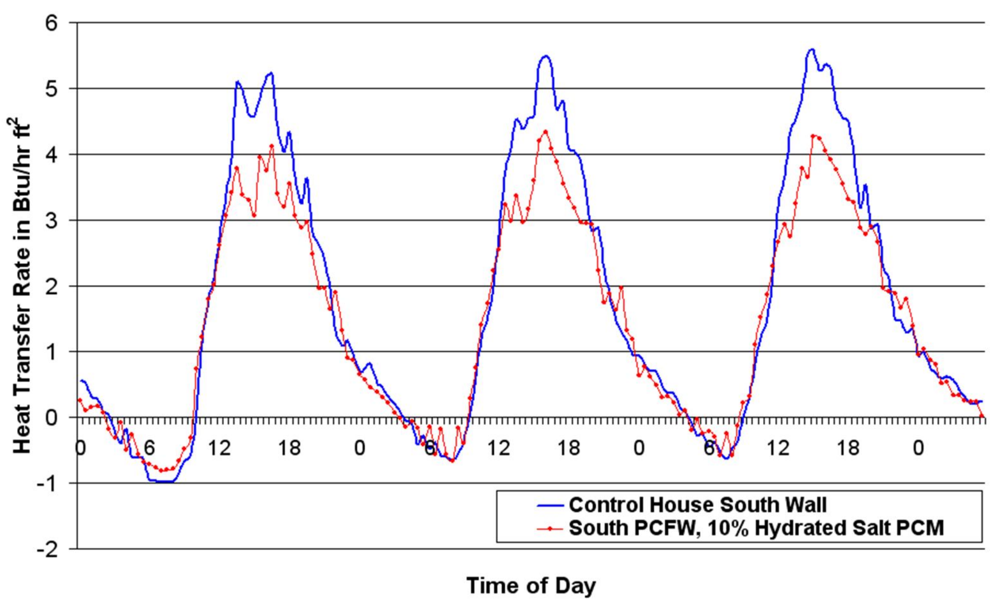

Figure 4.4 (b). Wall Heat Transfer Rates Across the South Walls at 10% PCM Concentration

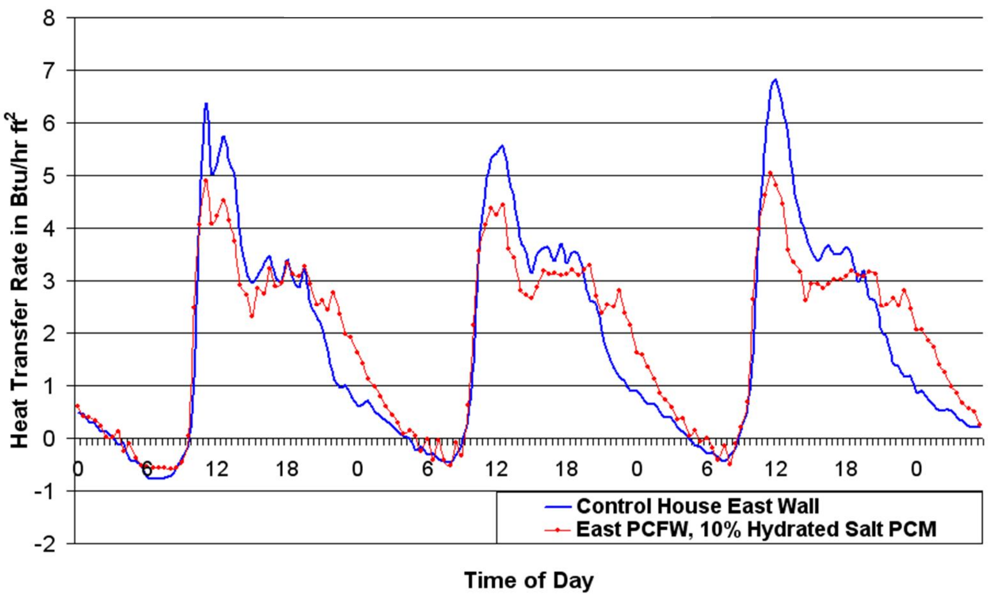

Figure 4.4 (c). Wall Heat Transfer Rates Across the East Walls at 10% PCM Concentration

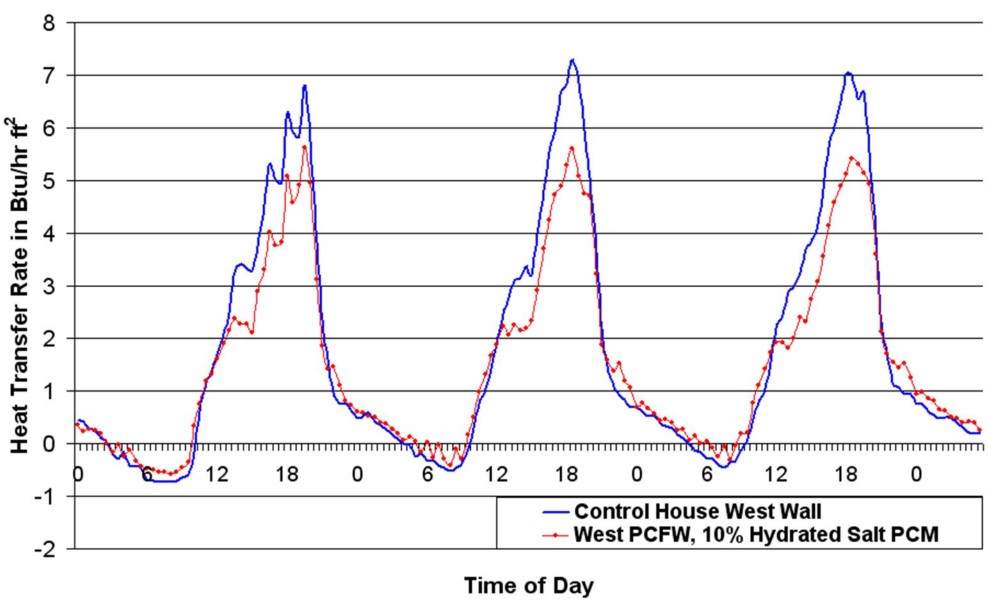

Figure 4.4 (d). Wall Heat Transfer Rates Across the West Walls at 10% PCM Concentration

The average indoor air temperature in test houses differed by approximately 0.22 °C (0.4 °F) during the experiments. That is, the control house had an average indoor air temperature of 23.2 °C (73.7 °F) while the retrofit house had an average indoor temperature of 23.4 °C (74.1 °F). Figure 4.5 shows the indoor air temperature of both test houses at during the experiments when the PCFW had a concentration of PCM of 10%.

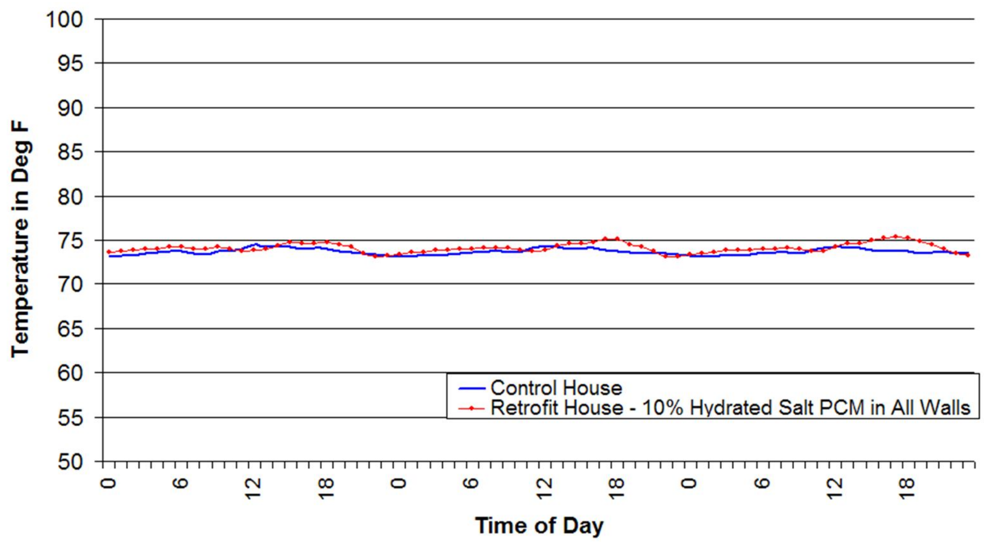

Figure 4.5. Indoor Air Temperatures at 10% PCM Concentration

4.2.2 Interior Wall Surface Temperatures

Figure 4.6 depicts how the PCFW was able to keep a more constant interior wall surface temperature and a narrower temperature swing (fluctuation) than the standard wall. For each wall represented in Figure 4.6, two segments are depicted. The segment in the left represents the data of the pre-retrofit period, while the segment in the right represents the data corresponding to retrofit period at 10% PCM concentration. Each segments shows indoor surface temperature for a PCFW and for the equivalent standard wall. For example, for the north walls in Figure 4.6, the indoor surface temperature of the control house was, on average, 23.6 °C (74.5 °F) while the surface temperature of the PCFW was 22.5 °C (72.5 °F). The temperature swing in the standard wall was 2.22 °C (4.0 °F) while it was 1.06 °C (1.9 °F) for the PCFW.

