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Phase Change Material as a Thermal Storage Device for Passive Houses

by

Kevin Ryan Campbell

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
In
Mechanical Engineering

Thesis Committee:
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Abstract

This study describes a simulation-based approach for informing the incorporation of Phase Change Materials (PCMs) in buildings designed to the "Passive House" standard. PCMs provide a minimally invasive method of adding thermal mass to a building, thus mitigating overheating events. Phase change transition temperature, quantity, and location of PCM were all considered while incrementally adding PCM to Passive House simulation models in multiple climate zones across the United States. Whole building energy simulations were performed using EnergyPlus from the US Department of Energy. A prototypical Passive House with a 1500 Watt electric heater and no mechanical cooling was modeled. The effectiveness of the PCM was determined by comparing the zone-hours and zone-degree-hours outside the ASHRAE defined comfort zone for all PCM cases against a control simulation without PCM.

Results show that adding PCM to Passive Houses can significantly increase thermal comfort so long as the house is in a dry or marine climate. The addition of PCM in moist climates will not significantly increase occupant comfort because the majority of discomfort in these climates arises due to latent load. For dry or marine climates, PCM has the most significant impact in climates with lower cooling degree-days, reducing by 93% the number of zone-hours outside of thermal comfort and by 98% the number of zone-degree-hours uncomfortable in Portland, Oregon. However, the application of PCM is not as well suited for very hot climates because the PCM becomes overcharged. Only single digit reductions in discomfort were realized when modeling

PCM in a Passive House in Phoenix, Arizona. It was found that regardless of the climate PCM should be placed in the top floor, focusing on zones with large southern glazing areas. Also, selecting PCM with a melt temperature of 25°C resulted in the most significant increases in thermal comfort for the majority of climates studied.

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1. Introduction

The present research aims to inform the integration of Phase Change Material (PCM) into the construction of buildings designed to the Passive House Standard using a prevalent whole building energy simulation tool from the United States Department of Energy. PCM is beneficial for Passive Houses because it possesses significant thermal mass, which contributes to reducing overheating during the summer and shoulder seasons. This study considers Passive Houses that do not have mechanical cooling and therefore overheating results directly in occupant discomfort.

1.1 Motivation

As global energy consumption has risen, strain on energy sources as well as energy costs have increased. This has placed pressure on energy consuming sectors to adopt more efficient practices. This shift is manifesting itself in the building industry through increasingly more efficient building codes and standards. The International Energy Conservation Code 2009 is estimated to be 15% more efficient than the 2006 version and there is a strong push to design the 2012 version to be 30% more efficient than the 2006 version (Karmol, 2010). In order to reduce the energy consumption of buildings, heating and cooling energy must be reduced. An energy consumption survey performed by the United States Department of Energy found that residential heating and air-conditioning consumes 49% of all residential energy usage in the United States (US DOE, 2009). With heating and cooling constituting such a large portion of

residential energy usage, improvements to the building envelope can have a significant impact on total energy consumption of the residential building stock.

Frameworks for identifying and implementing designs that will reduce building energy use are outlined by several building certification programs. The different building certification programs can be broken into two varieties: prescriptive and performance based. Prescriptive based certifications dictate individual components of a structure with the intent that by incorporating efficient components, the end structure will achieve a desired efficiency. Performance based standards gives the designer more freedom; however the design must meet post-design performance based metrics such as energy use index, heating demand and air tightness.

The current study is based on a residence that is designed to the Passive House Standard. Developed in Sweden in the 1990s, The Passive House Standard aims to create houses that use 90% less energy than conventional new houses (Feist, 2007). The Passive House Standard has three performance based requirements. The first requirement is that the house must have an annual primary energy requirement of less than 120 kWh/m^2 . Because this is a primary energy requirement, and thus includes considerations of inefficiencies at power plants, a conversion must be made to consider the source of the energy. Therefore if the house is run completely on electricity, one must consider losses in the electricity conversion process as well as transmission losses. The second requirement is that the annual heat demand must be less than 15 kWh/m^2 . Because this is a requirement on demand, conversion to source energy is not needed.

The final requirement is that the house must have an infiltration rate of less than 0.6 Air Changes per Hour (ACH) at 50 Pascals. In order to achieve the Passive House Certification, designers must demonstrate that their design meets all three requirements.

There are more than 25,000 certified Passive Houses worldwide, most of which are in Northwestern Europe. Because the Passive House Standard is performance based, there are many different design variations that meet the requirements. Nevertheless, all houses built to the Passive House Standard have very little heat transfer across their building envelopes and maximize passive and waste heat. This is achieved by increasing the insulation levels of walls, floors, roofs, and windows. In addition, care is taken during design and construction to ensure that infiltration and exfiltration are minimized. Even though the insulation values and air tightness of Passive Houses differs from typically constructed houses, Passive Houses are still built with common materials.

Modern construction practices and materials are beneficial in that they reduce construction cost and time; however their usage results in buildings with little thermal mass. A house built using modern construction practices can be 5 times less thermally massive compared to a similar house built from stone or brick (Barakat and Sander, 1982). Thermal mass is critical in storing thermal energy and moderating temperature fluctuations. In modern houses with mechanical cooling, the spike in energy crossing the building envelope during the middle of the day acts to heat up the space. Then the mechanical cooling system works to prevent the space from overheating. In houses

without mechanical cooling, midday indoor air temperature spikes result directly in occupant discomfort as there is no mechanical system to cool the space. By adding thermal mass to a house, a reduction and shift in temperature fluctuations can be achieved and occupant comfort can be increased without needing a mechanical cooling system. (Zhang et al., 2007)

Pouring an extra thick concrete slab or using dense materials in the interior design such as granite, marble and brick are common methods of adding thermal mass to wood framed houses. While these methods add thermal mass, the former requires considerable attention in the design phase and the latter changes the interior of the space. One method of adding thermal mass that lends itself to retrofits and is minimally invasive is installing PCM behind the wallboard. PCMs have the same effect as adding traditional thermal mass to a structure, however they have a much higher energy storage density because they utilize a change of phase in order to absorb and release heat. The latent heat of a material is a measure of the material's ability to store and release heat during the change of phase. Table 1.1 shows latent heat values and phase change temperatures for several material processes.

Table 1.1: Latent heat and phase change temperature of several material processes.

Process	Latent Heat (KJ/Kg)	Phase Change Temperature (°C)
Ice to Water	333	0
Water to Steam	2260	100
Melting of PCM used in Buildings	~200	20-30

There is a large amount of energy associated with the change of phase from water to steam. However, at atmospheric pressures this phase change happens at 100 °C, and therefore it can not be exploited to store energy in buildings. In order for PCMs to be useful in building applications, the phase change temperature must occur near room temperature. Consideration must also be given to the volumetric expansion between the two phases. If the volumetric expansion of a substance is too great, then it is difficult to contain the material after changing phase. The conversion of water to steam is an example of a process that results in a large volumetric expansion. After one cubic centimeter of water is converted to steam it will take up 1600 cubic centimeters.

Exploration into the field of PCMs applied to buildings is not a very new topic. Investigations into using PCMs in buildings began with macroencapsulated PCMs. The macroencapsulation refers to the quantity of PCM per containment unit. While there is no set range on what is considered macroencapsulated PCM, most macroencapsulated PCM products contain between 1 cubic centimeter to a liter of PCM per containment unit. The PCM is encapsulated by a casing in order to prevent the PCM from leaking out when in the liquid phase. While macroencapsulation of PCM has been investigated for many years, there has been a surge of interest in PCM over the last decade due to the advent of microencapsulation. Microencapsulated PCM is comprised of small, 2-20 micron in diameter, spheres of PCM encapsulated in a polymer casing. The primary benefit of microencapsulation is that the surface area to volume ratio is greatly increased, which improves heat transfer (Farid et al., 2004)

With the introduction of microencapsulation came several studies looking into PCM efficacy in different building styles and components. Studies have looked at mixing microencapsulated PCM into concrete slurries (Cabeza et al., 2007) and wallboard slurries (Shossig et al., 2005). Also, several studies have looked into adding PCM to buildings with the goal of reducing peak cooling load and energy usage in buildings with mechanical cooling. One experiment was performed on small test sheds in Arizona. Two identical sheds were constructed and macroencapsulated PCM was installed behind the walls, floor and roof of one of the sheds. Both sheds were equipped with mechanical cooling systems to maintain an interior set-point temperature. Peak load shifts of up to one hour, as well as a maximum of 29% reduction in monthly energy usage were achieved (Muruganantham et al., 2007).

