Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition
IMECE2011
November 11-17, 2011, Denver, Colorado, USA

IMECE2011-63273

PHASE CHANGE MATERIALS AS THERMAL STORAGE FOR HIGH PERFORMANCE HOMES

Kevin R. Campbell and David J. Sailor*
Green Building Research Laboratory
Portland State University
Portland, Oregon, USA

ABSTRACT

A minimally invasive method of adding thermal mass to a building is to apply Phase Change Material (PCM) to the interior of the structure. This paper describes a simulation-based approach for informing the integration of PCM in high performance homes without mechanical cooling. The analysis considers phase change transition temperature, quantity, and location of PCM within the building. The effectiveness of each test case was determined based on the number of hours that the indoor conditions were outside the ASHRAE defined comfort zone.

Results showed that for most climates a PCM melt temperature of 25°C yielded the largest increases in occupant comfort; however the magnitudes of increases in occupant comfort were highly climate dependant. Reductions of 93% of zone-hours and 98% of zone-degree-hours outside the thermal comfort were achieved for simulations in Portland, Oregon. However, reductions of only 6.4% of zone-hours and 7.3% of zone-degree-hours outside the thermal comfort zone were realized in Phoenix, Arizona.

INTRODUCTION

Modern construction practices have led to reduced build time and cost for residential homes. However, they have also resulted in homes with very little thermal mass. Wood framed houses can be 5 times less thermally massive than their stone or brick counterparts [1]. The lack of thermal mass results in modern houses with an inability to store significant amounts of thermal energy; leading (in the absence of mechanical heating/cooling) to large diurnal indoor air temperature fluctuations. Adding thermal mass will allow for increased thermal storage and thus mitigate temperature fluctuations [2].

The issue of insufficient thermal mass is pervasive not only in common modern houses, but also in modern high performance (super-insulated) homes. These homes are built to minimize heat loss across the building envelope, which is achieved by increased envelope insulation, an air tight construction, and highly insulative windows. In order to maintain comfort, these homes also take advantage of passive gains such as solar insolation and waste heat. They address the need for ventilation through heat-recovery ventilators that allow for exchange of air with the outside environment while minimizing exchange of heat.

A minimally invasive method of adding thermal mass that is suitable for new construction and retrofits is to add Phase Change Material (PCM) to the space. PCMs can be installed in many different locations in buildings. The placement behind drywall allows PCMs to be incorporated into a house without considerable design modifications and without any aesthetic impact.

The objective of this study is to inform the integration of PCMs in high performance homes. Whole building energy simulations were carried out with EnergyPlus from the US Department of Energy. Simulations were performed in eight different climate zones across the United States with consideration given to melt temperature, quantity and location of PCM.

BACKGROUND AND MOTIVATION

In order to reduce energy consumption, building codes and the technologies used in buildings have become more energy efficient. The application of PCMs in buildings is one of the emerging technologies that aims to reduce building energy usage and increase occupant comfort. The application of PCMs in building has seen a surge of research interest over the past decade. This research interest was spurred by the development of microencapsulated PCM. Microencapsulated, as opposed to macroencapsulated, PCM consists of 2-20 micron in diameter

* Corresponding author: sailor@cecs.pdx.edu

spheres of PCM that are encased in a thin polymer shell. This polymer shell acts to contain the PCM and prevent leakage when in the liquid phase. With such small parcels of PCM, the surface area to volume ratio is large. This results in increased heat transfer and fewer issues with container stress from volumetric expansion [3]. While there are benefits to microencapsulated PCM, the cost per unit of energy storage is considerably higher compared to traditional macroencapsulated PCMs. The PCM product investigated in this study is macroencapsulated and costs 2.5 times less per kJ of energy stored than its microencapsulated counterparts [4].

Prior experiments have been performed in order to determine PCMs efficacy as an energy saving technology. Muruganantham et al. [5] constructed two test sheds and applied macroencapsulated PCM behind the walls, floor and roof of one of the sheds. The sheds were located in Arizona and both had air conditioning units installed in order to maintain a set-point temperature. The peak and total conditioning loads were monitored in both sheds. Peak load shifts of up to an hour, were observed and a maximum of 29% reduction in monthly energy use was achieved.

Investigations have also considered PCM impact on occupant comfort. In Shossig et al.'s [6] recent study, two rooms were constructed, one of which was outfitted with wallboard that was impregnated with microencapsulated PCM. Internal air as well as surface temperatures were monitored for both rooms. It was determined that reductions in temperature fluctuations of 4°C could be achieved with the incorporation of PCM.

Shossig's study also noted the importance of night ventilation in order to discharge the PCM. This was further investigated at Lawrence Berkeley National Lab where a numerical analysis was conducted to simulate the incorporation of PCM in an office building [7]. The office building had a Variable Air Volume (VAV) ventilation system that provided night cooling to the space. It was determined that "PCM wallboard coupled with night ventilation in office buildings offers the opportunity for system downsizing in climates where the air temperature drops below 18°C at night."[7].

Night cooling was not the only parameter found to be critically important for the proper operation of PCMs in buildings. Virgone et al. performed a study using a microencapsulated PCM board in a non-conditioned school that had foregone renovations since it was constructed in the 1960s. They found that an efficient envelope was also critical in order to maximize the performance of PCM [8].

Drawing on the findings of previous studies, the present research seeks to apply PCMs to the subset of buildings where the increase in thermal performance will be maximized. This is the case for high performance "super-insulated" homes due to their extremely efficient envelopes as well as little inherent thermal mass. Also, the lack of cooling systems allows for the efficacy of the PCM system to be determined based directly on occupant comfort.