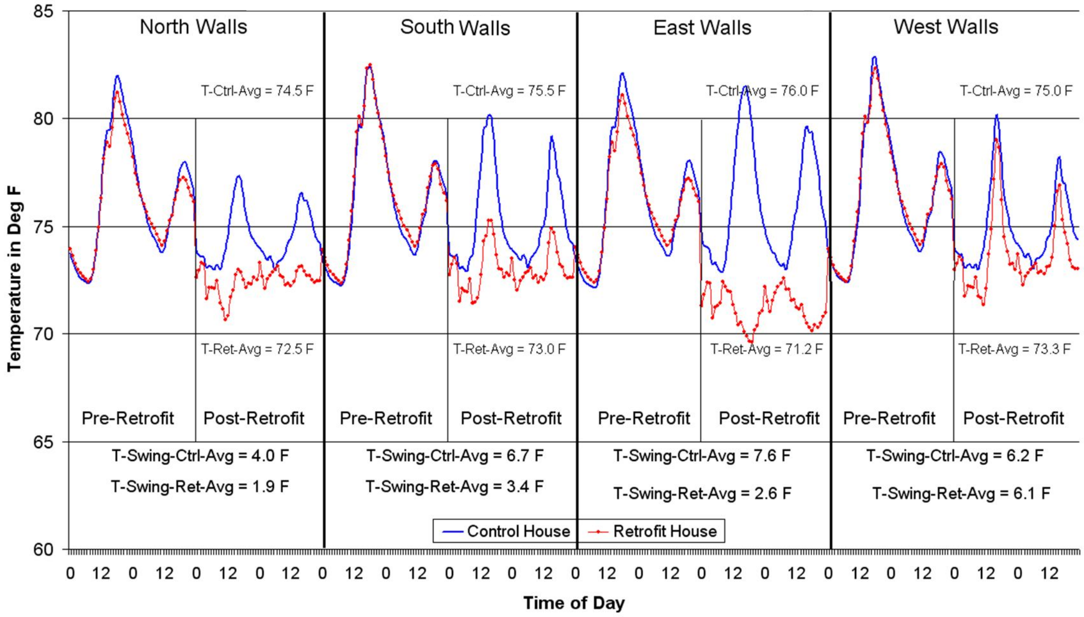

Figure 4.6. North, South, East, and West Walls Inside Surface Temperatures during Pre and Retrofit Tests at 10% PCM Concentration

Table 4.2 summarizes the findings related to the reductions in interior wall surface temperatures and the changes in daily temperature swings. Therefore, it showed that the PCFWs, containing PCM walls, were able to not only lower the interior wall surface temperature of the walls, but also their daily temperature fluctuations. From Table 4.2, an average reduction of inside wall surface temperature and daily temperature fluctuations were 1.44 °C (2.6 °F) and 1.44 °C (2.6 °F), respectively. These results could translate to human comfort and to increased life of the comfort equipment. This is the case because more constant surface temperatures mean longer "on" and "off" periods in the operation cycles of the equipment. This in turn translates to lower "on" "off" mechanical fatigue in the shafts of rotating equipment, such as fans and compressors.

Table 4.2. Reductions in Inside Wall Surface Temperatures and Reductions in Temperature Fluctuations from Using PCFWs at 10% PCM Concentration

Wall Orientation	Average Surface Temperature °C (°F)		Difference °C (°F)	Average Daily Temperature Swing °C (°F)		Difference °C (°F)
	Control	Retrofit		Control	Retrofit	
North	23.6 (74.5)	22.5 (72.5)	1.11 (2.0)	2.22 (4.0)	1.06 (1.9)	1.16 (2.1)
South	24.1 (75.3)	22.8 (73.0)	1.28 (2.3)	3.72 (6.7)	1.89 (3.4)	1.83 (3.3)
East	24.4 (76.0)	21.8 (71.2)	2.67 (4.8)	4.22 (7.6)	1.44 (2.6)	2.78 (5.0)
West	23.9 (75.0)	22.9 (73.3)	0.72 (1.3)	3.44 (6.2)	3.39 (6.1)	0.05 (0.1)
Average	24.0 (75.2)	22.6 (72.6)	1.44 (2.6)	3.39 (6.1)	1.94 (3.5)	1.44 (2.6)

4.2.3 Indoor Relative Humidity

One other key parameter that affects the comfort level of building occupants is relative humidity (RH). There was a concern that the use of the PCFWs would increase the indoor air RH. The imbibing method (IM) by immersing gypsum boards in PCM caused moisture transfer problems because the interior surfaces were covered with PCM, thus creating a moisture barrier. In this thesis, a main purpose of comparing indoor air RH of the retrofit house to the indoor RH of the control house was to observe whether the macrocapsule containment method (MCM) caused moisture transfer problems. From the experiments, it was found that the increase in relative humidity as a result of the retrofits was less than 5%. Therefore, the results indicated that indoor air relative humidity was not significantly affected by using PCFWs. Table 4.3 summarizes the results and Figure 4.7 shows them in graphical form for the pre-retrofit period and for the period after the application of the PCFWs.

Table 4.3. Changes in Indoor Air Relative Humidity from Using PCFWs at 10% PCM Concentration

	Control House (%)	Retrofit House (%)	Difference (%)
Calibration	68.0	68.0	0.0
10% PCM Tests	56.3	60.5	4.2

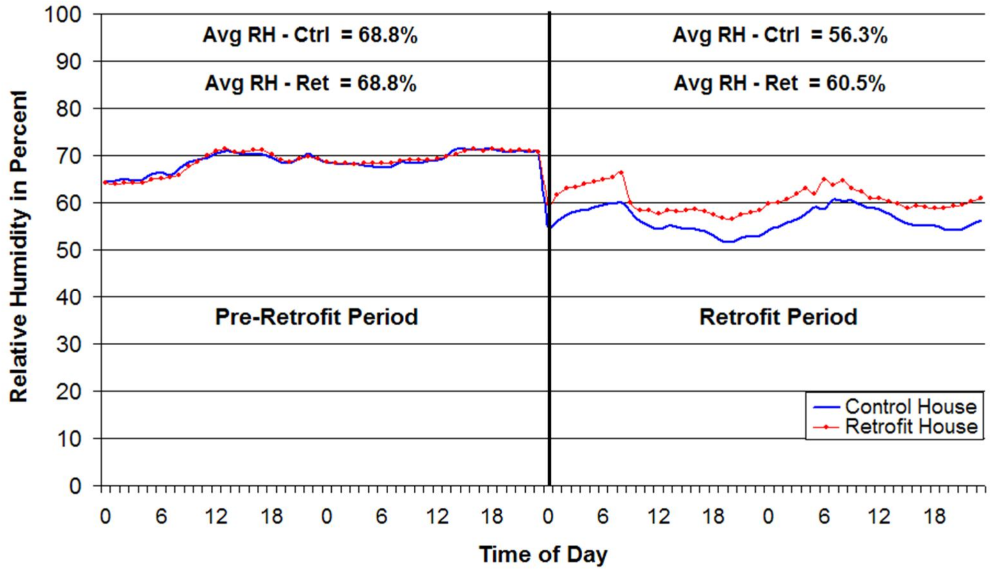

Figure 4.7. Indoor Air Relative Humidity during Pre and Retrofit Tests at 10% PCM Concentration

4.3 Performance of PCFWs at 20% PCM Concentration

The same analyses that were performed for the 10% PCM concentration were performed for a 20% PCM concentration. The testing protocol was the same, the only difference being that twice as much PCM was added to the retrofit house. The reductions in peak heat transfer rates and indoor surface temperatures between the control walls and the PCFWs at a PCM concentration of 20% were nearly identical to those obtained when the account of PCM corresponded to 10% PCM concentration.

This meant that doubling the amount of PCM did not produce a significant improvement.

4.3.1 Heat Transfer Rates Across the Walls

The average reduction in peak heat transfer rate when using the PCFW at 20% PCM concentration in the north, south, east and west walls were 27.1%, 29.2%, 25.7%, and 27.2%, respectively. Table 4.4 summarizes these results. From Table 4.4, and aside from the north-facing wall, it was observed that doubling the quantity of PCM in the PCFWs improved their performance by 3.6%, 1.4%, and 2.6% for the south, east, and west walls, respectively.

Table 4.4. Peak Heat Transfer Rate Reductions from Using PCFWs at 20% PCM Concentration and Comparison with at 10% PCM Concentration

Wall Orientation	Peak Heat Transfer Rate Reduction from Using PCFW		
	20% PCM Concentration (%)	10% PCM Concentration (%)	Difference (%)
North	27.1	33.7	-6.6
South	29.2	25.6	3.6
East	25.7	24.3	1.4
West	27.2	24.6	2.6
Average	27.3	27.1	0.2

Where Difference (%) = 20% PCM Concentration (%) - 10% PCM Concentration (%)

Figures 4.8 (a), (b), (c), (d) show the comparisons of heat transfer rates for the north, south, east and west walls.