Impacts on indoor air and surface temperatures due to PCM wallboard was investigated in Freiburg, Germany. In this study two rooms were constructed, one of which was outfitted with wallboard that had been impregnated with microencapsulated PCM while the other had standard wallboard. The two rooms were identical and were built with typical lightweight construction practices consisting of wood frames that were filled with insulation and then covered by wallboard. Year long studies were conducted focusing on indoor temperature profiles. It was determined that the room outfitted with PCM impregnated wallboard was able to achieve wall temperature reductions of 4°C. This study also noted the importance of night ventilation in order to adequately discharge the PCM (Shossig et al., 2005).

The impact of night ventilation to discharge the PCM was more fully investigated by a numerical analysis performed at Lawrence Berkeley National Labs (LBNL). RADCOOL, a building energy simulation program was used to evaluate the thermal performance of PCM wallboard in an office building environment. The office buildings simulated in this study had a VAV ventilation system that was used to simulate night ventilation. This study found 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.”(Stetiu and Feustel, 1998)

Similar simulation based studies have been performed to examine the performance of PCM in buildings. CoDyBa (a design tool for dynamic building performance simulations that was developed at the University of Lyon, France) was used as a simulation tool in a study conducted at the University of Lyon in France. This study focused on a non-mechanically cooled school that was built in the 1960’s and had gone without any major renovations. A microencapsulated PCM board that installs behind traditional wallboard and is commercially available in Europe was investigated. The study looked into impacts associated with changing the melt temperature of the PCM, thickness of PCM panel, and also how important envelope upgrades were to the thermal performance of the school. Using operative temperature as a metric for effectiveness, conclusions were drawn that a melt temperature of 22°C is more beneficial than 27°C. It was also concluded that “it is better to allocate a large area of material of low thickness than to large thicknesses.” In regards to other renovations,

every test performed significantly better after having envelope upgrades, and it was concluded that an efficient envelope is critical in order to maximize the performance of PCM. (Virgone et al., 2009)

The studies outlined provided guidance for the formulation of this study in the selection of investigating the integration of PCM in houses built to the Passive House Standard. The impact of PCM is maximized in Houses built to the Passive House Standard due to their extremely efficient building envelopes. Also, the lack of heating and cooling systems presents the most extreme case of mechanical conditioning equipment downsizing as noted in the LBNL study. The non-existence of these mechanical systems then allows for efficacy of the PCM to be determined based directly on occupant comfort.

While many recent studies have focused on microencapsulated PCM, this study investigated macroencapsulated PCM due to the reduced cost of energy storage. The price of energy storage potential is 2.5 times greater for microencapsulated PCM than for macroencapsulated PCM (BioPCM™, 2011).

1.2 Purpose

It is clear that incorporating PCM into a structure is an effective and minimally invasive method of adding thermal mass to a structure, and this increase in thermal mass can improve the thermal performance of the building. Increasing the thermal performance is beneficial for different reasons depending on the nature of the building.

If the building is mechanically cooled and heated, then the improvements are manifested as decrease in peak load and total space conditioning load. However, if the space has no mechanical heating or cooling, the heightened thermal performance acts to increase occupant comfort directly. The purpose of the present study was to isolate and investigate a subset of buildings that possess the largest potential impact from the application of PCM. After this was determined, an analysis was performed to develop informed design guidelines for the application of PCM in the identified structures.

The Passive House Building Standard was chosen as the type of building to focus on for several reasons. The first reason is that Passive Houses have very little energetic interaction across the building envelope. As Virgone et al. (2009) noted this is critical because the energy lost through an inefficient envelope greatly outweighs any benefit that PCM could provide. The second reason relates to one of the often commented drawbacks of Passive Houses. Due to high insulation levels, extreme air tightness, low thermal mass and considerable glazing areas, Passive Houses are prone to overheating during the summer and shoulder seasons. Therefore adding PCM (thermal mass) to the structure should help to reduce overheating events. The final reason has to do with the spirit of the Passive House Standard. As the name implies, Passive Houses are built to utilize passive strategies to achieve thermal comfort, therefore it is unusual to see Passive Houses with active HVAC equipment (outside of a heat/enthalpy recovery ventilator). While some Passive Houses have small ancillary heating systems, it is quite rare for them to have mechanical cooling systems. This means that overheating leads

directly to occupant discomfort. Thus adding PCM and improving the thermal performance of the space would result directly in increased occupant comfort.

2. Validation of Energy Modeling Techniques

This chapter outlines all simulations performed in order to evaluate PCM in Passive Houses. Included are simulations that were necessary to validate the heat balance algorithm used in EnergyPlus. In addition, numerical simulations of a laboratory experiment performed at the Thermal Sciences Center of Lyon were carried out to verify the Phase Change Module's ability to capture the building physics associated with PCMs.

This study used whole building energy modeling in order to simulate PCM in Passive Houses. Whole building energy modeling is commonly utilized in the design phase of a building project commonly in order to quantify the performance of a building and to investigate alternative designs. Building geometry, material properties, occupancy and equipment schedules, and mechanical systems are a few of the necessary inputs used to create a building model. The model is then paired with a weather file for a particular location and a simulation is performed. Outputs for a whole building energy simulation are numerous and include air temperatures, zone loads, energy usage, solar insolation and lighting levels.

Whole building energy simulations were performed using EnergyPlus from the United States Department of Energy. The software takes roots in the BLAST and DOE-2 platforms, and was selected for this project because of its availability and capability to

model PCMs. “EnergyPlus is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources.” (US DOE, 2010) A simulation manager module acts to call and organize different modules. The modular nature allows for a multitude of different building configurations. Due to the modularity, as well as EnergyPlus’ open source nature; code modifications and additions are frequent and simple. This allows for developers to add their own modules based on needs perceived by the users.

While EnergyPlus is a very flexible tool, it is best implemented with a third party’s graphical user interface . There are several interfaces currently available including DesignBuilder®, EnergyPlugged, and ©ECOTECT. EnergyPlus is not intended to replace the building designer or engineer. It relies heavily on the “Garbage in, Garbage out” principle, wherein it will not check to make sure input parameters are reasonable. For this reason diligence must be exercised when using it.

2.1 Heat Balance Algorithm

When modeling PCMs or other materials that have variable thermal properties in EnergyPlus, one cannot use the default Conduction Transfer Function (CTF) Heat Balance Algorithm. The CTF Heat Balance Algorithm cannot be used because the thermal properties cannot be updated at every timestep with this method. Instead, the Conduction Finite Difference (CFD) Heat Balance Algorithm must be used. The CFD Heat Balance Algorithm was added to EnergyPlus in 2007. Upon release this heat balance

algorithm had minimal validation performed. Figure 2.1 is the only verification that was published with the release of the CFD Heat Balance Algorithm.

Figure 2.1: Graph showing agreement between CFD and CTF heat balance algorithm. Also shown is effect of adding PCM on reducing temperature fluctuations (Pedersen, 2007)

Figure 2.1 is sensible cooling data from a simulation of a small office building with a floor area of 140 m² simulated in Minneapolis, Minnesota. The simulation period was during the summer design day and shows the sensible cooling load as modeled with the CTF Heat Balance Algorithm without PCM, the CFD Heat Balance Algorithm without PCM, and the CFD Heat Balance Algorithm with PCM in the wall constructions. It is important to note here that this simulation is not a model of an experiment. Therefore it

is very difficult to determine if the reduction in sensible cooling achieved by the addition of PCM is accurate.

Before using this heat balance algorithm to inform the integration of PCM into Passive Houses it was deemed necessary to ensure that it accurately modeled building energy performance. Therefore, a more robust analysis of the CFD Heat Balance Algorithm's ability to accurately model heat transfer in buildings was performed as part of the present study.

It was critical to ensure that the CFD Heat Balance Algorithm was able to accurately model heat transfer across the building envelope. Therefore a series of tests were devised to determine its ability to model heat transfer through the building fabric. Analytic tests were utilized in accordance with ASHRAE 1052-RP, *Development of an Analytical Verification Test Suite for Whole Building Energy Simulation Programs – Building Fabric*. A toolkit was developed as a part of ASHRAE 1052-RP to aid in determining analytic solutions of fundamental heat transfer scenarios in buildings. To test the CFD Heat Balance Algorithm, a 3m x 3m x 3m test cell was modeled with prescribed wall thicknesses and thermal properties (Henninger and Witte, 2010). Boundary conditions were then modified and simulations were carried out using the CFD Heat Balance Algorithm as well as the CTF Heat Balance Algorithm. The results from the CFD Heat Balance Algorithm tests were then compared to both the analytic results from the toolkit as well as the results from the CTF Heat Balance Algorithm.