PASSIVE HOUSE STANDARD

Homes built to the Passive House Standard [9] were chosen as the high performance benchmark home to investigate. Homes built to the Passive House Standard were chosen for several reasons. The first is that while they have considerable insulation, they contain very little thermal mass. The second reason has to do with their energy consumption. Homes built to the Passive House Standard seek to achieve a 90% reduction in energy use compared to conventionally built new homes [9]. Due to the relatively small energetic exchange across the building envelope, the energy stored by PCM will have a larger impact on the thermal comfort of the space than for a typical home. The reduction in energy consumption is achieved by Passive Houses through increased insulation, air tightness, and the presence of heat recovery ventilators (HRV). HRVs are used in nearly all Passive Houses to exchange heat between the supply and exhaust air steams with sensible efficiencies exceeding 80%. The vastly reduced energy demand in Passive Houses coupled with their lack of thermal mass makes them good test cases for a PCM system to act as a thermal storage device.

Passive Houses also commonly have large glazing areas in order to take advantage of daylighting and solar heat gains during the heating season. This large glazing area can however act as a thermal penalty on the home during the summer as it can lead to overheating. Overheating occurs in Passive Houses because the majority of them do not have mechanical cooling. Thus the primary benefit of adding PCM to Passive Houses is improved occupant comfort, although it can also be argued that PCM can help avoid the initial capital cost of air conditioning.

VALIDATION OF ENERGY MODELING TECHNIQUES

Whole building energy simulations were carried out with EnergyPlus from the US Department of Energy. EnergyPlus is a whole-building energy simulation tool maintained and updated semi-annually. It is constructed in a modular framework that allows developers to create add-ins based on perceived needs. Because of this modular nature, EnergyPlus has an existing Phase Change Materials Module that has been incorporated in the standard release since 2007. The Phase Change Materials Module was released along with the Conduction Finite Difference (CFD) Heat Balance Algorithm. The CFD Heat Balance Algorithm must be used when modeling phase change materials because it is the only heat balance algorithm available in EnergyPlus that allows for thermal properties to be updated every timestep.

When the CFD Heat Balance Algorithm was released in 2007 it had minimal verification of its ability to accurately model building physics [10]. Therefore, as an initial step in the present work, a more thorough analysis of accuracy was performed for both the CFD Heat Balance Algorithm and the Phase Change Material Module.

The ASHRAE 1052-RP toolkit: *Development of an Analytical Verification Test Suite for While Building Energy Simulation Programs – Building Fabric*, was used in order to determine the CFD Heat Balance Algorithm's ability to accurately model heat transfer across the building envelope. During these tests, the CFD Heat Balance Algorithm performed within 3% of the traditional Conduction Transfer Function (CTF) algorithm and analytic results. Subsequent to testing with the ASHRAE toolkit the Energyplus modules were evaluated against data from a published experiment [11]. This experiment was performed at the Thermal Sciences Center of Lyon in a test chamber named MINIBAT. MINIBAT is a 3.1m x 3.1m x 2.5m experimental test cell that is located inside a thermal chamber. One of MINIBAT's faces is a 1.5m x 1.5m window outside of which is a solar simulator consisting of 12 spotlights that are each 1000 Watts. The spotlights are metal halide gas-discharge lamps that are situated to be lit in a sequence that mimics the path of the sun. The initial simulation consisted of a 48 hour period during a typical summer day in Lyon, France. The outside air temperature followed a diurnal cycle with a maximum of 30°C and a minimum of 15°C [11]. For the baseline simulation, no PCM was integrated into the space. This simulation was run twice, once with the CFD Heat Balance Algorithm and once with the more traditional CTF Heat Balance Algorithm.

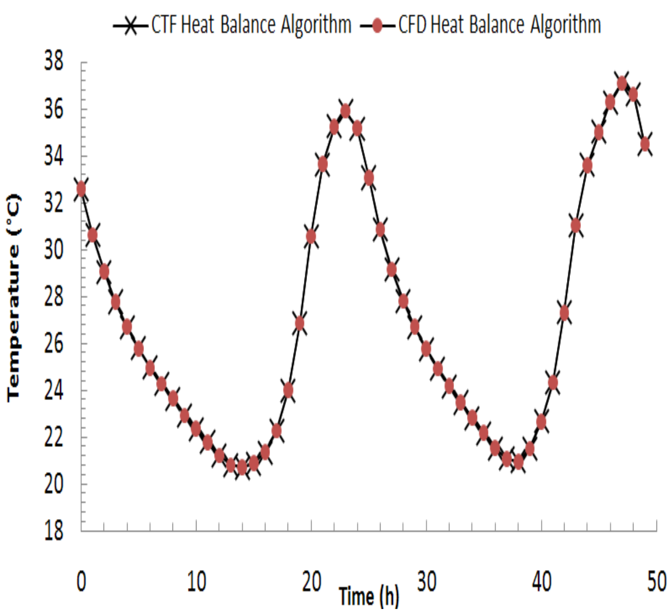

Figure 1: Comparison of Conduction Finite Difference and Conduction Transfer Function Heat Balance Algorithms in EnergyPlus.

As shown in Figure 1, the CFD and CTF Heat Balance Algorithms matched extremely well for the initial MINIBAT simulation. After verifying that both heat balance algorithms modeled heat transfer across the building envelope in a similar manner, PCM was added to the model. As was performed in the experimental case, PCM was added to the 3 walls that did not have any glazing. The test was re-run and the reductions in temperature fluctuations achieved from the addition of PCM were compared.

The reduction in temperature fluctuations (max-min) achieved by adding PCM in the EnergyPlus simulation was 4.9°C, which compares well with the value of 4.7 °C found in the experiments by Kuznik. This provided the necessary confidence in the CFD Heat Balance Algorithm's ability to model PCMs.

MODELING PCM IN HIGH PERFORMANCE HOMES

A model was created based on design details from a Passive House duplex that was in the construction phase in Portland, Oregon. This particular design (Figure 2) was ideal for experimentation because it consists of side-by-side identical duplexes, allowing for one duplex to host PCM and the other to act as a control. During construction numerous sensors (air and surface temperatures, CO_2, humidity, energy consumption) were also deployed in the house to allow for more thorough validation of modeling results against observations. As this structure is not yet completed or occupied, such intercomparison will be the subject of a future manuscript.