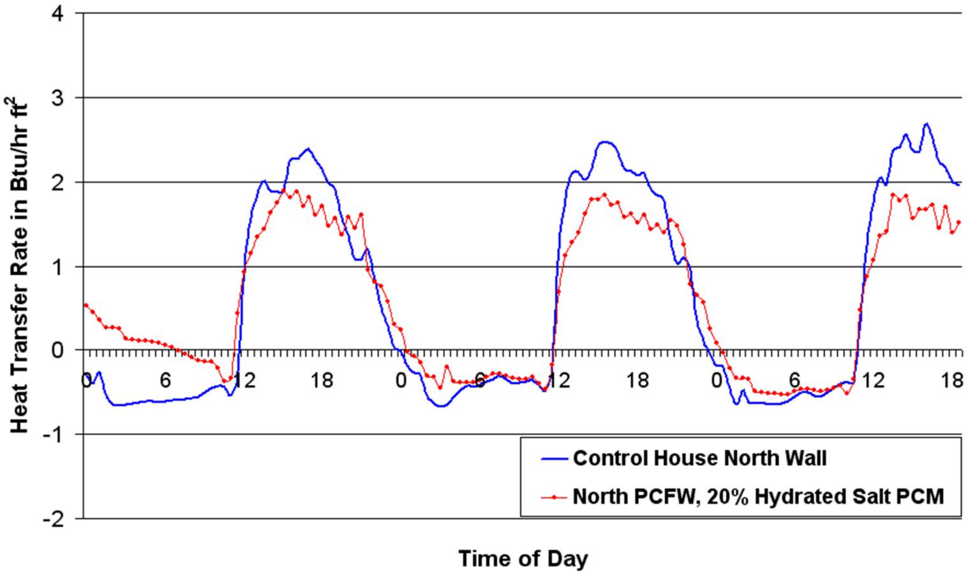

Figure 4.8 (a). Wall Heat Transfer Rates Across the North Walls at 20% PCM Concentration

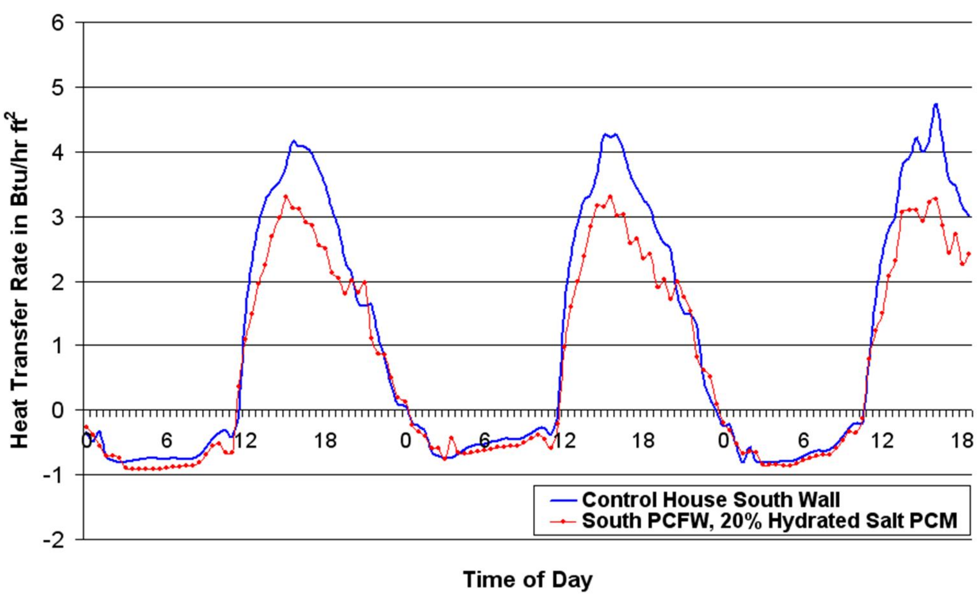

Figure 4.8 (b). Wall Heat Transfer Rates Across the South Walls at 20% PCM Concentration

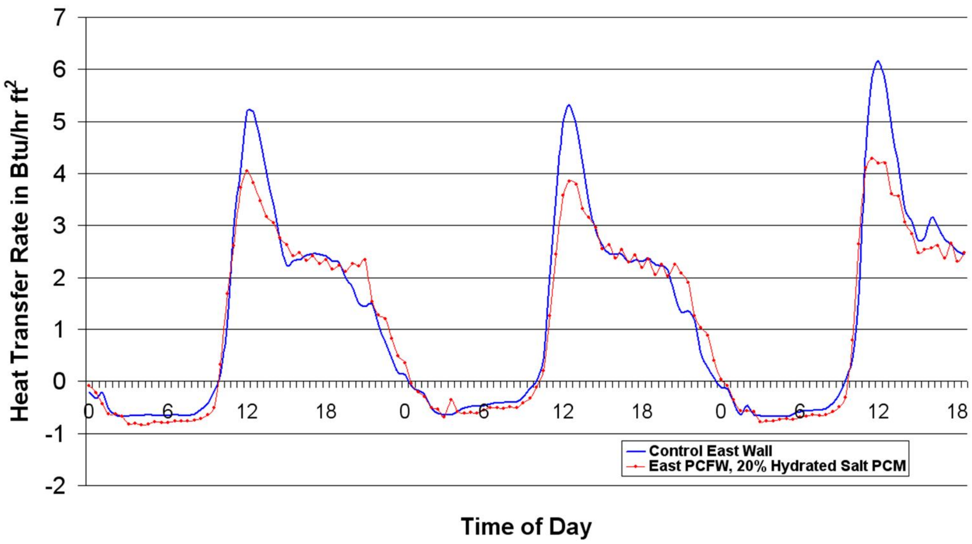

Figure 4.8 (c). Wall Heat Transfer Rates Across the East Walls at 20% PCM Concentration

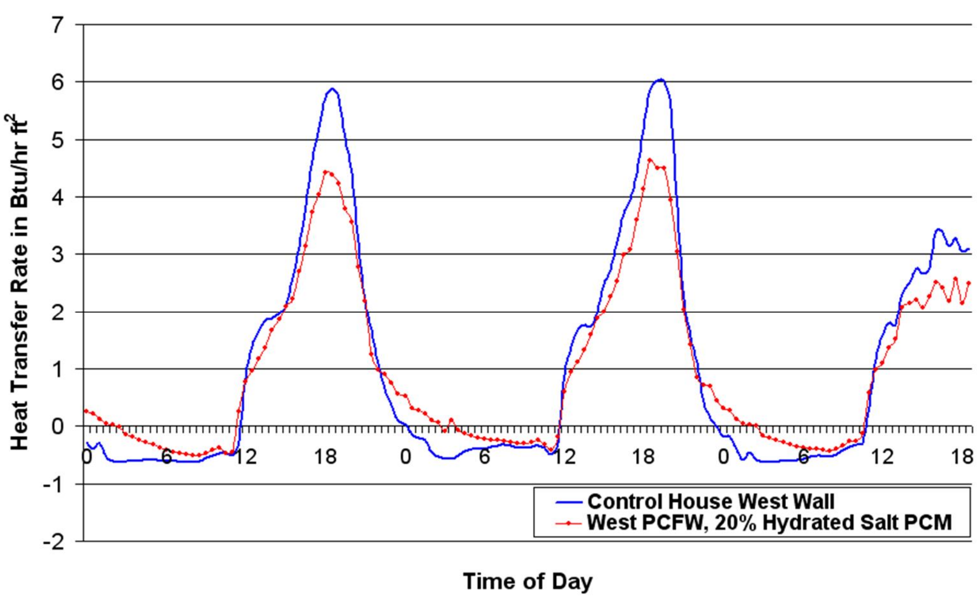

Figure 4.8 (d). Wall Heat Transfer Rates Across the West Walls at 20% PCM Concentration

4.3.2 Interior Wall Surface Temperatures

Table 4.5 summarizes indoor surface temperatures in the control and PCFW walls for a PCM concentration of 20% in the PCFWs. The average indoor surface temperature of the four control walls was 23.9 °C (75.0 °F) while the indoor surface temperatures in the PCFWs was 22.4 °C (72.3 °F), or a reduction of 1.50 °C (2.7 °F). The average temperature fluctuation (swing) in the control walls was 3.17 °C (5.7 °F) while it was 1.72 °C (3.1 °F) in the PCFW, or a reduction of 1.44 °C (2.6 °F) for the temperature fluctuations. These values were almost identical to the values obtained when the PCM concentration in the PCFWs was 10%. The surface temperatures of the PCFWs were, as expected, more constant than the control walls. The results are shown graphically in Figure 4.9.

Table 4.5. Reductions in Inside Wall Surface Temperatures and Reductions in Temperature Fluctuations from Using PCFWs at 20% PCM Concentration

Wall Orientation	Average Surface Temperature °C (°F)		Difference °C (°F)	Average Daily Temperature Swing °C (°F)		Difference °C (°F)
	Control	Retrofit		Control	Retrofit	
North	23.6 (74.5)	22.3 (72.2)	1.28 (2.3)	2.17 (3.9)	0.83 (1.5)	1.33 (2.4)
South	24.2 (75.5)	22.7 (72.8)	1.50 (2.7)	4.17 (7.5)	2.06 (3.7)	2.11 (3.8)
East	24.1 (75.3)	21.7 (71.1)	2.33 (4.2)	3.28 (5.9)	1.06 (1.9)	2.22 (4.0)
West	23.8 (74.8)	22.9 (73.2)	0.89 (1.6)	3.00 (5.4)	2.94 (5.3)	0.06 (0.1)
Averages	23.9 (75.0)	22.4 (72.3)	1.50 (2.7)	3.17 (5.7)	1.72 (3.1)	1.44 (2.6)

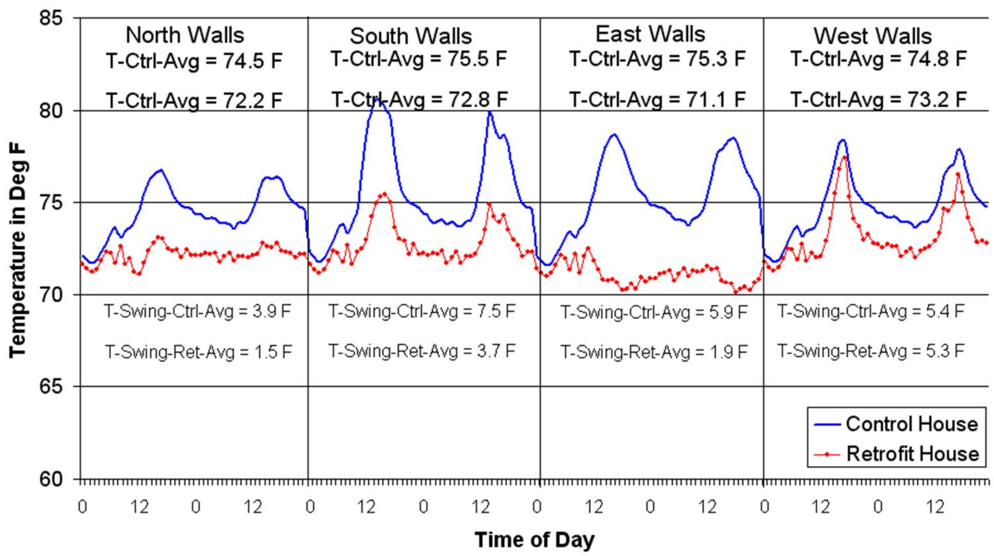

Figure 4.9. North, South, East, and West Walls Inside Surface Temperatures during Pre and Retrofit Tests at 20% PCM Concentration

4.3.3 Indoor Relative Humidity

As summarized in Table 4.6, for the case of a PCM concentration of 20% the relative humidity of both houses remained virtually the same at about 64%. Figure 4.10 shows the RH for the pre-retrofit period and for the period after the application of the PCFWs at a PCM concentration of 20%.