For all tests performed for the present research, solar irradiation, long wave radiation, infiltration and internal heat gains were eliminated. Also, for all tests performed five of the zone walls were adiabatic, leaving one non-adiabatic. The initial tests on the CFD Heat Balance Algorithms ability to model heat transfer across the building envelope were steady state tests that investigated how heat is convected and conducted across the building envelope. Table 2.1 shows the results of the test; it is the most basic test performed and is based on a constant temperature difference across a single homogenous layer.

Table 2.1: Steady state test using single homogeneous construction layer

Metric	EnergyPlus CFD	Analytic Results	EnergyPlus CTF
Heat Flux (W/m ²)	29.25	29.27	29.25
Zone Load (W)	263.29	263.41	263.29
Inside Surface Temp (C)	29.75	29.76	29.75
Outside Surface Temp (C)	32.68	32.68	32.68

The tests outlined by The ASHRAE 1052 Research Project are designed to incrementally increase in complexity. This allows the user to pinpoint any deficiency in the building energy simulation tool's ability to accurately model heat transfer across the building fabric. The next test performed was also steady state, however it consisted of multiple homogeneous construction layers. Results of this test are shown in Table 2.2

Table 2.2: Steady state test using multiple homogeneous construction layers

Metric	EnergyPlus CFD	Analytic Results	EnergyPlus CTF
Heat Flux (W/m ²)	7.18	7.19	7.18
Zone Load (W)	64.64	64.67	64.64
Inside Surface Temp (C)	22.39	22.40	22.39
Outside Surface Temp (C)	38.19	38.20	38.19

There is very good agreement between the three calculation methods in both tests. The difference between any of the methods is never greater than 0.05%. These results instilled confidence in the CTF Heat Balance Algorithm's ability to handle steady state cases and allowed more complex transient cases to be investigated.

The following tests were transient and assessed the CFD Heat Balance Algorithm's ability to handle changes in environmental conditions. The external temperature underwent an increase from 20 °C to 70 °C over one hour while the internal temperature of the zone was allowed to float. Figure 2.2 shows the internal and external surface temperature profiles for the analytic as well as the CTF and CFD Heat Balance Algorithms.

Figure 2.2: Comparison of surface temperature profiles for the three calculation methods for a step in external air temperature and floating internal air temperature.

Very good agreement was shown in the first transient test; comparing internal and external surface temperature profiles from the CFD Heat Balance Algorithm to the CTF Heat Balance Algorithm and ASHRAE 1052. After sufficient time both inside and outside surfaces approach the outdoor air temperature because there is no conditioning, nor other loads in the space.

For this case the same step in outdoor air temperature is simulated, however the internal air temperature is now maintained at 20°C. External surface temperature profile, internal surface temperature profile, and zone cooling load are all monitored and shown in Figure 2.3.

Figure 2.3: Comparison of surface temperature profiles and zone cooling loads for the three calculation methods for a step in external air temperature and a constant internal air temperature of 20°C.

During this test the total zone cooling energy over a 48 hour period was also recorded and compared for each of the calculation methods. Results from the 48 hour zone cooling load are shown in Table 2.3.

Table 2.3: 48 hour zone cooling load for transient test with internal air temperature maintained at 20°C.

Metric	EnergyPlus CFD	EnergyPlus CTF	Analytic Results
48 hour Zone Load (kW-hr)	22.8	22.7	23.3
% Difference from CFD	NA	0.1	2.2

The two heat balance algorithms employed in EnergyPlus behave very similarly; however there is a small difference between the EnergyPlus based calculations and the analytic results. This difference in zone cooling load occurs during the transient period directly after the step change in outdoor air temperature. The difference arises due to the external surface temperature reacting faster to the change in air temperature. In the hour immediately following the step change, the external surface temperature is 24°C warmer in the analytical case. This difference though quickly diminishes. The difference in surface temperatures is reduced to less than 1°C after 3 hours from the step change.

The final test performed was the most similar to actual building conditions. This test simulates a diurnal change in outdoor air temperature. The indoor air temperature is maintained constant at 20°C while the outdoor air temperature follows a sinusoidal function with a mean of 20°C and amplitude of 15°C. The zone load profile is monitored and depicted in Figure 2.4.

Figure 2.4: Profile of zone load and outdoor temperature for three calculation methods under sinusoidal outdoor temperature profile.

Figure 2.4 shows that the CFD heat balance algorithm is able to precisely model a zone load induced by a more realistic boundary condition consisting of a diurnal outdoor temperature profile. The zone loads matched very well between the CFD, CTF and analytic results for this test.

Upon completion of the tests using the ASHRAE 1052 Toolkit, it was concluded that the Conduction Finite Difference Heat Balance Algorithm can accurately model heat transfer across the building fabric. It is able to handle steady state boundary conditions as well as transient cases. The transient cases showed that temperature profiles and

zone cooling loads can be accurately modeled given step or sinusoidal temperature based boundary conditions.

2.2 PCM Module

The PCM module in EnergyPlus must be used with the CFD Heat Balance Algorithm because this is the only heat balance algorithm that allows thermal properties to be updated at every time step. The CFD heat balance algorithm uses an implicit finite difference scheme:

$$\frac{\rho c_p \Delta x (T_{i,new} - T_{i,old})}{\Delta t} = \frac{k(T_{i-1,new} - T_{i,new})}{\Delta x} + \frac{k(T_{i+1,new} - T_{i,new})}{\Delta x} \quad (1)$$

The subscripts refer to the nodes and applicable time steps. When modeling PCMs it is necessary to invoke a specific heat function which is defined as :

$$Cp = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}} \quad (2)$$

Here h is enthalpy and T is temperature. As enthalpy is a function of temperature, the user must define an enthalpy temperature function for any modeled PCM. This is the function that defines the melt temperature and the amount of latent energy storage of the material. The new and old enthalpies are determined based on the new and old temperatures at each node. The solution manager determines the number of nodes in layer based on the Fourier stability criteria where the node

thicknesses are selected such that the time step is near the explicit limit. For any material though a minimum of two nodes are used (one internal and two half thickness representing layer surface temperatures) (US DOE, 2011).

While the tests performed in accordance with ASHRAE 1052-RP examined the CFD Heat Balance Algorithm's ability to model heat transfer across typical building envelopes; they did not assess its ability to model PCMs. In order to determine EnergyPlus' ability to accurately model PCMs, a pre-existing experiment was modeled and numerical results were compared to the experimental results. In order to validate EnergyPlus' ability to model PCM, a laboratory based experiment was modeled. MINBAT is a 3.1m x 3.1m x 2.5m experimental test cell built using typical low mass construction practices, which is located at The Thermal Sciences Center of Lyon, France. On 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 emit a spectrum similar to the solar spectrum. Also, the lights are situated so they can be lit in a sequence that mimics the path of the sun. The MINIBAT test cell is located inside a climactic chamber, allowing control of the exterior air temperature (Kuznik et al., 2008b).

Figure 2.5: Isometric diagram of MINIBAT from Kuznik et al. (2008b)

A model of MINIBAT was constructed in EnergyPlus, and then a baseline simulation was run without any PCM in the structure. The simulation consisted of a two day period during a typical summer day in Lyon, France. The outside temperature followed a diurnal cycle with a peak at 30 °C and a trough at 15 °C. After the baseline simulation was run, PCM was added to the model directly behind the wallboard on the north, east, and west walls of MINIBAT. The Simulation was re-run using the same environmental conditions. During both simulations the internal air temperature was allowed to float and was used as a metric to compare the effect of PCM. The primary metric analyzed was reduction of internal air temperature fluctuations achieved by adding PCM to the structure. The reduction in temperature fluctuations found from

numerical modeling in EnergyPlus was then compared to the experimental results published by Kuznik et al. (2008b). A comparison of the results is shown in Figure 2.6.

Figure 2.6: (a) Shows the EnergyPlus based indoor air temperature profile in MINIBAT. (b) Shows the experimental indoor air temperature profile inside MINIBAT. T_1 is taken at a height of 0.85 meters and T_2 is measuring at a height of 1.70 meters.

In part (a) of figure 2.6 both the CTF and CFD Heat Balance Algorithms were simulated without PCM. This was done to demonstrate good agreement between the two calculation methods when including solar insolation because the previous tests using the ASHRAE toolkit did not include solar radiation. The agreement between the

two cases is so good that the CTF data points are almost entirely hidden behind the CFD data points. As can be seen in both the simulation (a) and experimental (b) cases, reductions in temperature fluctuations were achieved by adding PCM to the structure.