Figure 2: Three dimensional rendering of the modeled Passive House.

A floorplan of the house is illustrated in Figure 3. A notable design feature is the large amount of southern glazing area with overhangs. Some of the most significant design parameters are summarized in Table 1.

Table 1: Design parameters used for modeled Passive House.

Parameter	Value
U Value – Walls (W/(m^2°C))	0.13
U Value – Roof (W/(m^2°C))	0.07
U Value – Slab (W/(m^2°C))	0.17
U Value – Windows (W/(m^2°C))	0.97
Floor Area – Per Unit (m^2)	126.0
Floor to Ceiling Height – 1st Floor (m)	2.5
Floor to Ceiling Height – 2nd Floor (m)	3.0
Glazing Area – (%)	13.0
Occupancy – (people/unit)	2.9
Miscellaneous Loads – (Watt/m^2)	2.0
Air Tightness – (ACH$_{50}$)	0.6
Electric Heater – (W)	1500

One parameter not included in Table 1, but critical in the model was the nightflush. A nightfulsh was simulated in the EnergyPlus model so that 20% of the window area would open when the interior air temperature was higher than the set-point and also the exterior air temperature was lower than the interior air temperature. It is also worth noting that only one unit of the duplex was modeled in EnergyPlus. A symetrical design allowed for only the west unit to be modeled with the dividing wall modeled as adiabatic.

After the model was created, full-year baseline simulations were run in EnergyPlus with no PCM in the house. These baseline simulations were run for the same home located in each of eight climate zones across the United States. Metrics analyzed in the simulation results were zone-hours (ZH) and zone-degree-hours (ZDH) outside the ASHRAE defined thermal comfort zone (Figure 4).

The model was created with five different zones (excluding the unconditioned workspace), therefore one ZH uncomfortable means that only one zone was uncomfortable for one hour. ZH and ZDH were used instead of hours and degree-hours (which lumps all discomfort together for the entire house) due to significant temperature variation between diferent zones at any instant in time. With ZH and ZDH, the level of discomfort can be weighted based on the number of zones that are uncomfortable. Also, ZDH was considered in addition to simply ZH because it quantifies the extenet of discomfort.

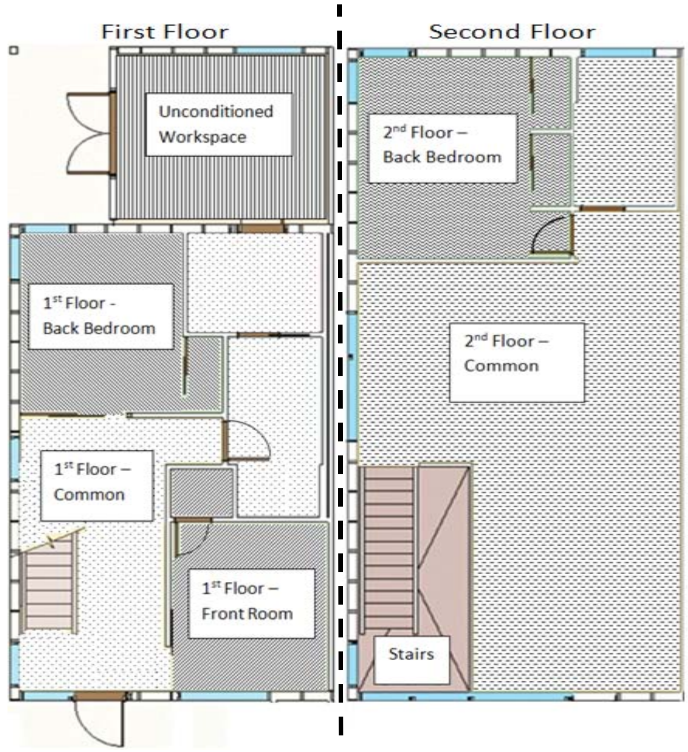

Figure 3. Floor plan of one unit of the modeled Passive House. The left side panel in this figure shows the first floor and the right side shows the second floor.

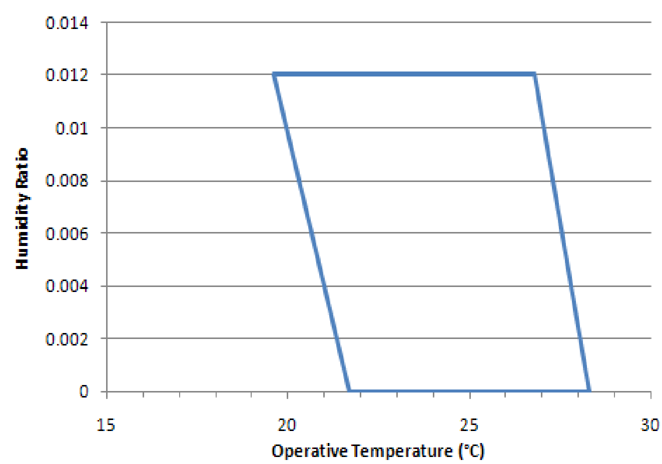

Figure 4. Thermal comfort zone used to determine occupant comfort. Adapted from ASHRAE Standard 55.