Table 4.6. Changes in Indoor Air Relative Humidity from Using PCFWs at 20% PCM Concentration

	Control House (%)	Retrofit House (%)	Difference (%)
Calibration	68.0	68.0	0.0
20% PCM Tests	64.0	64.4	0.4

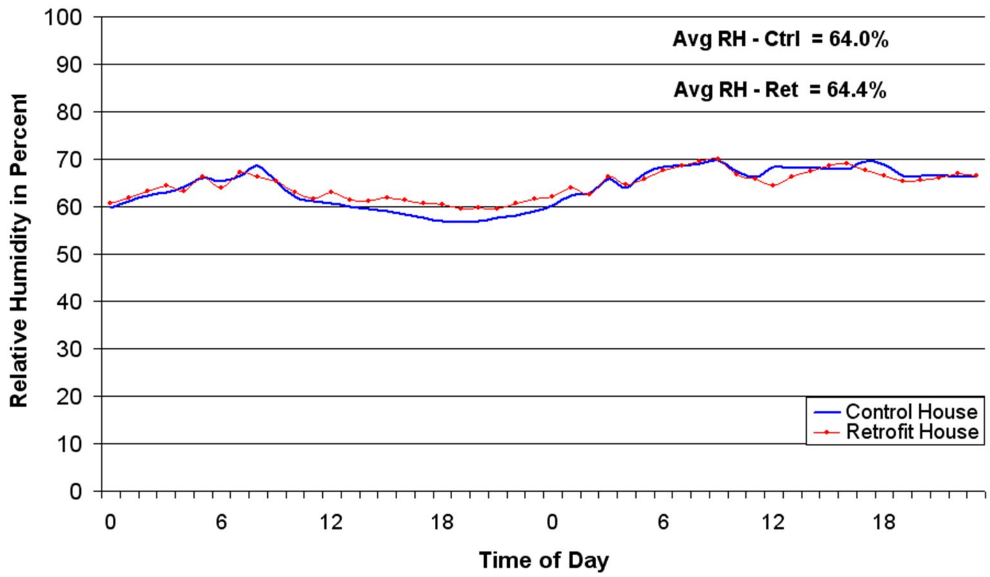

Figure 4.10. Indoor Air Relative Humidity during Pre and Retrofit Tests at 20% PCM Concentration

CHAPTER V

EXTRAPOLATION OF RESULTS FOR CALIFORNIA CLIMATES

5.1 Refinement of an Existing Computer Model

An existing computer model was refined to predict heat transfer rates across PCFWs in California climates. The model was verified against experimental data for a control wall and PCFWs at 10% and 20% PCM concentrations located in Lawrence, KS climate.

5.1.1 Refinement and Assumptions

A computer model that had been developed to predict heat transfer across residential walls by Fang (2009) was refined to add the heat transfer during melting and solidification of the PCMs in the walls. In addition, the model was verified against experimental data to assess its accuracy. The purpose for this was that a verified model could be used to translate experimental results to full-scale buildings located in basically all climates.

Several methods were explored during the development of the phase change heat transfer process module. Of these, the two that were the most robust and commonly used were the enthalpy method (EM) and effective heat capacity method (EHCM). In this thesis, the effective heat capacity method was selected, but was modified according to several observations and experimentations conducted at by peers at the University of Kansas. For example, it is inherent in the EHCM that latent heat, Q_{lat}, is released during phase change as a function of temperature. However, instead of using the original specific heat c_p for either solid or liquid state of the PCM during the phase change process, an additional value was added, which resulted in a large effective c_p. This was done to simulate the slow temperature change during the phase change process. Similarly, several relationships between c_p and phase change temperature could have been assumed. However, a simple linear relationship proved to give the best results. Therefore, the value of c_p was simulated as a linear function of temperature.

A typical wood frame wall of a residential house was chosen as the control volume to use to refine the model. The schematic of the wall is shown in Figure 5.1. To simplify the problem, the effects of the studs in the walls were neglected. Because the heat transfer rate across the studs lags the heat transfer rate across the insulation part of the wall, it was assumed that the simplification of not accounting for the studs would create only a small error. The exterior of the wall was considered to be 1.59 cm (5/8 in.) plywood sheathing. The insulation was assumed to be 8.89 cm (3 1/2 in.) thick 1.94 m^2 K/W (11 ft^2 hr °F/Btu, R11) fiberglass batt, which was assumed to fill the whole cavity between studs. In addition, air transfer and moisture transfer that are part of the mass transfer mechanisms were also neglected. In heat transfer modeling of wall systems, the air transfer is often neglected. The moisture transfer, however, in the form of water vapor, is sometimes included. Errors of not including the moisture transfer may be significant, but only during late night and early hours of the morning. In this study, however, these time periods are not as relevant as the ones that take place during solar activity. This is because it is during periods of solar activity that the PCM melts and offers the potential to reduce the heat transfer rate and thus energy use in air conditioning. A 1.27 cm (1/2 in.) gypsum board was assumed for the inside sheathing. Set of 2.68 cm (1 1/16 in.) diameter, type 'M' copper tubes were used to encapsulate the PCM. The simulated PCM was a commercially-available n-paraffin-based PCM with a melting point of 27 °C (80.6 °F). The PCM was sold under the brand name RT27. The model positioned the pipes within the insulation section very similar to the actual conditions. The interior convective heat transfer coefficient was assumed to have a constant value of 8.29 W/m^2 K (1.46 Btu/hr ft^2 °F). The external walls' convective heat transfer coefficient was assumed to be 22.71 W/m^2 K (4.0 Btu/hr ft^2 °F).

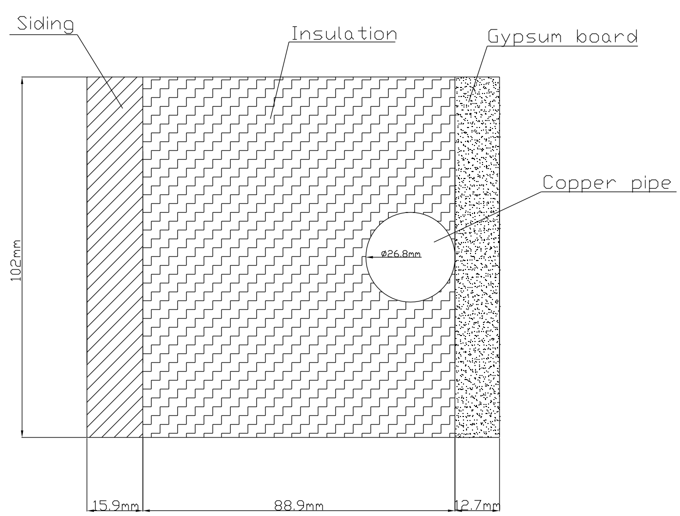

Figure 5.1. Schematic of Simulated Wall

5.1.2 Model Verification

The model was implemented by writing a computer program in FORTRAN. The program used an iterative process to predict temperatures and heat fluxes using finite difference principles. The first stage in the programming process was to input the wall construction component (e.g., sheathing layer) dimensions and materials properties. Next, the parameters used in the phase change calculations were input. These included the description, via properties, of the selected phase change materials. These were density, melting temperature, and solidification temperature. Convection and radiation parameters were also input to the program. These included convection heat transfer coefficients and surface emissivities. Then, hourly weather data was input (one time step at a time). These weather data included: hour of the day, date, and outdoors air temperature. The indoor air temperature was assumed constant. During the model verification, time series of actual indoor air temperatures were used.

The structure of the model was based on subroutines. As such, once the values of the various computed parameters (e.g., radiation coefficients) were returned to the main program, temperature data were sent to a matrix subroutine, which used these values to compute temperatures. An iterative process was used in which new values of temperatures were calculated and compared to previous values of temperatures by taking their differences. That is, $T_{\text{surface i at time j}}$ was compared to $T_{\text{surface i at time j+time step}}$ in terms of their differences. The iteration would stop until a tolerance value of 0.05 °C (0.1 °F) was reached. That is, if the new values computed in the last iteration subtracted by the value of the next to the last iterations differed by more than the tolerance, the process was started over (the newly calculated values were used to re-estimate all coefficients) until convergence was achieved. After convergence was attained, the heat fluxes were calculated.

The outputs of the program were hourly surface temperatures and heat fluxes (heat transfer rates per unit area). Of all the many parameters that could be estimated with the program, the most valuable for this study was wall heat transfer rate. As such, most of the performance evaluations of PCFW were based on wall heat flux reductions. Most of the comparisons between control and retrofit houses as well as between model predictions and the experimental data are therefore presented in terms of wall heat fluxes.

The "base case" term was used to refer to a wall without PCM. Savings produced as a result of using a PCFW must be evaluated on the basis that there existed a model house with outer walls with no PCM; this was considered the base or control case. Figure 5.2 shows model predictions compared against experimental data for the control case. Figures 5.3 and 5.4 compare model predictions to experimental data for a case with a PCM concentration of 10% and a case with a PCM concentration of 20%, respectively. As observed in the figures, the predictions were in relatively good agreement with the data, especially during peak times.