For the experimental and simulation based cases, reductions in temperature fluctuations (max-min) were achieved and were similar in their magnitudes. The reduction in temperature fluctuation achieved by adding PCM in the EnergyPlus simulation was 4.9°C and a reduction of 4.7°C was found in experiments by Kuznik. The agreement between the simulations and the experiment provided confidence in the EnergyPlus' ability to model PCMs.

3 Methods – Modeling PCM in Passive House Applications

Following the verification of EnergyPlus to effectively model PCM, EnergyPlus was used as a tool to inform the integration of PCM in Passive Houses. A model of a Passive House was constructed using DesignBuilder®. DesignBuilder® is one of many graphical user interfaces that utilize EnergyPlus as its simulation engine. It is very useful because models can be created in DesignBuilder®, and then exported to EnergyPlus for further modification. Construction and design parameters were taken directly from a Passive House that was in the design phase in Portland, Oregon. The Passive House is two stories and actually consists of side-by-side identical duplexes. A floor plan of the Passive House is illustrated in Figure 3.1.

Figure 3.1: Floor plan of Passive House modeled in experiments. Note that the left hand side is the 1st floor and the right hand side is the 2nd floor.

This design was chosen because it utilizes the latest in Passive House design features, and also because the owner was interested in using the duplexes as an experimental test site for validation of the numerical PCM modeling. Details of the parameters used in the modeled of the Passive House are shown in Table 3.1.

Table 3.1: Modeling parameters for modeled Passive House

Parameter	Value
U Value – Walls ($W/(m^2 \cdot ^\circ C)$)	0.13
U Value – Roof ($W/(m^2 \cdot ^\circ C)$)	0.07
U Value – Slab ($W/(m^2 \cdot ^\circ C)$)	0.17
U Value – Windows ($W/(m^2 \cdot ^\circ C)$)	0.97
Floor Area – Per Unit (m^2)	126
Floor to Ceiling Height – 1 st Floor (m)	2.5
Floor to Ceiling Height – 2 nd Floor (m)	3.0
Glazing Area – (%)	13
Occupancy – (people/unit)	3
Lighting Power – ($Watt/m^2$ -100 lux)	0.4
Miscellaneous Loads – ($Watt/m^2$)	2.0
Air Tightness – (ACH_{50})	0.60
Electric Heater (W)	1500

One of the innovative design features found in many Passive Houses that is also present in the Passive House modeled in this study is the use of a heat recovery ventilator. Heat recovery ventilators exchange heat between the exhaust and supply air, which pre-conditions the supply air without using mechanical heating or cooling. They operate around 85% sensible efficiency. In more humid climates, enthalpy recovery ventilators are used that can also transfer moisture between the exhaust and supply air streams. Enthalpy recovery ventilators have latent efficiencies up to 60% and similar sensible efficiencies to heat recovery ventilators.

From the outset, this house was designed with the intention of reducing energy consumption by 90% compared to standard construction houses. One of the components that aided in achieving this was the super-insulated walls. A cross section view of the exterior walls is shown in Figure 3.2

Figure 3.2: Cross section view of super-insulated walls of Passive House.

In addition to insulation, consideration was also given to orientation, size and geometry in order to minimize energy usage. The aspect ratio of the structure is 0.89, the conditioned area is 126 m² and overhangs are present on all southern glazings. A rendering of the modeled Passive House is shown in Figure 3.3.

Figure 3.3: Rendering of modeled Passive House that is being built in Southeast Portland, Oregon.

As can be seen in the rendering, the southern exposure has a high glazing percentage and also has overhangs that prevent direct sunlight from entering the space during summer. Also, due to an air barrier and diligent construction practices, the house is designed to achieve an air tightness value of 0.6 Air Changes per Hour at 50 Pascals.

When creating the building model, it was determined that only the west half of the Passive House needed to be modeled. Modeling only half of the Passive House is sufficient because it is symmetrical and both spaces will be conditioned. It was chosen to model the west unit because it is the unit which will receive PCM as validation for the

numerical modeling. While the west half will receive PCM, the east half will not so it can act as a control for the experiment.

After creation of the Passive House model in DesignBuilder®, the model was exported to EnergyPlus and baseline simulations were run in major cities in eight different climate zones defined by The United States Department of Energy. The baseline simulations had a run period of one year, and all simulations utilized a nighttime flush in order to take advantage of low nighttime temperatures to cool the space. A nighttime flush consists of simply opening the windows at night to allow the building to vent and discharge stored heat. This was chosen due to recommendations from Shossig et al., (2005) and Stetiu and Feustel (1998). It was implemented such that 20% of the window area would open during the night when the interior air temperature was higher than the set point and the exterior air temperature was lower than the interior air temperature.

Metrics analyzed in the baseline simulations were zone-hours (ZH) and zone-degree-hours (ZDH) outside the ASHRAE defined thermal comfort zone. The modeled Passive House has five different zones, therefore one ZH uncomfortable means that only one of the five zones was outside of the thermal comfort zone for one hour. Given that there are 8760 hours in a typical year and that the Passive House modeled has five zones, the maximum ZH uncomfortable is 43,800 hours. ZH and ZDH were used instead of simply hours and degree-hours due to significant zone air temperature differences 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. In order to account for surface temperatures in addition to air temperature, both ZH and ZDH are based on operative temperature and humidity ratio. Figure 3.4 outlines the thermal comfort zone used in this study.

Figure 3.4: Thermal Comfort Zone used to determine occupant comfort. Thermal Comfort Zone adapted from ASHRAE Standard 55.

ZDH were considered in addition to simply ZH outside the thermal comfort zone because this quantifies the level of discomfort of the occupant. It is important to note that this study is not considering discomfort that arises from the occupant being cold. This was chosen because while Passive Houses may have a small mechanical heating system that can maintain an occupant set point temperature during the heating season, they rarely have any mechanical cooling. Also, even though thermal comfort is based on operative temperature, it has been noted that occupants are comfortable in temperatures below the ASHRAE defined Thermal Comfort Zone. A large European

study, CEPHEUS, found that temperatures that were judged to be ‘exactly right’ went as low as 19.4°C (Schnieders et al., 2006). Minimized drafts and a more even temperature distribution play a role in satisfying thermal comfort at operative temperatures lower than defined by The ASHRAE Thermal Comfort Zone. In order to quantify any possible impact adding PCM has during the heating season, total energy consumption was also recorded.

3.1 Modeled Phase Change Material

The PCM that was modeled in the Passive House is BioPCM™, made by Phase Change Energy Solutions. It is derived from refined soy and palm kernel oil. The Properties of the product are listed in Table 3.2.

Table 3.2: Thermophysical properties of PCM used in simulations.
(Muruganantham et al., 2010)

Description	BioPCM™
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)	.015
Melt Temperature (°C)	23,25,27,29

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

There are four different melt temperatures of this product that were investigated. This product is available in the United States and is comprised of pouches that contain roughly 17 grams of PCM per pouch. Pouches are held together on sheets

which can then be installed between studs behind drywall. An example of an installation of BioPCM is shown in Figure 3.5.

Figure 3.5: Typical installation of BioPCM™ in a wall cavity (BioPCM™, 2011)

In order to model the PCM in EnergyPlus an enthalpy temperature function had to be developed. Raw data of heat flux as a function of temperature during the melting process was received directly from the manufacturer of BioPCM™. This data was then converted to specific heat as a function of temperature.

Figure 3.6: 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.

While the BioPCMTM products are listed as having specific melt temperatures of 23, 25, 27, and 29°C it can be seen in Figure 3.6 that these melt temperatures are nominal values, and that the actual melt temperatures of the products may vary by as much as 2°C from the product description. It is interesting to note that the actual melt temperatures of the 25°C and 27°C products vary by less than 1°C. The specific heat functions in Figure 3.5 were used to create enthalpy temperature functions that are needed as inputs in the Phase Change Module in EnergyPlus. The enthalpy temperature functions describe the change in enthalpy from a selected reference point. The reference point used for this study was 0°C, at which the enthalpy was defined as 0 KJ/Kg.

When PCM is placed in wall cavity it acts to prevent the wall from overheating. In order to quantify this, simulations were carried out with and without 25°C melt temperature BioPCM in a wall cavity of the Passive House model. Simulations were run during the summer design day in Denver, Colorado. Figure 3.7 shows the nodal temperatures in the wall cavity..

Figure 3.7: Nodal temperatures in the Passive House wall construction (a) without PCM and (b) with BioPCM with a melt temperature of 25°C in the wall cavity.