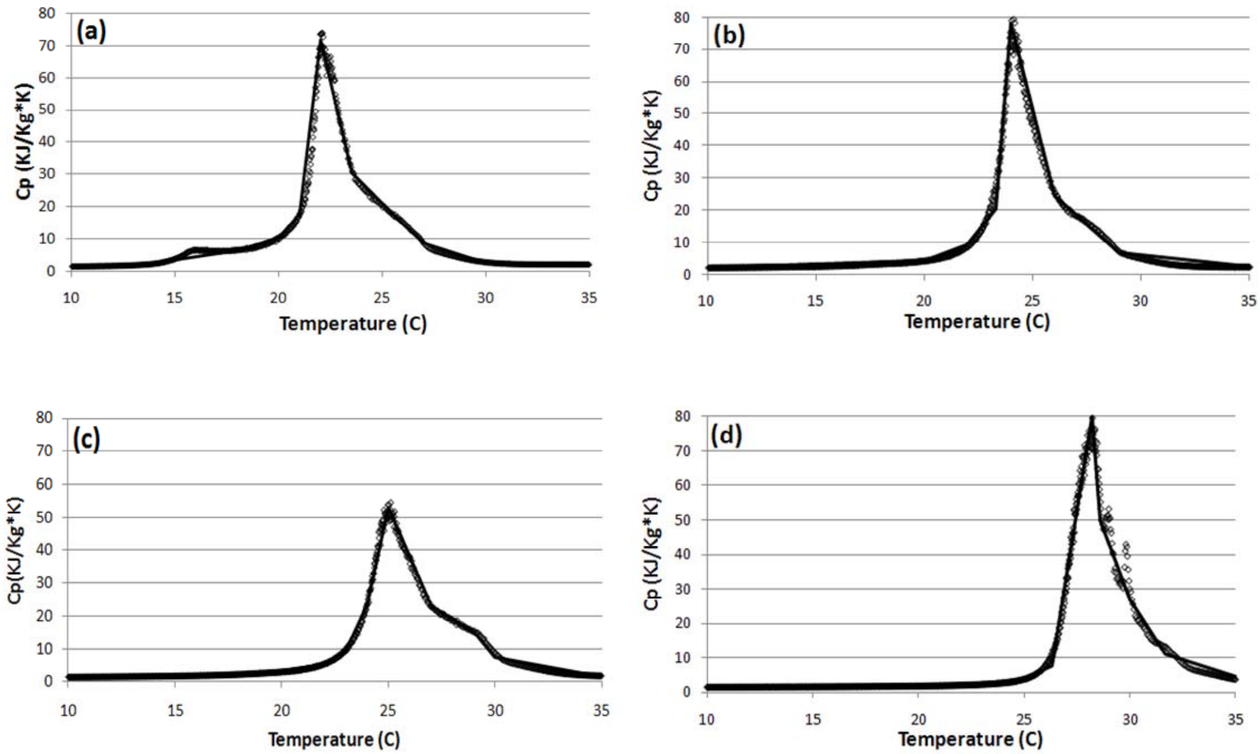

Figure 5: Specific heat as a function of temperature for PCM melt temperatures of (a) 23 °C, (b) 25 °C, (c) 27° C, and (d) 29 °C. Plots generated from manufacturers' raw data. Lines are piecewise linear curve fits for use in the EnergyPlus model.

The thermal comfort zone used in this study is derived from ASHRAE standard 55 and is based on operative temperature and humiditiy ratio. One important note of the current study is that discomfort when the occupant was too cold was not considered because of the low set-point temperatures used in Passive Houses. It has been noted that occupants in Passive Houses are comfortable in temperatures as low as 19.4°C [12]. Minimized drafts as well as a more even temperature distribution play a role in satisfying themal comfort at operative temperatures lower than defined by the ASHRAE comfort zone. Also, in order to quantify any possible impact adding PCM has during the heating season, total energy consumption was recorded.

MODELED PHASE CHANGE MATERIAL

The phase change material product modeled in this study was BioPCM™ from Phase Change Energy. It is macroencapsulated and dervied from refined soy and palm kernal oil. The product consists of pouches that contain roughly 17 grams of PCM per pouch. The pouches are held together on plastic sheets which are then installed between studs and behind drywall.

Four different melt temperatures of BioPCM™ were modeled in this study. In order to model the PCM in EnegyPlus specific heat data for each of the BioPCM™ products were obtained from the manufacturer (see Figure 5). These data were then converted into temperature-dependent enthalpy functions for use in the energy model. The Thermophysical properties of the PCM product are summarized in Table 2.

Table 2: Thermophysical properties of PCM used in simulations. [5]

Density (Kg/m^3)	235
Specific Heat (kJ/(kg °C)	1.97
Latent Heat (KJ/kg °C)	*208
Thermal Conductivity (W/m °C)	.2
Thickness (m)	0.015
Melt Temperature (°C)	23,25,27,29

* Latent heat values vary less than 7% based on melt temperature.

PASSIVE HOUSE BASELINE SIMULATION RESULTS

After establishing confidence in EnergyPlus' ability to accurately model PCM in buildings. Simulations were performed to inform the integration of PCM in Passive Houses. Baseline simulations were initally conducted in eight different climate zones across the United States. Because PCM can only store sensible heat and thermal comfort is a function of both temperature and humiditiy, an initial investigation on the cause of discomfort in each climate zone was conducted. The ASHRAE thermal comfort threshold humidity ratio limit is 0.12. The percentage of uncomfortable hours due high humidity ratio is given in Table 3 for each climate zone (per ASHRAE

90.1-2007). These instances represent conditions when PCM can have no impact on thermal comfort.

Table 3. Thermal comfort assessment for baseline simulataions in different ASHRAE climate zones.

Location	Climate Zone	ZH not comfortable (hr)	ZDH not comfortable (°C-hr)	Percentage of ZH not comfortable that also have a humidity ratio > 0.012
Miami, FL	1	15152	34235	99
Phoenix, AZ	2	16895	80763	24
Los Angeles, CA	3	1625	2458	45
Portland, OR	4	245	261	19
Denver, CO	5	708	809	8
Minneapolis, MN	6	811	1475	84
Duluth, MN	7	92	147	91
Fairbanks, AK	8	12	6	0

Locations east of the the Rocky Mountains have the majority of discomfort arising from high humidity ratio. In these regions, any addition of PCM would not be able to increase occupant comfort significantly. Therfore, it was decided to focus the investigation on four locations; Phoenix, Los Angeles, Portland, and Denver representing major cities where PCM holds promise with respect to improving thermal comfort.