The cumulative differences between the model and experimental data were less than about 13% and 2.1% for peak times for the 10% concentration case and 20% concentration case, respectively. In modeling efforts a 13% difference in overall prediction is still considered satisfactory, especially because the model under and over predicted in all cases being modeled. That is, the differences in accuracy cancelled out. The modeling of phase change heat transfer and the fact that the modeling did not take moisture transport effects into account were responsible for the accuracy differences.

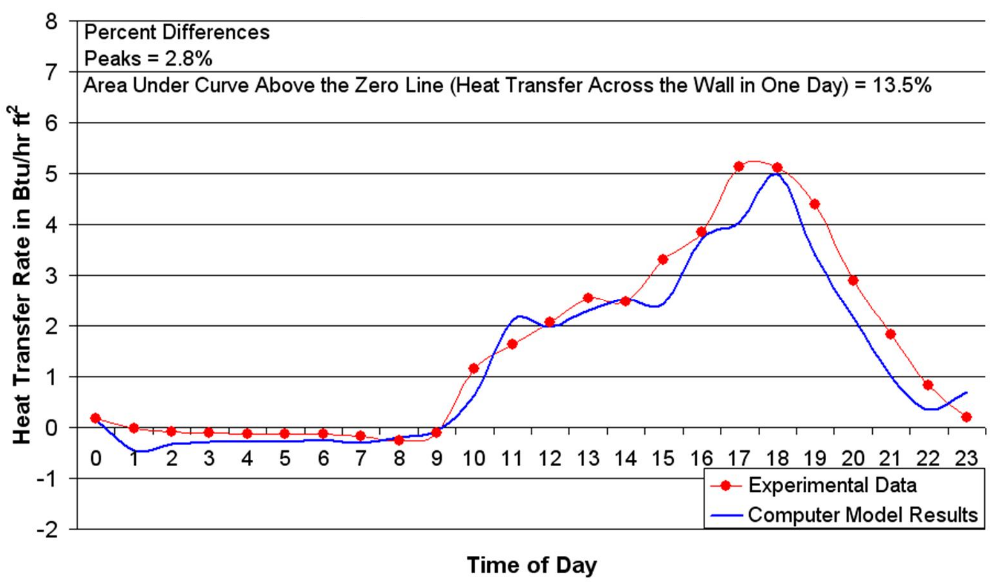

Figure 5.2. Comparisons of Heat Transfer Rates between Computer Model and Experimental Data at Control Case

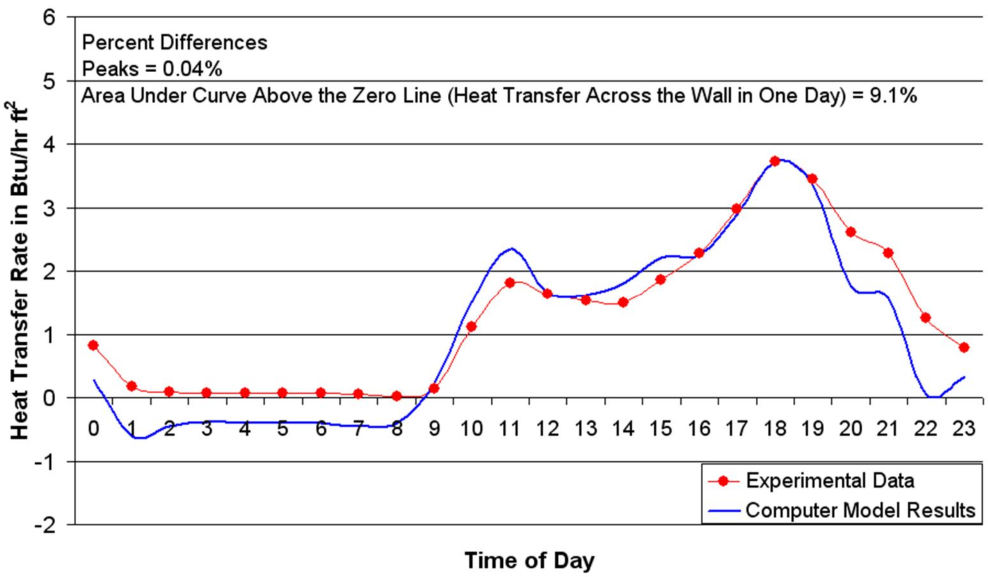

Figure 5.3. Comparisons of Heat Transfer Rates between Computer Model and Experimental Data at 10% PCM Concentration

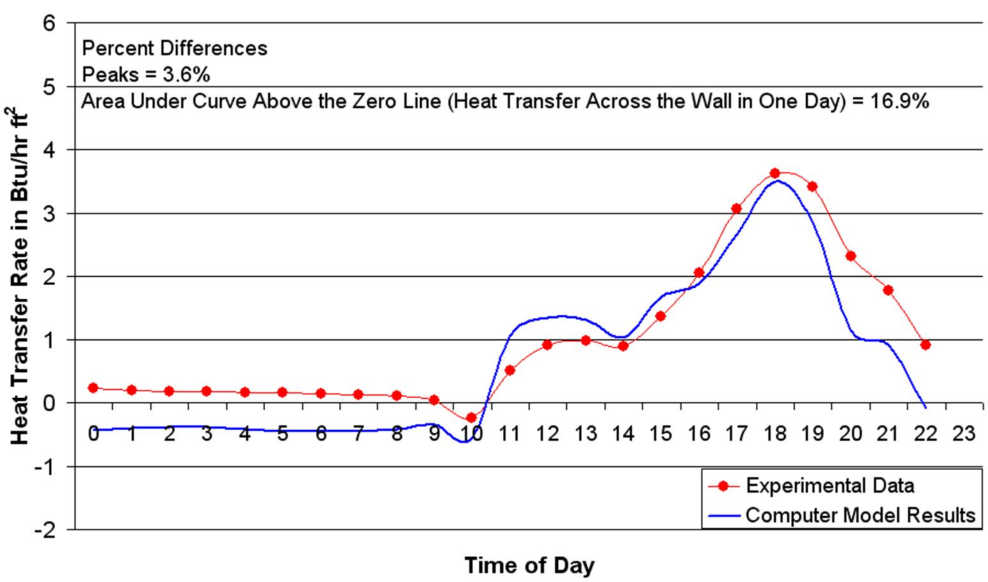

Figure 5.4. Comparisons of Heat Transfer Rates between Computer Model and Experimental Data at 20% PCM Concentration

For the simulations that follow the model under predicted by an average of about 13% but it did it consistently for every case. Therefore, as stated above, the comparisons of the model results for a base (control) case vs. the cases when the PCFWs were at 10% and 20% PCM concentrations would be closer to what would be observed in experimental cases.

5.2 Computer Simulations

The model results were used to predict reductions in heat transfer rate and space cooling loads. The results from the model were integrated into the code of a commercially-available building energy simulation program known as *EnergyPro.* EnergyPro is one of the energy analysis computer programs for residential buildings approved by the California Energy Commission. Weather tapes for several cities located in coastal and transitional climates in the State of California were used. These cities are stated and mapped below.

5.2.1 California Climate Zones

For energy calculation purposes, the California Energy Commission (CEC) has divided the State of California into 16 climate zones (CEC, 2004). The standard weather tapes that represent these zones were developed using statistical data of typical hourly values of each of the parameters used to run the program. That is, the parameter values were based on historical data from actual meteorological sites. The 16 California climate zones are shown in the map of Figure 5.5.

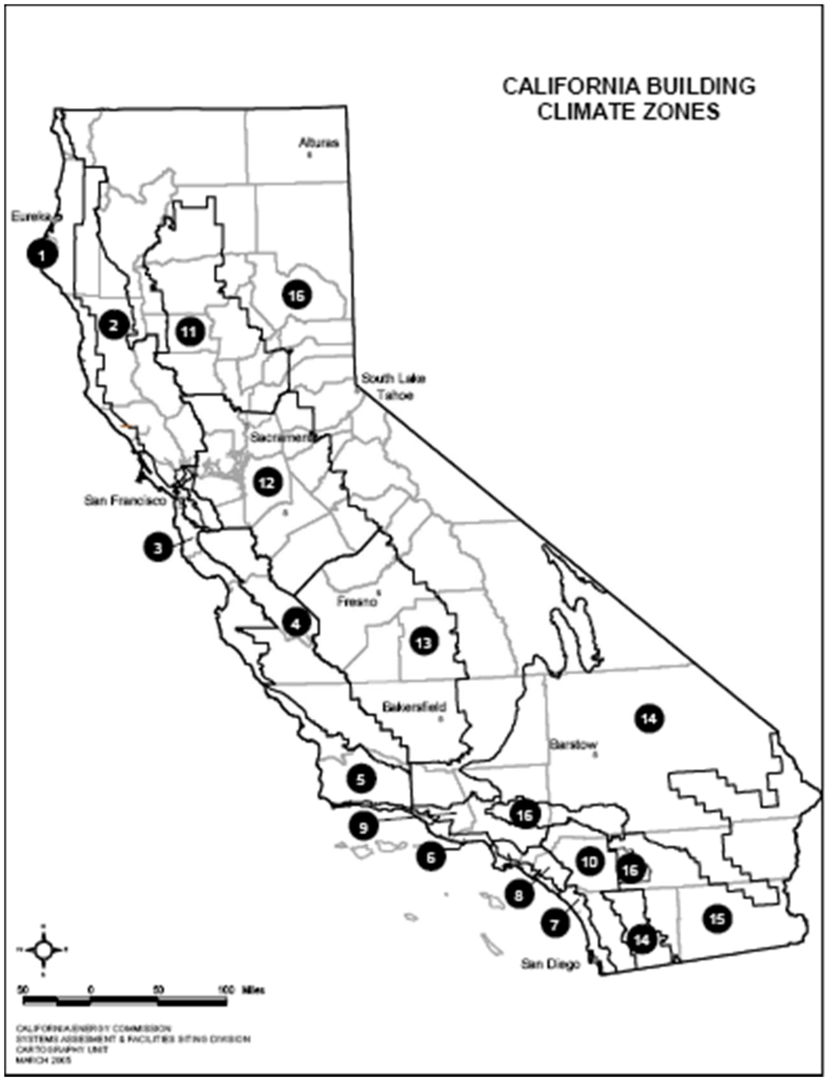

Figure 5.5. California Climate Zones (Source: CEC, 2004; Joint appendices)

Six climate zones were coastal locations (1, 3, 4, 5, 6, and 7), and four were transitional climate zones (2, 8, 9, and 10). The remaining three were in the Central Valley (11, 12, and 13) and one in the desert (14). More precisely, the term "transitional" climate referred to locations from 16.1 to 48.3 km (10 to 30 miles) inland with climates intermediate between the marine-dominated coast and the climate of the Central Valley or the semi-arid desert areas of southern California (Huang and Zhang, 1995).