As can be seen in Figure 3.7, the nodal temperatures throughout the wall are much lower when PCM is placed in the wall cavity. Nodes 5, 6 and 7 have been

highlighted as those are the nodes that correspond to the PCM layer. Note how these nodes do not increase in temperature nearly as fast as the other nodes and also how the presence of PCM cools down the entire wall construction and not just the nodes within the PCM layer.

4. Passive House Simulation Results

This chapter contains results on the application of PCM in the Passive House model. Baseline models were first established for the Passive House in different climates while monitoring occupant comfort. Then, different configurations of PCM were integrated into the Passive House. The simulations were run with the addition of PCM and occupant comfort was once again monitored and used as a means to quantify effectiveness.

After establishing confidence in both the CFD Heat Balance Algorithm and the capability of the Phase Change Module to accurately simulate PCMs in building constructions, simulations were conducted to inform the integration of PCMs in Passive Houses. Baselines were initially established for Passive Houses in 8 different climate zones defined by The United States Department of Energy (ICC, 2009). These climate zones are shown in Figure 4.1.

Figure 4.1: Climate zones of the United States of America (ICC, 2009).

In order run simulations in each of the eight climate zones, cities within each of the climate zones had to be selected. The cities and corresponding climate zones that were initially modeled are shown in Table 4.1.

Table 4.1: Locations and respective climate zones for Passive House baselines.

Location	Climate Zone
Miami, Florida	1
Houston, Texas	2
Los Angeles, California	3
Portland, Oregon	4
Chicago, Illinois	5
Minneapolis, Minnesota	6
Duluth, Minnesota	7
Fairbanks, Alaska	8

Two parameters were monitored for each of these baseline models. The parameters monitored were ZH outside the comfort zone and ZDH outside the comfort zone. The only change made to the Passive House modeled in each climate zone was

that for locations east of the Rockies (climate zones 1, 2, 5, 6, and 7) an Enthalpy Recovery Ventilator (ERV) was used in place of the Heat Recovery Ventilator (HRV). This was determined per recommendation from a heat/enthalpy recovery ventilator technical sales representative (Groves, 2010). The ERV is used in climates with humid summers and or dry winters in order to keep moisture levels inside the space at desirable levels.

Upon investigation of the baseline models, it was found that moisture was the primary source of discomfort in several of the climates. For locations east of the Rockies (climate zones 1, 2, 5, 6, and 7), the majority of ZH outside the thermal comfort zone arose due to too much moisture in the air regardless of temperature. As shown in Figure 4.2, this occurs when the humidity ratio is above 0.012. A summary of the ZH outside the comfort zone, ZDH outside the comfort zone, and the percentage of ZH outside comfort zone that also have a humidity ratio greater than 0.012 are shown in Table 4.2.

Table 4.2: Thermal comfort assessment for baseline simulations in different locations.

Location	ZH not comfortable (hr)	ZDH not comfortable (°C-hr)	Percentage of ZH not comfortable that also have a humidity ratio > 0.012
Miami, Florida	15152	34235	99
Houston, Texas	8384	20702	99
Los Angeles, California	1625	2458	45
Portland, Oregon	245	261	19
Chicago, Illinois	945	1852	82
Minneapolis, Minnesota	811	1475	84
Duluth, Minnesota	92	147	91
Fairbanks, Alaska	12	6	0

Even with an enthalpy recovery ventilator, baseline models that were simulated in locations east of the Rockies suffered significant discomfort due to elevated moisture. For locations east of the Rockies, the humidity ratio was too high for the enthalpy recovery ventilator to mitigate. Many of these climates had average humidity ratios during the cooling season well above 0.012, the upper limit of comfort as defined by ASHRAE. These locations would not be able to achieve significant benefit from PCM because PCM can only increase sensible thermal comfort and not latent thermal comfort. Therefore the discomfort sensed by the occupants when the humidity ratio is above 0.012 would not be aided by any addition of PCM to the space. Given these results, it was decided to re-evaluate the locations chosen to simulate Passive Houses with PCM.

New locations were chosen that were located in either dry or marine climate zones. A summary of counties that are considered dry, marine and moist are published in IECC 2009 (ICC, 2009). It was also concluded that climate zone 7 and 8 need not be investigated. Two reasons existed for not modeling these climates. The first reason is that there are not many ZH or ZDH outside the thermal comfort zone that arise from overheating. Therefore, there is not a significant potential impact for PCM in building applications. The second reason is that these two climate zones are the least populated climate zones in the United States. Based on the updated criteria for locations of interest, baseline models were re-run in four different locations.

The first step in ensuring that these models could be used to analyze the effectiveness of PCM in Passive Houses, was to ensure that the Passive House model met the Passive House performance based requirements in each climate zones. Just because the Passive House model meets the requirements in one location does not mean that it will meet the requirements in any other location. Table 4.3 shows results of the modeled Passive House in each of new locations, as well as the Passive House performance certification requirements.

Table 4.3: Passive House requirement verification in each climate zone studied.

Location	Climate Zone	Heating Demand (kWh/m ²)	Primary Energy (kWh/m ²)	Air Tightness (ACH ₅₀)
Phoenix, AZ	2	0.5	72.4	0.6
Los Angeles, CA	3	0.9	73.4	0.6
Portland, OR	4	12.6	105.0	0.6
Denver, CO	5	13.8	108.2	0.6
Certification Limits	NA	15	120	0.6

After establishing that the baseline models met by each of the Passive House requirements in all the new locations, a thermal comfort performance baseline was established for each location. Table 4.4 summarizes the number of ZH outside the comfort zone, ZDH outside the comfort zone, and the percentage of ZH outside comfort zone where the humidity ratio is greater than 0.012 for each of the new locations.

Table 4.4: Thermal comfort assessment for baseline simulations in revised locations.

Location	ZH not comfortable (hr)	ZDH not comfortable (°C-hr)	Percentage of ZH not comfortable that also have a humidity ratio > 0.012
Phoenix, AZ	16895	80763	24
Los Angeles, CA	1625	2458	45

Portland, OR	245	261	19
Denver, CO	708	809	8

As can be seen in Table 4.4 the new locations have much lower percentage of ZH outside of the thermal comfort zone where the humidity ratio is also above the threshold when compared to the locations in the moist (east of the Rockies) zones. Therefore with more of discomfort arising from excess sensible load, the PCM should have a greater impact on occupant comfort.

4.1 Impact of PCM in Passive House – Phoenix, Arizona

Phoenix presented the largest sensible load to which the PCM was exposed. In the baseline simulation there were ten times more ZH and thirty times more ZDH outside of the thermal comfort zone than any other location analyzed. When looking at the baseline model, it was clear that the largest portion of the ZH and ZDH outside the comfort zone occurred in the 2nd floor; however there was still considerable discomfort on the 1st floor. The average ZDH uncomfortable in the first floor zones was 12,300°C-hr, whereas the average value in the 2nd floor zones was 21,900°C-hr. This significant increase in discomfort can be associated with 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 first floor has 45% more internal wall surface area than the 2nd floor. These internal walls have gypsum board on both sides of them, which acts as thermal mass. The upstairs area is much more open, and therefore has less interior wall area, resulting in less thermal mass.

Even though the 2nd floor had more ZH and ZDH outside the comfort zone, the 1st floor zones still had a considerable amount of discomfort. The entire Passive House was too hot for such long periods of time that an initial set of simulations were performed with PCM placed in all walls to establish an upper limit for the impact of PCM in the house. Further simulations were also carried out with reduced quantities of PCM. After simulating PCM on every wall, PCM was sequentially removed from walls in zones beginning with the zone with the fewest ZDH uncomfortable. This was chosen because the zone with the fewest ZDH uncomfortable was contributing the least to the discomfort of the entire house. The results of these simulations are shown for different melt temperatures of PCM in Figure 4.2.

Figure 4.2: Comparison of (a) ZH and (b) ZDH outside the thermal comfort zone for different configurations of PCM in a Passive House in Phoenix, Arizona.

The amount of PCM added is recorded as a mass of PCM per square meter of floor area. The mass per unit floor area that corresponds to covering all of the walls with PCM is 8.4 (Kg/m²_{floor area}). If reducing both the ZH and ZDH uncomfortable is desired, a melt temperature of 27 °C for PCM should be selected. However, due to the extreme

temperatures seen in Phoenix, this selection is only capable of reducing the ZH uncomfortable by 6.4% and the ZDH uncomfortable by 7.3%. If it is decided that the ASHRAE comfort zone is too conservative and what is sought is minimizing the extent of discomfort, then a higher melt temperature should be chosen. A melt temperature of 29 °C results in a reduction of ZDH uncomfortable by 8.5 % when PCM is applied to every wall in the house. A melt temperature of 29°C results in the greatest reduction of ZDH because it is able to discharge the most frequently of all the PCM melt temperatures investigated. PCM with a lower melt temperature is rarely allowed to discharge due to the sustained elevated air temperatures.