PHOENIX PCM RESULTS

Of the climates analyzed, Phoenix presented the largest sensible load. In the baseline simulation there was a factor of ten more ZH uncomfortable and more than thirty times more ZDH than any of the other four locations investigated. When considering discomfort at the zone level, it was clear that the largest portion of discomfort occurred on the 2nd floor; however there was still considerable discomfort on the 1st floor. The average ZDH uncomfortable for the 1st floor zones was 12,300°C-hr, whereas the average value in the 2nd floor zones was 21,900°C-hr. The significant difference in discomfort can be explained by a few factors. The first is the stack effect, where hot air in the 1st floor rises into the 2nd floor due to buoyancy. The other reason is that the 1st floor has 45% more internal wall surface area than the 2nd floor. These internal walls have 5/8” (1.59 cm) gypsum board on both sides, which acts as thermal mass.

Due to the extent of the overheating in the baseline simulation, a set of simulations was performed with PCM placed in all walls (interior and exterior). After simulating PCM on every wall, PCM was incrementally removed from walls in zones beginning with the zone with the fewest ZDH uncomfortable. This approach was chosen because the zone with the fewest ZDH uncomfortable was contributing the least to the discomfort of the entire space. Results for four different levels of PCM installation are given in Figure 6. The coverage of PCM is presented as a percent of the conditioned floor area, and even with complete coverage (8.4 Kg/m^2) of PCM there is minimal improvement in occupant comfort.

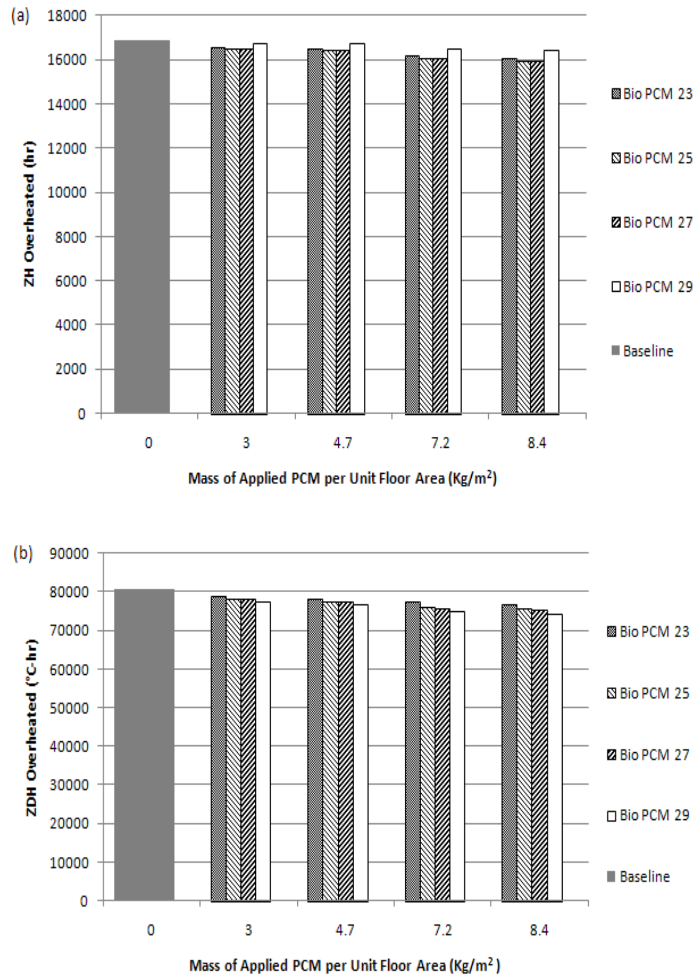

Figure 6: Comparison of (a) ZH and (b) ZDH outside the thermal comfort zone for different configurations of PCM in a Passive House in Phoenix, Arizona.

For all cases the PCM is rarely able to discharge because of the sustained elevated temperatures in the building. PCM with a melt temperature of 27°C has the greatest impact on occupant comfort; resulting in reductions of 6.4% of ZH and 7.3% of ZDH uncomfortable when placed on every wall. A system this size, however, would cost $12,800 based on current market price [4]. The result is a very expensive system that yields relatively small improvements in thermal comfort.

LOS ANGELES PCM RESULTS

While Los Angeles typically has several very hot weeks during the summer, the high temperatures and hot spells pale in comparison to those of Phoenix. The baseline model for Los Angeles had 1625 ZH and 2458 ZDH outside the thermal comfort zone. The first step in adding PCM to the Passive House model in Los Angeles was to isolate the overheating zones. It was determined that 80% of the ZH and 88% of the ZDH occurred in the 2nd floor zones. Within the 2nd floor zones, there were 1.5 times more ZH and 2 times more ZDH uncomfortable in the 2nd floor common zone than in the 2nd floor back bedroom zone. The common zone is large, open, and has considerable southern glazing area (refer back to Figure 3). Also, this is the zone that is connected to the 1st floor zones via a stairwell, so hot air rises directly into it. The high concentration of overheating in the 2nd floor common zone presented the largest potential impact for PCM and thus became the area of focus for PCM integration. After isolating the zone of interest, individual surfaces were investigated. All interior surfaces that could accommodate PCM were investigated including exterior walls, interior partitions, floors and ceilings. PCM was incrementally added to surfaces in the 2nd floor common zone beginning with those that had the highest simulated daytime temperatures during overheating days. The ZH and ZDH outside the thermal comfort zone were monitored for each configuration of PCM and at each of the four PCM melt temperatures.