The areas used in the simulations (coastal and transitional climates) were Climate Zone 2 through 10. Climate Zone 1, although mentioned in the following table, was not included in the analyses because it was much different in terms of environmental variables and in terms of energy consumption though it is one of the coastal climate zones. These zones are indicated in Table 5.1.

Table 5.1. Climatic Data for the Ten Zones That Represent the Coastal Transitional Climates of the State of California (Source: CEC, 2004; Joint appendices)

Climate Zone		City	County	Lat. (°)	Elev. (ft)	Outdoor Design Temperatures				
						Cooling (1%)			Heating	
						DB	MCWB	RH (%)	Winter Median of Extremes	HDD
1	Coastal	Arcata	Humboldt	41.0	218	68	59	59	28	5029
2	Transitional	Santa Rosa	Sonoma	38.5	167	95	68	24	24	2980
3	Coastal	Oakland AP	Alameda	37.7	6	82	64	37	32	2909
4	Coastal	Sunnyvale	Santa Clara	37.3	97	86	66	34	29	2511
5	Coastal	Santa Maria AP	Santa Barbara	34.9	236	82	63	34	25	3053
6	Coastal	Los Angeles AP	Los Angeles	33.9	97	83	67	44	37	1819
7	Coastal	San Diego AP	San Diego	32.7	13	82	69	52	38	1507
8	Transitional	El Toro MCAS	Orange	33.7	380	87	69	40	34	1591
9	Transitional	Burbank AP	Los Angeles	34.2	699	94	68	26	29	1701
10	Transitional	Riverside FS3	Riverside	34.0	840	99	68	19	27	1818

DB: Dry bulb Temperature (ºF)
MCWB: Mean Coincident Wetbulb Temperature (ºF)
HDD: Heating Degree Days
1% DB and 1% MCWB are interpolated:
The interpolation formula used was *2.0% value + 0.6667 (0.5% value – 2.0% value + 0.5)*. The 2% and 5% values referred to values what would only be exceeded 2% and 5% of the time during the summer. These are design values used in the field to size air conditioning systems.

5.2.2 Computer Model Simulation Results and Discussion

Based on the model simulations, peak seasonal average data were plotted for each zone as a function of wall orientation. The averaged peak heat transfer rate reductions were given in terms of percentage when the PCFWs were used. The computer model simulation results for climate zones 2 through 10 are summarized in Table 5.2.

Table 5.2. Summer Averaged Peak Heat Transfer Rate Reduction for Climate Zones 2 through 10

	Reductions in Peak Heat Transfer Rates When Using PCFWs (%)									
	10% Concentration					20% Concentration				
Wall Orientations	N	S	E	W	Avg.	N	S	E	W	Avg.
Zone 2-Transitional	17.2	18.6	0.5	24.6	15.2	22.3	27.1	7.8	34.5	22.9
Zone 3-Coastal	0.0	13.7	0.0	19.5	8.3	0.0	19.7	0.0	25.8	11.4
Zone 4-Coastal	10.8	17.8	0.0	33.3	15.5	15.3	25.9	4.0	40.2	21.4
Zone 5-Coastal	0.0	13.6	16.7	5.1	8.9	0.0	19.8	23.2	11.7	13.7
Zone 6-Coastal	0.0	7.9	1.1	10.0	4.8	0.0	13.9	7.4	16.6	9.5
Zone 7-Coastal	0.0	0.0	2.5	3.8	1.6	0.0	1.6	7.6	10.4	4.9
Zone 8-Transitional	13.4	17.1	16.6	18.0	16.3	18.3	25.3	23.2	26.8	23.4
Zone 9-Transitional	18.9	21.7	13.2	23.2	19.3	24.4	30.0	31.2	32.5	29.5
Zone 10-Transitional	19.1	24.4	24.6	26.6	23.7	26.2	33.1	32.1	35.6	31.8

Table 5.3 summarizes the results of Table 5.2 by climate type. The average peak heat transfer rates reductions of all four orientations when a PCFW at 10% PCM concentration was used was 13.2% (7.8% and 18.6% reductions in the coastal and transitional climates, respectively) and 19.6% at 20% PCM concentration (12.2% and 26.9% reductions in the coastal and transitional climates, respectively).

From the results in Table 5.3, the average increment of all four orientations in both climates when doubling the percent PCM in the PCFW was 6.4% (4.4% and 8.3% increment in the coastal and transitional climates, respectively). The average increment, considering all four orientations and producing one average comparing the results for coastal climates to those of the transitional climates for a 10% PCM concentration PCFW was 10.8% and 14.7% for the 20% PCM concentration, or a combined average of 12.8%. The north-facing wall was the one that changed the most in going from a coastal climate to a transitional climate, but it was the one that changed the least when the PCM concentration was doubled. On the other hand, the west-facing wall appeared to be the most affected in going from a PCM concentration of 10% to one of 20%, but it was also the least affected when going across zones. Figures 5.6 and 5.7 are graphical representations of the same data.

Table 5.3. Reductions in Peak Heat Transfer Rates as a Result of Using PCFWs at 10% and 20% PCM Concentrations for the Four Cardinal Orientations in Coastal and Transitional Climates

	Reductions in Peak Heat Transfer Rates When Using PCFWs									
	10% Concentration					20% Concentration				
Wall Orientations	N	S	E	W	Avg.	N	S	E	W	Avg.
Coastal Climates	2.2	10.6	4.1	14.3	7.8	3.1	16.2	8.4	20.9	12.2
Transitional Climates	17.2	20.5	13.7	23.1	18.6	22.8	28.9	23.6	32.4	26.9
Average	9.7	15.6	8.9	18.7	13.2	13.0	22.6	16.0	26.7	19.6

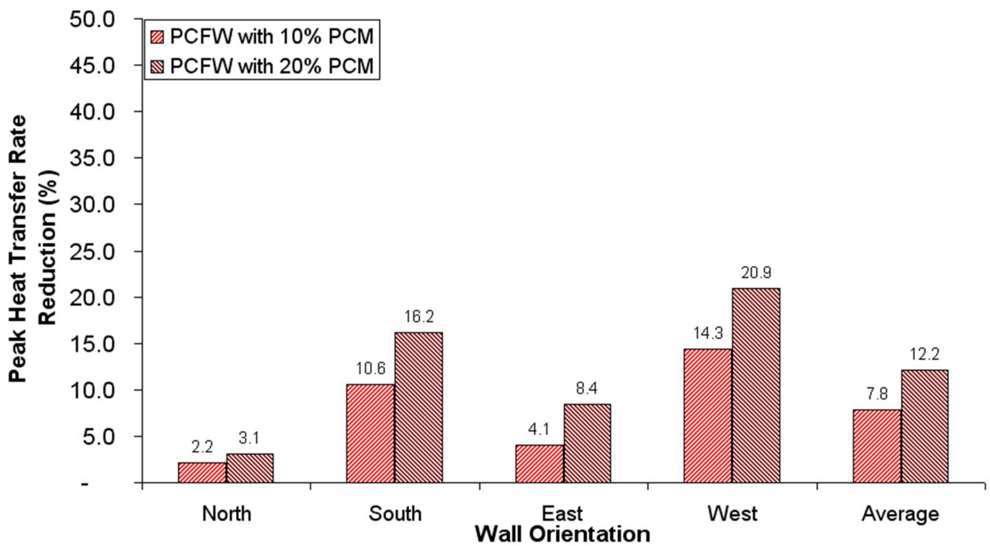

Figure 5.6. Summer Averaged Peak Heat Transfer Rate Reduction for All Coastal Zones

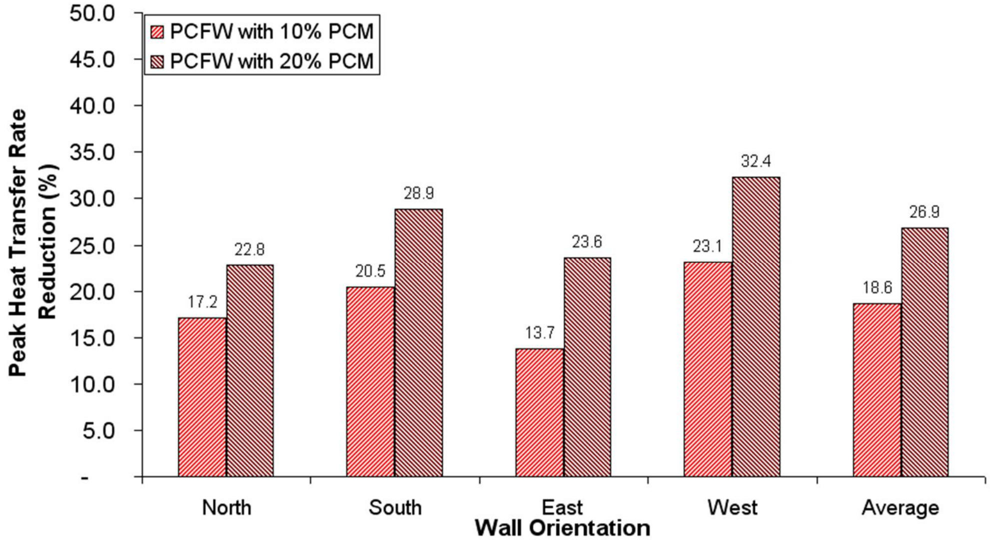

Figure 5.7. Summer Averaged Peak Heat Transfer Rate Reduction for All Transitional Zones

5.2.3 Simulation Discussion

In 2008, the California Energy Commission updated energy efficiency standards for new buildings. The document is known as "The California Building Energy Efficiency Standards (Title 24, Part 6)". These standards will continue to be updated periodically to allow considerations and possible incorporation of new energy efficiency technologies and methods.