PCM placement on every wall (interior and exterior) in the Passive House, resulted in modest improvements in thermal comfort. A PCM system of this size would cost \$12,800 based on current market price (BioPCM™, 2011). The result is a very expensive system that yields insubstantial improvements in thermal comfort.

4.2 Impact of PCM in Passive House – Los Angeles, California

Los Angeles typically has several very hot weeks during the summer. The high temperatures and the duration of hot spells pale in comparison, however, to those of Phoenix. The Pacific Ocean acts as a buffer to prevent excessive temperature fluctuations in Los Angeles and the entire San Fernando Valley. When modeling the Los Angeles Area, the Burbank-Glendale-Pasadena-Bob Hope Airport TMY3 weather data was used. This weather data was used because at 15 miles, it was the furthest weather

station from the ocean while still in the Los Angeles area. Several other weather stations are located within several miles of the ocean; therefore they are not subject to temperature fluctuations representative of the majority of the region.

The baseline Passive House model in Los Angeles had 1,630 ZH and 2,460 ZDH not comfortable. An informed process to incrementally add PCM to the space was performed in order to increase occupant comfort. The first step in the process was to investigate which floor and zones in the Passive House were overheating. It was determined that 80 % of the ZH and 88 % of the ZDH overheated occurred in the 2nd floor zones. Within the 2nd floor zones, there were 1.5 times more ZH and 2 times more ZDH overheating in the common zone than in the back bedroom zone. This 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, surfaces were investigated. It was noted that all surfaces in the 2nd floor zone cooled down to similar nighttime low temperatures due to the nighttime flush. This results in each surface discharging PCM similarly, therefore surface selection criteria was based on maximum daytime surface temperature from the baseline model. Multiple overheating days were investigated to ensure appropriate surface selection. All surfaces that could accommodate PCM were investigated, including exterior walls, interior partitions, floors and ceilings. A process was then established to incrementally add PCM to surfaces beginning with those that had the highest daytime temperatures. ZH and ZDH outside the thermal comfort zone were

monitored for each configuration of PCM and at each of the 4 melt temperatures investigated. Figure 4.3 highlights the number of ZH and ZDH outside the thermal comfort zone at each of these configurations.

Figure 4.3: Comparison of (a) ZH and (b) ZDH outside thermal comfort zone for different configurations of PCM integration in a Passive House in Los Angeles, California.

From Figure 4.3 it is clear that adding PCM to a Passive House in the Los Angeles area has significantly more impact than adding PCM to a similar structure in Phoenix. This is due to the lesser severity and duration of overheating events in Los Angeles.

It is also clear that PCM melt temperatures of 25°C and 27°C increase occupant comfort more than melt temperatures of 23°C and 29°C. However, the differences between 25°C and 27°C are not as pronounced. While the ZDH outside the thermal comfort zone are very similar for both melt temperatures, the ZH outside the thermal comfort zone are less over the entire coverage band for 25°C. Due to this, 25°C is recommended for its greater impact on reducing ZH outside the thermal comfort zone.

While PCM can improve thermal comfort, it is important to note the theoretical limit restricting PCMs' impact on occupant comfort. This limit is set by the number of ZH uncomfortable where the humidity ratio is less than the threshold humidity ratio for occupant comfort. Table 4.4 showed that for the baseline model in Los, Angeles 45 % of the ZH uncomfortable occurred when the humidity ratio was above the comfort threshold humidity ratio. This means that of the 1625 ZH uncomfortable for Los Angeles, PCM can only have an impact on 884 of them. Therefore, if the performance is re-evaluated based on this value (884 ZH), then the most effective configuration (4.7 Kg/m²_{floor area} of PCM and a melt temperature of 25 °C) results in an 80% reduction in ZH uncomfortable.

4.3 Impact of PCM in Passive House – Portland, Oregon

Portland, Oregon is in climate zone 4 and is typical of a marine climate. Summers in Portland are warm and dry with cool nights, while winters are wet and mild. The majority of solar insolation is received during the summer months due to significant cloud coverage during the winter. Located in the Willamette Valley and only 60 miles from the Pacific Ocean, Portland rarely sees the extremes that other cities of similar latitude experience. Portland is the least extreme climate modeled in this study with the baseline having only 245 ZH and 261 ZDH outside the thermal comfort zone.

An identical process of identifying overheating zones, and then surfaces with highest daytime temperature was performed. It was determined that all of the overheating occurred in the 2nd floor zones with 80% of overheating occurring in the 2nd floor common zone and 20% occurring in the 2nd floor back bedroom zone. PCM application was chosen to be focused on the 2nd floor common zone due to the concentration of overheating in the zone. After isolating the zone of interest, PCM was incrementally added to surfaces with the largest contribution to overheating. Plots of the ZH and ZDH outside of the thermal comfort zone are shown in Figure 4.4.

Figure 4.4: Comparison of (a) ZH and (b) ZDH outside thermal comfort zone for different configurations of PCM integration in a Passive House in Portland, Oregon.

As can be seen in Figure 4.4, a melt temperature of 25°C yields the most significant improvements in thermal comfort over the entire coverage band. It is clear that from the 4 melt temperatures analyzed, 25°C is the best melt temperature for non-

mechanically cooled Passive Houses in Portland, Oregon. Reductions of 93% of the ZH and 98% of the ZDH uncomfortable were achieved by applying $3.1 \text{ Kg/m}^2_{\text{floor area}}$ of PCM to the 2nd floor common zone. The application of PCM results in larger reductions in ZH and ZDH for Portland compared to Los Angeles because there is less moisture in the air during summer in Portland. For the Portland Baseline, only 19 % of ZH uncomfortable are beyond the humidity ratio threshold; compared to 45 % for Los Angeles.

4.4 Impact of PCM in Passive House – Denver, Colorado

Denver is the coldest climate of any analyzed in this study. Lying within the semi-arid high-plains, Denver is known for having hot and dry summers, and cold to cool winters. Because winters in Denver are considerably colder than the other climates studied, the performance requirements in Denver were the closest to the threshold limits for Passive House Certification. While Denver is located in climate zone 5, one climate zone colder than Portland, it actually has hotter summers than Portland. This can be seen in the ZH and ZDH outside the thermal comfort zone. The baseline values in Denver are 708 ZH and 809 ZDH outside of the thermal comfort zone.

An identical process was carried out for the addition of PCM as was performed in the Los Angeles and Portland cases. The 2nd floor common zone and the 2nd floor back bedroom zone accounted for 70% and 29% of all ZH uncomfortable, respectively. From this it was decided to concentrate the placement of the PCM in the 2nd floor common zone. The same incremental process of adding PCM to the structure was carried out,

focusing on surfaces that reached the highest daytime temperatures. ZH and ZDH outside the thermal comfort zone for each configuration of PCM are shown in Figure 4.5.

Figure 4.5: Comparison of (a) ZH and (b) ZDH outside thermal comfort zone for different configurations of PCM integration in a Passive House in Denver, Colorado.

Significant reductions in ZH and ZDH outside the thermal comfort zone were achieved with the application of PCM in Denver. Once again, a PCM melt temperature of 25°C yielded the most significant increase to occupant comfort. Reductions of 79% of the ZH and 89% of the ZDH uncomfortable were achieved by 3.1 Kg/m²_{floor area} of PCM to the 2nd floor common zone. The considerable reductions can be associated with the very small number of uncomfortable ZH where the humidity ratio is greater than the humidity ratio threshold. For the Denver area, only 8% of discomfort arises due to too high of humidity ratio. Therefore, there remains the vast majority of ZH uncomfortable that can be mitigated by the application of PCM.

5. Conclusions

The modularity of EnergyPlus has facilitated the development of the Conduction Finite Difference Heat Balance Algorithm as well as the Phase Change Module. The CFD Heat Balance Algorithm provides users the ability to accurately model materials with variable thermal properties, including PCMs. This heat balance algorithm's ability to model heat transfer across the building envelope was tested and compared to both analytic and other numerical simulation methods. The CFD Heat Balance Algorithm achieved excellent agreement with both the analytic and the other numerical methods.