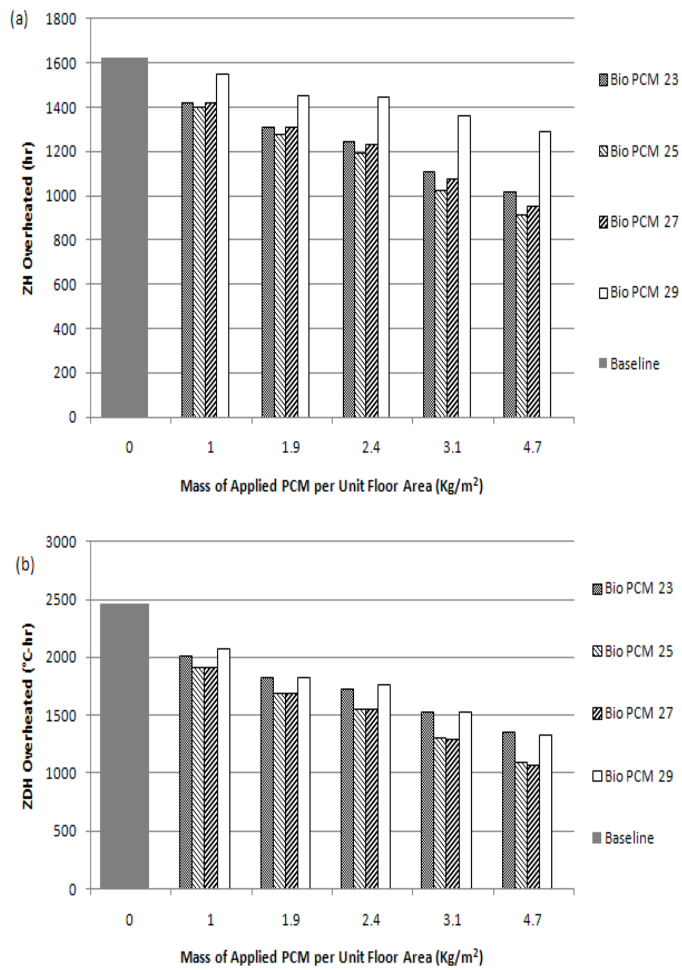

Figure 7: Comparison of (a) ZH and (b) ZDH outside the thermal comfort zone for different configurations of PCM in a Passive House in Los Angeles, California.

It is clear from Figure 7 that adding PCM in Los Angeles has significantly more impact than it did in Phoenix. This is due to the reduced severity of hot spells in Los Angeles. Reductions of up to 44% of ZH and 55% of ZDH uncomfortable were achieved by placing 4.7 Kg/m^2 (based on floor area) of PCM in the house.

PORTLAND PCM RESULTS

Portland, Oregon is located in climate zone 4 and is typical of a marine climate. Summers in Portland are warm and dry with cool nights, and winters are wet and mild. Portland is the mildest climate investigated with the baseline model having only 245 ZH and 261 ZDH uncomfortable.

It was found that all of the overheating occurred in the 2nd floor with 80% occurring in the 2nd floor common zone. An identical procedure of incrementally adding PCM to overheating surfaces in the 2nd floor common zone was carried out. Figure 8 shows the impact of PCM on thermal comfort for the Portland simulations.

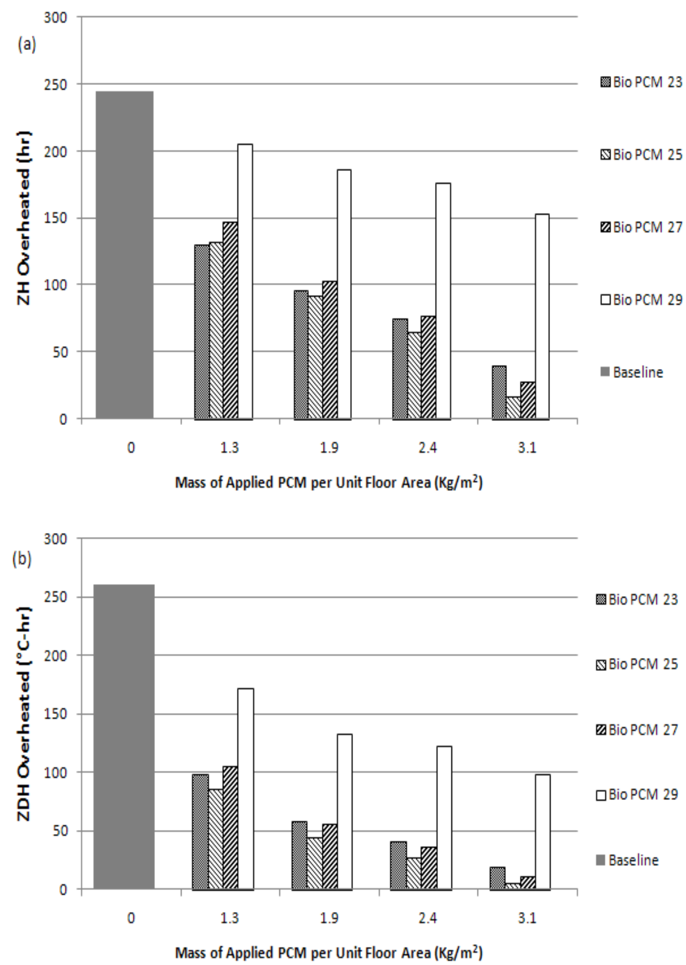

Figure 8: Comparison of (a) ZH and (b) ZDH outside the thermal comfort zone for different configurations of PCM in a Passive House in Portland, Oregon.

A PCM melt temperature of 25°C results in the most significant reductions in discomfort across the entire PCM product options. Reductions of 93% of the ZH and 98% of the ZDH uncomfortable were achieved by applying 3.1 Kg/m^2 of PCM with a melt temperature of 25°C. These large reductions can be associated with a number of factors. Less extreme daytime high temperatures coupled with low nighttime temperatures allow for proper charging and discharging of the PCM. Also, Portland has dry summers therefore discomfort due to latent loads is relatively uncommon.