The performance standards established an energy budget for the building in terms of energy consumption per square foot of floor space. The performance method of complying with the Standards is by calculating the Time Dependent Valuation (TDV) energy use of the proposed design and comparing it to the TDV energy for the standard design. The standard design is a building with the same size as the proposed design, but incorporating all features of the standard design.

The Energy Commission uses a public domain computer program to calculate estimated energy consumption of buildings and also approves the use of privately developed computer programs as alternatives. These computer programs simulate thermal behavior of buildings by calculating hourly heat flows into and out of various thermal zones of the building. The programs then calculate the TDV energy use of the standard design.

The model or standard house used in this thesis was the model house that the CEC recommended and was presented in "*Assembly Bill 970 (2001 Update): Contractor's Report.*" *(CEC, 2000)* This house was a 163.6 m^2 (1,761 ft^2) two-story, slab-on-grade residence. The information of the house is presented in Table 5.4 and the basic drawings of this house are presented in Figure 5.8.

Table 5.4. Model House Basic Information (Source: CEC, 2000)

Conditioned Floor Area	163.6 m^2 (1,761 ft^2)
Construction Type	New
Front Orientation	East
Number of Stories	Two
Floor Construction Type	Slab on Grade
Number of Building Zones	One
Conditioned Volume	441.4 m^3 (15,588 ft^3)
Slab on Grade Area	85.9 m^2 (925 ft^2)
Glazing Percentage	16 percent of Floor Area
Average Glazing U-Value	2.05 W/m^2 (0.65 Btu/hr ft^2)
Average Glazing SHGC	0.4
Average Ceiling Height	2.7 m (8.9 ft)

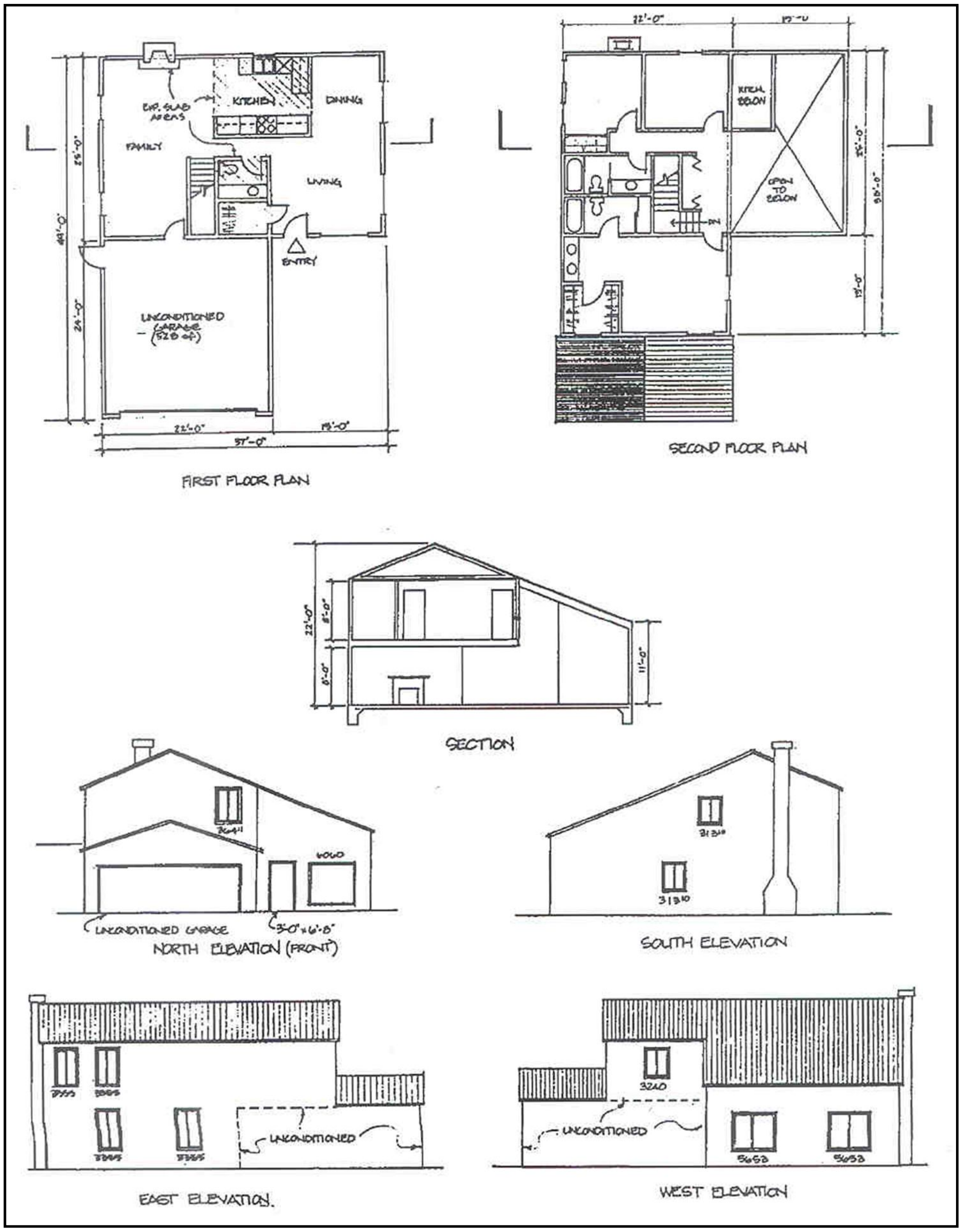

Figure 5.8. House Model Used in the Modeling of Cooling Loads (Source: CEC, 2000)

After the simulations, the results were not different for whether the concentration of PCM of the PCFW was 10% or 20% for space cooling load (plus fan energy) and annual energy consumption simulations. This was consistent with experimental data. From this reason, only data related to the 10% PCM concentration PCFW are presented.

Figure 5.9 shows the space cooling loads, to which fan energy was added, for each zone for the base case house and for the same house once the PCFWs had replaced the standard walls. The results indicated that cooling load (plus fan power) was reduced from 6.0% for Zone 6 (Coastal Climate) to 14.3% for Zone 2 (Transitional Climate). More energy would be saved in the transitional climates than in the coastal climates.

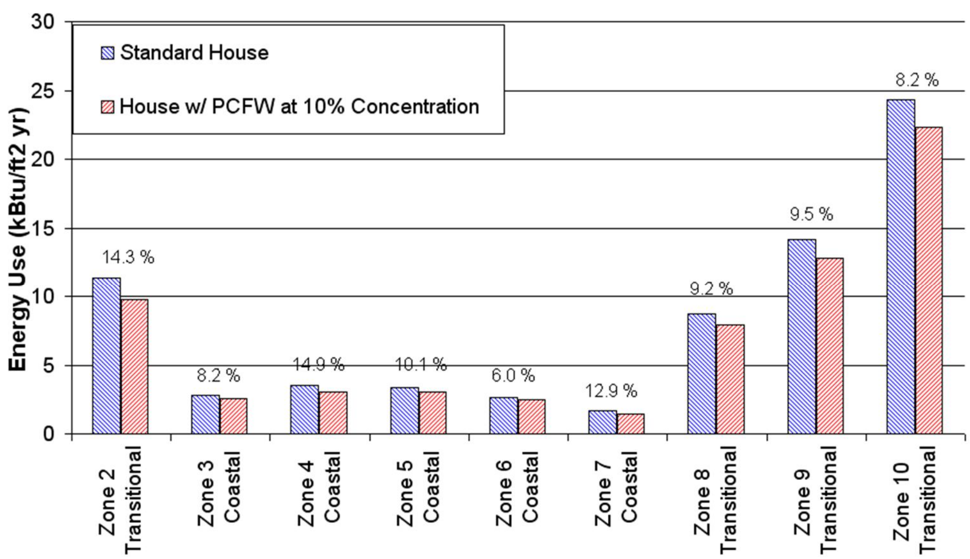

Figure 5.9. Annual Space Cooling Load and Fan Energy for All Nine Climate Zones

Figures 5.10 and 5.11 separate the coastal and transitional climates, and therefore averages are presented for space heating, space cooling, fan energy, water heating, and total energy consumption for the base case and for the retrofit case.

According to the results, the coastal climates and the transitional climates used approximately the same amount of energy for space heating. The reduction from using PCFWs was about 13.5%.

In relation to space cooling load, the transitional climates used more than six times the amount used by residences in the coastal climates used. The percent reduction in coastal and transitional climates, from using PCFWs was about 9.8%. However, in terms of heat transfer rate reduction, the average of the transitional climates yielded 3.72 kWh/m^2 yr (1.18 $kBtu/ft^2$ yr) while the average of the coastal climates was a 0.60 kWh/m^2 yr (0.19 $kBtu/ft^2$ yr).

Similarly, the fan energy usage for a base house was three times more in the transitional climates than in the coastal climates. Energy savings from using PCFWs came to about 11%.