The successful verification of the CFD Heat Balance Algorithm's ability to model heat transfer across the building envelope under a variety of boundary conditions allowed for testing of EnergyPlus' ability to model PCMs. This was achieved by modeling a pre-existing experiment that involved PCM in a simple structure. A 4.3% difference in the temperature reductions achieved by adding PCM was found between the experimental results and the numerical results using EnergyPlus. With this good agreement, novel modeling could be performed using EnergyPlus to investigate the performance of PCM in non-mechanically cooled Passive Houses across the United States.

It was found that the vast majority of discomfort in non-mechanically cooled Passive Houses that are located in moist (east of the Rockies) climates, occurs at least in part due to the humidity ratio exceeding the threshold limit of 0.012. In these climates,

ZH uncomfortable due solely to sensible heat and not moisture accounted for only 1% to 19% of the total ZH uncomfortable. Therefore, while adding PCM to Passive Houses in moist climates may be able to reduce the operative temperature, it often would not result in an increase in occupant comfort because the space would still be too humid. While PCM cannot substantially improve occupant comfort in moist climates it was found to have considerable impacts on occupant comfort in dry and marine climates.

Substantial benefits were realized for Passive Houses simulated in Portland, Denver, and Los Angeles. Portland, Oregon proved to be the location where the largest reductions in ZH and ZDH uncomfortable were achieved after adding PCM. Reductions of 93% of the ZH and 98% of the ZDH uncomfortable were realized by adding 391 Kg ($3.1 \text{ Kg/m}^2_{\text{floor area}}$) of PCM with a melt temperature of 25°C . These large reductions in occupant discomfort can be attributed to several factors: low summer humidity ratio, mild summer peak temperatures and the presence of cool nights to facilitate discharging of the PCM.

Denver, Colorado is the location where PCM had the second most significant impact. Integrating 391 Kg ($3.1 \text{ Kg/m}^2_{\text{floor area}}$) of PCM with a melt temperature of 25°C into the Passive House resulted in reductions of 79% of the ZH and 89% of the ZDH outside the thermal comfort zone. While Denver also has very dry summers, its daytime high temperatures in the summer are considerably higher than Portland. This results in an overcharging of PCM beyond the phase change region, leading to instances where the PCM cannot discharge at night.

PCM had considerably less impact on occupant comfort when applied to a Passive House in Los Angeles. There are two primary reasons for this. First, the humidity ratio in Los Angeles was the highest, on average, of all locations studied. 45% of discomfort occurred when the humidity ratio was above the threshold value. Also, Los Angeles has high daytime and nighttime temperatures. Due to the proximity to the Pacific Ocean, the Los Angeles area has relatively small diurnal temperature fluctuations. The difference between the monthly average high and low temperatures during the summer months in Los Angeles is only 5°C (NOAA, 2004). This results in the PCM not being able to discharge at night. Due to the small diurnal temperature fluctuations and high summer humidity ratios, reductions of only 44% of the ZH and 55% of the ZDH were achieved by placing 593 Kg ($4.7 \text{ Kg/m}^2_{\text{floor area}}$) of PCM with a melt temperature of 25°C in the Passive House.

A Passive House in Phoenix, Arizona had the least benefit from the addition of PCM. The extreme heat of Phoenix presents too much load for PCM to store without overcharging. Even with using a melt temperature of 29°C, the PCM becomes overcharged very quickly. Another major issue is that average nighttime low temperature in Phoenix during the months of July and August is above the maximum temperature for thermal comfort. Therefore, even with a nighttime flush and full discharge of the PCM, the occupants will still be uncomfortable. Even when PCM was added to every wall in the Passive House that could accommodate PCM (1,061 Kg of PCM), only single digit reductions in discomfort were achieved.

While increasing thermal comfort is the desired outcome of adding PCM, It is important to not only consider the increase in thermal 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 (BioPCM™, 2011). A breakdown of the cost of the PCM system as a function of quantity is shown in Table 5.1.

Table 5.1: 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

The prices shown in Table 5.1 are based on current retail price of BioPCM™ and are subject to change. Commercial PCM products for building applications are a rather new technology, therefore the cost of the products are highly volatile and may change dramatically with increase in production, refinement of processing and enhancement of the product. It is difficult to make a single recommendation for the quantity of PCM to place in the house as occupant comfort is subjective. Also, because Passive Houses are typically designed without mechanical cooling, the benefit of adding PCM is in increasing occupant comfort, which is hard to place a dollar value on.

While the primary benefit of adding PCM is in occupant comfort, it can also reduce the total energy consumption; even for buildings without mechanical cooling. While the savings are modest, annual energy consumption reductions ranged from 0.5%

in Phoenix to 3.1% in Denver. Without the presence of mechanical cooling, these reductions come from heating energy savings. They arise during the shoulder seasons, when the added thermal mass stores mid-day heat so that the heating system does not have to work as hard during the night. While these savings are not extraordinarily substantial, they could be the difference from a prospective Passive Houses meeting the Primary Energy or Heat Demand Criteria.

The results of this study should be used as a guideline when considering using PCM in a Passive House. It is very important to consider the climate that the Passive House will be located in. Climates with warm to hot and dry summers are ideal for utilizing PCM. Also, the benefits are increased when the diurnal temperature fluctuations are large as this allows the PCM to discharge at night. When considering location within the house to place PCM, first focus on the top floor. This floor typically has overheating problems due to the stack effect. Then consider which rooms within the top floor have considerable glazing areas, especially on the south and western exposures (for Northern Hemisphere). It is also important to consider the use of the space. While occupant comfort is critical in living spaces it may not be as important in bathrooms or storage areas.

5.1 Future Work

As was mentioned in Chapter 3 of this paper, the Passive House modeled in this study actually consists of side-by-side identical duplexes and it is currently being built in

Portland, Oregon. At the outset of the project, the owner and designer of the Passive House were interested in monitoring both of the duplexes in order to gain insight on how occupant behavior impacts thermal performance. However, upon hearing of the modeling work performed on the integration of PCM in Passive Houses, the owner became interested in running an experiment. The experiment consists of outfitting one of the duplexes with PCM, as informed by the modeling results, and keeping the other unit unmodified (No PCM) in order to act as a control.

An instrumentation package has been designed for each of the duplexes consisting of a surface and air temperature sensors, relative humidity sensors, window and door ajar sensors, and power consumption monitors. Also a weather station will be located on site collecting data on ambient temperature, humidity, wind speed, and solar insolation values. On-site data will be collected over a period of one year and verification of the numerical modeling will be performed.

While the present study focused on non-mechanically cooled Passive Houses for the application of PCM; it was determined that this limited the climates where the application of PCM was feasible. This is due in large to the high humidity ratios seen in climates east of the Rockies during the summer months. An interesting extension of the modeling work performed in this study would be to investigate PCM in Passive Houses that utilize mechanical cooling to dehumidify and reduce some of the heat load in moist climates. In these instances, PCM may have the potential to reduce and shift the peak and total load seen by the mechanical cooling equipment. While load shifting and

reducing has already been performed (Muruganantham et al., 2010), it has not been paired with any sort of occupiable building, let alone a Passive House. This would allow the integration of PCM to positively impact the thermal performance of Passive Houses in more climates.

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Appendix A.

Phoenix BioPCM Results		Baseline Hrs 16895		Baseline Degree Hours 80763	
PCM Coverage (Kg/m ²)	9.5	PCM Coverage (Kg/m ²)	9.5		
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort		
23	15997	23	76632		
25	15803	25	75238		
27	15811	27	74863		
29	16344	29	73911		
PCM Coverage (Kg/m ²)	8.4	PCM Coverage (Kg/m ²)	8.4		
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort		
23	16068	23	76870		
25	15908	25	75560		
27	15928	27	75203		
29	16424	29	74287		
PCM Coverage (Kg/m ²)	7.2	PCM Coverage (Kg/m ²)	7.2		
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort		
23	16160	23	77247		
25	16030	25	76031		
27	16057	27	75694		
29	16486	29	74819		
PCM Coverage (Kg/m ²)	4.7	PCM Coverage (Kg/m ²)	4.7		
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort		
23	16476	23	78213		
25	16417	25	77465		
27	16442	27	77304		
29	16704	29	76783		

PCM Coverage (Kg/m ²)	3.1	PCM Coverage (Kg/m ²)	3.1
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort
23	16530	23	78759
25	16481	25	78124
27	16501	27	77972
29	16710	29	77522

PCM Coverage (Kg/m ²)	9.5	PCM Coverage (Kg/m ²)	9.5
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction-Degree Hours Outside Comfort (%)
23	5.3	23	5.1
25	6.5	25	6.8
27	6.4	27	7.3
29	3.3	29	8.5