DENVER PCM RESULTS

Located in the semi-arid high plains, Denver is the coldest climate of any investigated in this study. While Denver is in climate zone 5 (generally a colder climate zone than Portland), it actually has hotter summers than Portland. The baseline comfort values in Denver are 708 ZH and 809 ZDH uncomfortable.

Once again the majority of discomfort in the baseline model occurred in the 2^{nd} floor, with 79% of all discomfort occurring in the 2^{nd} floor common zone and 20% in the 2^{nd} floor back bedroom zone. So, the 2^{nd} floor common zone again became the focus for PCM integration. As with the other cities, a process of incrementally placing PCM on overheating surfaces in the 2^{nd} floor common zone was then carried out.

Significant reductions in discomfort were realized for PCM integration in Denver. As shown in Figure 9, a PCM melt temperature of 25°C resulted in the largest improvements, yielding reductions of 79% of ZH and 89% of ZDH uncomfortable after integrating 3.1 Kg/m^2 (based on floor area) into the space. With only 8% of discomfort hours arising due to elevated humidity ratio, Denver offered a high potential for PCM to mitigate discomfort. This coupled with cool nights allowed for significant reductions in occupant discomfort.

CONCLUSIONS

In Passive Houses east of the Rockies, the majority of discomfort arises from latent loads, which cannot be reduced by the application of PCM. In these climates discomfort due solely to sensible load accounts for less than 20% of the total ZH uncomfortable. This, however, is not the case for climates west of the Rockies where discomfort is driven by sensible loads.

Substantial improvements in occupant comfort were realized for Passive Houses located in Portland, Denver and Los Angeles. Portland, Oregon proved to be the location where the most substantial benefits were achieved. Reductions of 93% of ZH and 98% of ZDH uncomfortable were realized by adding 391 Kg (3.1 Kg per square meter of floor area) of PCM with a melt temperature of 25°C. Improvements in occupant comfort were similar, though lower for Denver and lower again for Los Angeles. Phoenix, Arizona presented a climate where the inclusion of PCM does not have a significant benefit to occupant comfort. This is because the PCM does not have a high enough storage density to substantially mitigate the load. Another major issue is the relatively warm temperatures through the night. The average nighttime low temperature in Phoenix during the months of July and August is above the maximum temperature for thermal comfort. Therefore, even with successful discharging of the PCM at night, the occupants remain uncomfortable (in the absence of mechanical cooling).

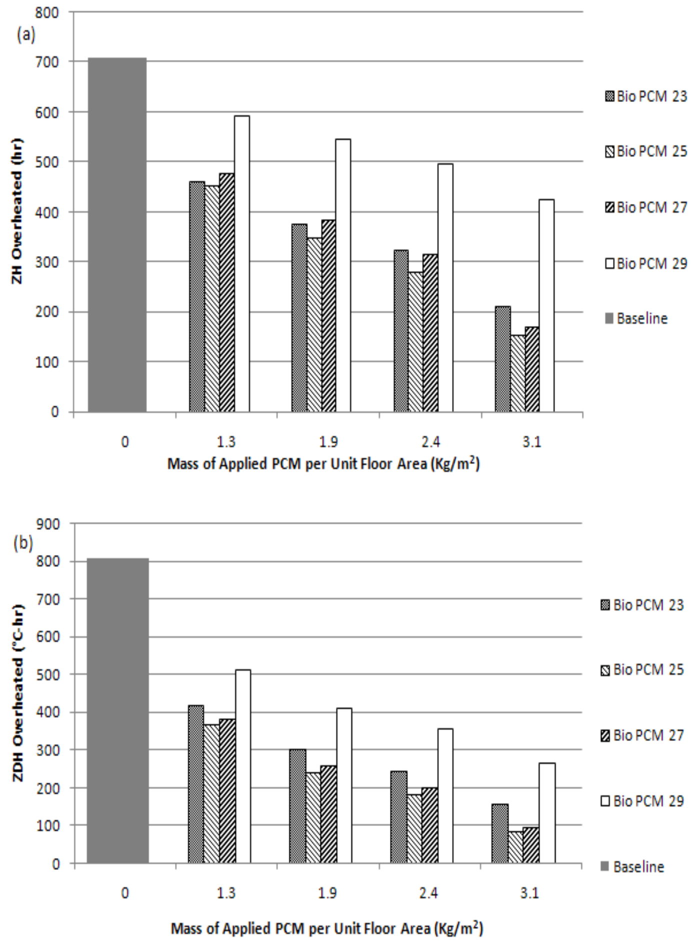

Figure 9: Comparison of (a) ZH and (b) ZDH outside the thermal comfort zone for different configurations of PCM in a Passive House in Denver, Colorado.

In all locations studied, the majority of discomfort occurred in the 2^{nd} floor, with higher concentrations in the common zone. The 2^{nd} floor was more prone to overheating because of stack effect as well as less internal wall area providing thermal mass in the 2^{nd} floor. The 2^{nd} floor common zone overheated more than the back bedroom zone due to two primary factors. First of all, the southern exposure in the common zone has more than 50% glazing area, therefore the zone has very high solar loads. Also, the common zone is where the open staircase to the 1^{st} floor is located. Therefore hot buoyant air from the 1^{st} floor rises directly into the 2^{nd} floor common zone.

While increasing occupant comfort is the desired outcome of adding PCM, it is important to not only consider the increase in comfort but also the cost of the PCM system that precipitated the increase. The PCM product investigated in this study retails at $3.49/SF [4]. The costs associated with each of the test cases explored for the four cities are summarized in Table 4.

Table 4: Quantities of PCM investigated and their associated costs.