In total energy usage the savings from using the PCFWs came to 5.61 kWh/m^2 yr (1.78 $kBtu/ft^2$ yr) as an average for the coastal climates and 9.21 kWh/m^2 yr (2.92 $kBtu/ft^2$ yr) for the transitional climates. For this base house, these values for the coastal climates and the transitional climates would translate to approximately 0.92 MWh/yr (3.13 MMBtu/yr) and 1.51 MWh/yr (5.15 MMBtu/yr) in energy savings, respectively.

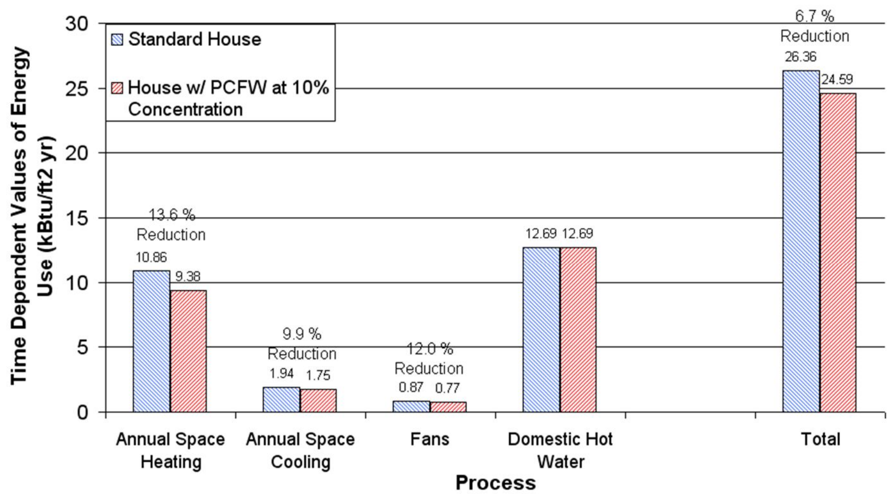

Figure 5.10. Average Annual Energy Consumption Comparisons between the Base Case House and the House with PCFWs at 10% PCM Concentration for All Coastal Climates

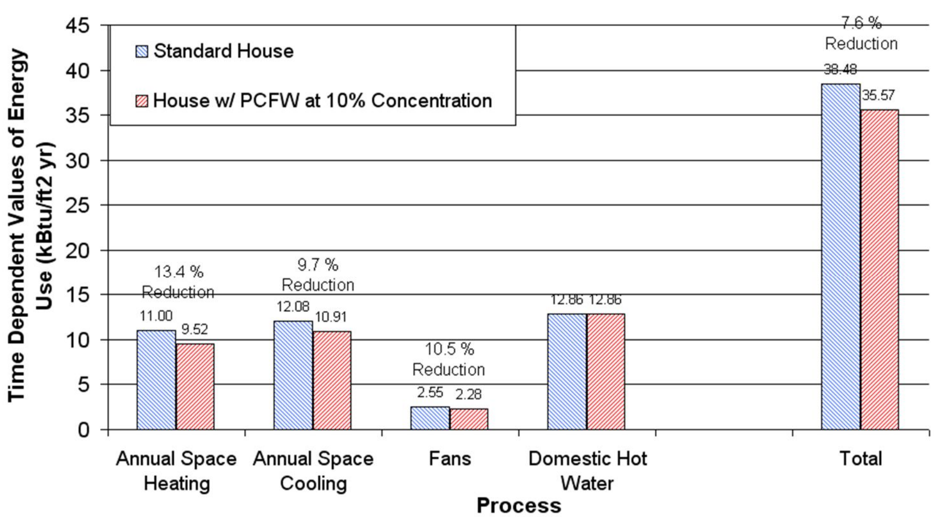

Figure 5.11. Average Annual Energy Consumption Comparisons between the Base Case House and the House with PCFW at 10% PCM Concentration for All Transitional Climates

Figure 5.12 presents a parametric analysis based on climate zone temperature. The figure indicates that the PCFWs would produce more energy savings in zones with increasing outdoor air temperature.

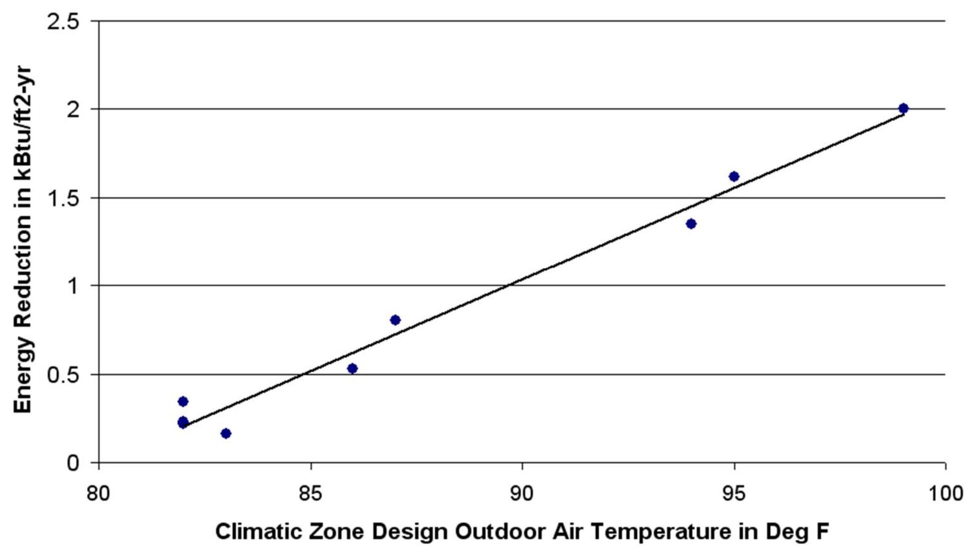

Figure 5.12. Parameterization of Space Cooling and Fan Energy Reductions as a Function of Climatic Zone Design Outdoor Air Temperature for PCFWs at 10% PCM Concentration

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

PCMs are substances (e.g., hydrated salts, paraffins, and/or fatty acids) that have high latent heat of fusion while they change from solid to liquid and from solid to liquid as function of temperature. The Phase Change Frame Walls (PCFWs), which was a thermally enhanced frame wall, was evaluated for residential buildings located in coastal and transitional climates in the State of California. The PCFW incorporated PCMs in typical residential frame wall to enhance the energy storage capabilities of the wall.

The PCM used in this work was a hydrated salt PCM, commercially known as TH29. The PCM had a melting and solidification temperature range from 28.0 °C to 30.0 °C (82.4 °F to 86.0 °F). The PCMs were integrated into the PCFW via macro-encapsulation using copper pipes at PCM concentrations of 10% and 20% by weight of the interior sheathing.

For experimental tests, two identical wood framed test houses with space conditioning systems were used; one was used as a control and the other is for retrofit with PCFWs. Thermal performance parameters (i.e., heat transfer rates, surface temperatures, air temperatures and relative humidities) were measured and collected using a monitoring system.

Prior to the tests of the PCFWs, calibration tests were conducted to verify that two test houses had identical thermal performance. During the calibration tests, the indoor air temperatures of both test houses were maintained at differences of less than 0.06 °C (0.1 °F) and average the peak heat transfer rates across the walls were less than 3%.

The peak heat transfer rates of the retrofit were reduced when compared to standard walls facing the same orientation. For example, at a 10% PCM concentration, the reduction in peak heat transfer for the north, south, east and west facing walls were 33.7%, 25.6%, 24.3% and 24.6%, respectively. The average reduction in the peak heat transfer rate considering all orientations was approximately 27.0%. On average, the interior wall surface temperatures in the PCFWs were 1.44 °C (2.6 °F) less. Also, the temperature fluctuations of the interior surface of the PCFW were reduced by 1.44 °C (2.6 °F) on average. The load shifting was observed to be about one hour. The relative humidity in the retrofit house was 4.2% higher than the control house.

At a PCM concentration of 20%, the reduction in peak heat transfer in the north, south, east and west facing walls were 27.1%, 29.2%, 25.7% and 27.2%, respectively. The average reduction in peak heat transfer rate of all four walls was 27.3%. For the retrofit house, the interior surface temperatures were reduced by 1.50 °C (2.7 °F) and the temperature fluctuations by 1.44 °C (2.6 °F). At this concentration there was no difference in relative humidities between both houses.

For the simulation aspect of this research, a computer model and EnergyPro were used. The computer model was used to extrapolate the results for coastal and transitional climates in the State of California and EnergyPro program was used to calculate savings in space cooling energy.

The simulated results indicated that the peak heat transfer rates across the PCFWs at a PCM concentration of 10% were reduced by 8% for coastal climates and 19% for transitional climates on averages. The highest heat transfer rate reductions occurred in the south and west facing walls. These reductions were 10.5% and 20.5% for the coastal and transitional climates, respectively, in south facing walls and 14.3% and 23.1% for the coastal and transitional climates, respectively, in west facing walls. For the PCFWs at 20% PCM concentration, the average peak heat transfer reductions for the coastal and transitional climates were 12.2% and 27%, respectively. For the south facing walls, the reductions were 16.2% and 28.9% for the coastal and transitional climates, respectively. For the west facing walls, the reductions were 20.9% and 32.4% for the coastal and transitional climates, respectively.

From the EneryPro computer simulation, the results were not different whether the PCM concentrations were 10% or 20%. At a 10% PCM concentration, the space cooling load, including fan energy, was reduced by 10.4% average in all both zones (10.4% and 10.3% for coastal and transitional climates, respectively). According to the simulated results, the use of the PCFWs reduced the annual energy consumption by 7.2% on average in both climate zones (6.7% and 7.6% for coastal and transitional climates, respectively). The simulated data showed that PCFWs would produce better results in energy savings as the outdoor air temperature increased.

For future research it is recommended that more practical PCMs application methods be developed. In addition, it is recommended that more PCM types be studies for the present application. In this thesis, PCM was applied only in walls. It is recommended that PCMs be applied in ceilings, roofs and floors.

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