PCM Coverage (Kg/m ²)	8.4	PCM Coverage (Kg/m ²)	8.4
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction-Degree Hours Outside Comfort (%)
23	4.9	23	4.8
25	5.8	25	6.4
27	5.7	27	6.9
29	2.8	29	8.0

PCM Coverage (Kg/m ²)	7.2	PCM Coverage (Kg/m ²)	7.2
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction-Degree Hours Outside Comfort (%)
23	4.4	23	4.4
25	5.1	25	5.9
27	5.0	27	6.3
29	2.4	29	7.4

PCM Coverage (Kg/m ²)	4.7	PCM Coverage (Kg/m ²)	4.7
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)

23	2.5	23	3.2
25	2.8	25	4.1
27	2.7	27	4.3
29	1.1	29	4.9

PCM Coverage (Kg/m ²)	3.1	PCM Coverage (Kg/m ²)	3.1
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	2.2	23	2.5
25	2.5	25	3.3
27	2.3	27	3.5
29	1.1	29	4.0

LA BioPCM Results

Baseline Hours	Baseline Degree-Hours
1625	2458

PCM coverage (Kg/m ²)	4.7	PCM coverage (Kg/m ²)	4.7
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort
23	1017	23	1358
25	915	25	1095
27	956	27	1074
29	1289	29	1334

PCM coverage (Kg/m ²)	3.1	PCM coverage (Kg/m ²)	3.1
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort
23	1108	23	1534
25	1022	25	1307
27	1076	27	1291
29	1364	29	1524

PCM coverage (Kg/m ²)	2.4	PCM coverage (Kg/m ²)	2.4
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort
23	1242	23	1728
25	1194	25	1556
27	1231	27	1559
29	1446	29	1770

PCM coverage (Kg/m ²)	1.9	PCM coverage (Kg/m ²)	1.9
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort
23	1310	23	1827
25	1277	25	1691
27	1313	27	1688
29	1450	29	1821

PCM coverage (Kg/m ²)	1.3	PCM coverage (Kg/m ²)	1.3
Melt Temp	Hours Outside Comfort	Melt Temp	Degree-Hours Outside Comfort
23	1419	23	2010
25	1400	25	1915
27	1419	27	1917
29	1548	29	2074

PCM coverage (Kg/m ²)	4.7	PCM coverage (Kg/m ²)	4.7
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	37.4	23	44.8
25	43.7	25	55.5
27	41.2	27	56.3
29	20.7	29	45.7

PCM coverage (Kg/m ²)	3.1	PCM coverage (Kg/m ²)	3.1
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	31.8	23	37.6
25	37.1	25	46.8
27	33.8	27	47.5
29	16.1	29	38.0

PCM coverage (Kg/m ²)	2.4	PCM coverage (Kg/m ²)	2.4
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	23.6	23	29.7
25	26.5	25	36.7
27	24.2	27	36.6
29	11.0	29	28.0

PCM coverage (Kg/m ²)	1.9	PCM coverage (Kg/m ²)	1.9
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	19.4	23	25.7
25	21.4	25	31.2
27	19.2	27	31.3
29	10.8	29	25.9

PCM coverage (Kg/m ²)	1.3	PCM coverage (Kg/m ²)	1.3
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	12.7	23	18.2
25	13.8	25	22.1
27	12.7	27	22.0
29	4.7	29	15.6

Portland BioPCM Results

 Baseline Hours
245

 Baseline Degree-Hours
261.2

PCM coverage (Kg/m ²)	3.1	PCM coverage (Kg/m ²)	3.1
Melt Temp	Hours Outside Comfort	Melt Temp	Degree Hours-Outside Comfort
23	39	23	19.3
25	16	25	5.16
27	27	27	11.5
29	153	29	98.25

PCM coverage (Kg/m ²)	2.4	PCM coverage (Kg/m ²)	2.4
Melt Temp	Hours Outside Comfort	Melt Temp	Degree Hours-Outside Comfort
23	75	23	40.8
25	65	25	26.6
27	77	27	36.4
29	176	29	122.6

PCM coverage (Kg/m ²)	1.9	PCM coverage (Kg/m ²)	1.9
Melt Temp	Hours Outside Comfort	Melt Temp	Degree Hours-Outside Comfort
23	96	23	58.4
25	92	25	43.8
27	103	27	55.6
29	186	29	132.3

PCM coverage (Kg/m ²)	1.3	PCM coverage (Kg/m ²)	1.3
Melt Temp	Hours Outside Comfort	Melt Temp	Degree Hours-Outside Comfort
23	130	23	98.7
25	132	25	86.1
27	147	27	105.6
29	205	29	171.6

PCM coverage (Kg/m ²)	3.1	PCM coverage (Kg/m ²)	3.1
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	84.1	23	92.6
25	93.5	25	98.0
27	89.0	27	95.6
29	37.6	29	62.4

PCM coverage (Kg/m ²)	2.4	PCM coverage (Kg/m ²)	2.4
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	69.4	23	84.4
25	73.5	25	89.8
27	68.6	27	86.1
29	28.2	29	53.1

PCM coverage (Kg/m ²)	1.9	PCM coverage (Kg/m ²)	1.9
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	60.8	23	77.6
25	62.4	25	83.2
27	58.0	27	78.7
29	24.1	29	49.3

PCM coverage (Kg/m ²)	1.3	PCM coverage (Kg/m ²)	1.3
Melt Temp	Reduction Hours Outside Comfort (%)	Melt Temp	Reduction Degree-Hours Outside Comfort (%)
23	46.9	23	62.2
25	46.1	25	67.0
27	40.0	27	59.6
29	16.3	29	34.3

Denver BioPCM Results

Baseline Hours
708

Baseline Degree-Hours
809.23

PCM coverage (Kg/m ²)	3.1	PCM coverage (Kg/m ²)	3.1
Melt Temp (°C)	Hours Outside Comfort (hrs)	Melt Temp (°C)	Degree-Hours Outside Comfort (°C-hrs)
23	209	23	155.49
25	152	25	82.22
27	169	27	96.37
29	422	29	264.07

PCM coverage (Kg/m ²)	2.4	PCM coverage (Kg/m ²)	2.4
Melt Temp (°C)	Hours Outside Comfort (hrs)	Melt Temp (°C)	Degree-Hours Outside Comfort (°C-hrs)
23	322	23	244.83
25	278	25	181.06
27	313	27	199.56
29	495	29	355.56

PCM coverage (Kg/m ²)	1.9	PCM coverage (Kg/m ²)	1.9
Melt Temp (°C)	Hours Outside Comfort (hrs)	Melt Temp (°C)	Degree-Hours Outside Comfort (°C-hrs)
23	374	23	301.49
25	346	25	241.53
27	383	27	256.63
29	543	29	411.97

PCM coverage (Kg/m ²)	1.3	PCM coverage (Kg/m ²)	1.3
Melt Temp (°C)	Hours Outside Comfort (hrs)	Melt Temp (°C)	Degree-Hours Outside Comfort (°C-hrs)
23	458	23	417.13
25	450	25	367.63
27	476	27	382.77
29	591	29	513.15

PCM coverage (Kg/m ²)	3.1	PCM coverage (Kg/m ²)	3.1
Melt Temp (°C)	Reduction Hours Outside Comfort (%)	Melt Temp (°C)	Reduction Degree-Hours Outside Comfort (%)
23	70.5	23	80.8
25	78.5	25	89.8
27	76.1	27	88.1
29	40.4	29	67.4

PCM coverage (Kg/m ²)	2.4	PCM coverage (Kg/m ²)	2.4
Melt Temp (°C)	Reduction Hours Outside Comfort (%)	Melt Temp (°C)	Reduction Degree-Hours Outside Comfort (%)
23	54.5	23	69.7
25	60.7	25	77.6
27	55.8	27	75.3
29	30.1	29	56.1

PCM coverage (Kg/m ²)	1.9	PCM coverage (Kg/m ²)	1.9
Melt Temp (°C)	Reduction Hours Outside Comfort (%)	Melt Temp (°C)	Reduction Degree-Hours Outside Comfort (%)
23	47.2	23	62.7
25	51.1	25	70.2
27	45.9	27	68.3
29	23.3	29	49.1

PCM coverage (Kg/m ²)	1.3	PCM coverage (Kg/m ²)	1.3
Melt Temp (°C)	Reduction Hours Outside Comfort (%)	Melt Temp (°C)	Reduction Degree-Hours Outside Comfort (%)
23	35.3	23	48.5
25	36.4	25	54.6
27	32.8	27	52.7
29	16.5	29	36.6