PCM mass per unit floor area (Kg/m^2)	PCM mass (Kg)	PCM wall area (m^2)	Cost ($)
1.3	164	46	1,708
1.9	240	70	2,610
2.4	303	85	3,183
3.1	391	112	4,212
4.7	593	167	6,260

Commercially produced PCMs are an immature technology. Thus, the costs may decrease substantially in time due to increases in production, improvements in the manufacturing process, and enhancement of the product formulation. This coupled with the subjectivity of comfort makes it difficult to make a single recommendation for the ideal quantity of PCM to place in a house. However, when considering PCM system costs it is also important to consider the potential offset by capital cost savings in climates where PCM enables foregoing the installation of mechanical cooling. This capital cost savings can be substantial as residential air-conditioners typically cost between $1500 – $10,000.

The houses studied did not have mechanical cooling equipment, so the energy stored by the PCM was manifested as an increase in occupant comfort. The houses did, however, have a small (1500 Watt) mechanical heater. In order to quantify the impact PCM had on the space during the heating season, annual energy consumption was also investigated. Simulated annual energy savings from 0.5% in Phoenix to 3.1% in Denver were achieved with the application of PCM.

FUTURE WORK

As mentioned previously, the Passive House modeled in this study actually consists of side-by-side identical duplexes that are currently being built in Portland, Oregon. The owner of the house agreed to allow use of the duplexes as a test site for the integration of PCM. The experiment allows for verification of the present modeling work and will consist of outfitting one of the units with PCM, per the recommendation of this study. The other unit will be left unmodified (no PCM) and will act as a control. A total of 185 Kg (1.5 Kg/m^2) of PCM will be placed in the wall cavity in the 2nd floor common zone of one of the units.

Instrumentation packages have been designed for each unit consisting of surface and air temperature sensors, relative humidity sensors, window and door ajar sensors and power consumption monitors. Also, a weather station will be placed on site. Data will be collected over the course of one year, and verification of the numerical modeling will be performed.

Since the present study focused on non-mechanically cooled passive houses for the application of PCM; this limited the number of climates where the application of PCM was viable. This is due to PCM's inability to reduce latent loads, which drive discomfort for much of the United States during the summer months. The question remains, what kind of impact can PCM have in super-insulated homes located in humid climates when coupled with dehumidification? In these instances PCM may have the potential to reduce and shift the peak and total cooling load seen by the mechanical equipment. While load shifting and reduction associated with the application of PCM has been investigated [4], it has not been investigated in situ, nor has it been evaluated in super-insulated homes. When coupled with super-insulated homes, energy savings from PCM may be significant enough to result in downsizing of mechanical equipment.

ACKNOWLEDGMENTS

The authors would like to thank Ella Wong and Robert Hawthorne for their support and enthusiasm. This research has been supported by the US Department of Energy under award DE-EE0003870.

REFERENCES

[1] Barakat, S. and D. Sander. “Utilization of Solar Gain Through Windows for Heating Houses.” *Division of Building Research – National Research Council of Canada.* March 1982. Web 12 Apr. 2011

[2] Zhang, Yinping, Guobing Zhou, Kunping Lin, Qunli Zhang, and Hongfa Di. “Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook.” *Building and Environment 42,6* (2007); 2197-2209. Science Direct. Elsevier, 21 July 2006. Web 03 Apr. 2011

[3] Farid, Mohammed, Amar M. Khudhair, Siddique Ali K. Razack, and Said Al-Hallaj. “A review of phase change energy storage: materials and applications.” *Energy and Conversion Management 45* (2004); 1597-1615. Science Direct. Elsevier, 12 Sept. 2003. Web 15 June 2010.

[4] "BioPCM™." *Energy Smart Company*. Web. 18 Apr. 2011. <http://www.energysmartcompany.com/page/bio-pcm-phase-change-material>.

[5] Muruganantham, Karthik, Patrick Phelan, Peter Horwath, David Ludlam, and Timothy McDonald. *Energy Smart Company*. Proc. of ASME International Conference on Energy and Sustainability, Phoenix. Web. 12 Sept. 2010

[6] Schossig, P., H. Henning, S. Gschwander, and T. Haussmann. "Micro-encapsulated phase-change Materials Integrated into Construction Materials." *Solar Energy Materials & Solar Cells* 89 (2005): 297-

306. *Science Direct*. Elsevier, 4 May 2005. Web. 08 June 2010.

[7] Stetiu, Corina, and Helmut E. Feustel. “Phase-Change Wallboard and Mechanical Night Ventilation in Commercial Buildings.”*American Council for an Energy-Efficient Economy* (1998) Washington D.C.

[8] Virgone, Joseph, Jean Noel, and Raymond Reisdorf. "Numerical Study of the Influence of the Thickness and Melting Point on the Effectiveness of Phase Change Materials: Application to the Renovation of a Low Inertia School." *Building Simulation* (2009): 408-13. *Science Direct*. Building Simulation. Web. 08 June

[9] Feist, Wolfgang. "Improving Energy Efficiency by a Factor of 10 - The Passive House Standard." 2007 Energy Efficiency Global Forum and Exposition. Washington D.C. 13 Apr. 2011.

[10] Pedersen, C. O. *Advanced Zone Simulation in EnergyPlus: Incorporating of Variable Properties and Phase Change Material (PCM) Capability*. Proc. of International Building Performance Simulation Association (2007), Beijing. Building Simulation. Web. 18 June 2010.

[11] Kuznik, Frederic, Joseph Virgone, and Jean-Jacques Roux. "Energetic Efficiency of Room Wall Containing PCM Wallboard: A Full-scale Experimental Investigation." *Energy and Buildings* 40 (2008b): 148-56. *Science Direct*. Elsevier, 24 Jan. 2007. Web. 08 June 2010.

[12] Schnieders, Jurgen, and Andreas Hermelink. "CEPHEUS Results: Measurements and Occupants' Satisfaction Provide Evidence for Passive Houses Being an Option for Sustainable Building." *Energy Policy* 34 (2006): 151-71. *Science Direct*. Elsevier, 5 Oct. 2004. Web. 20 Mar. 2011.