

PROCEEDINGS



## **THERMAL STORAGE WITH PCM vs. THERMAL INSULATION IN WARM AND HOT CLIMATES**

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## **ADDRESSING THE BUILDING ENVELOPE**

## **ABSTRACT**

This paper discusses an alternative system of providing energy-efficiency improvements for buildings in hot and mild climates by installation of phase-change materials (PCM). It will detail a comparative analytical research project of thermal energy flows and interior temperature fluctuations of buildings with increased insulation values and increased thermal storage. The numerical analysis used the hygrothermal software, WUFI, by Germany's Fraunhofer Institute. The findings show positive results regarding heating and cooling energy demands as well as interior temperature fluctuations. This indicates a need to perform further research to allow such insulation alternatives to be considered in the building energy codes.

## **SPEAKER**

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CHRISTOPH SPAEH has received construction engineering degrees in Germany and Great Britain. Since 1994, he has practiced as an engineering consultant in both Germany and the United States, focusing since 2006 on building physics issues, including moisture in building enclosures, hygrothermal analysis, energy efficiency, and air barriers. Mr. Spaeh completed a master's degree in building physics at the University of Stuttgart in collaboration with Dr. Hartwig Kunzel of the Fraunhofer Institute. Mr. Spaeh is a licensed professional engineer based in North Carolina.

# THERMAL STORAGE WITH PCM VS. THERMAL INSULATION IN WARM AND HOT CLIMATES

## INTRODUCTION

According to the United States Department of Energy, approximately 40% of energy consumption and greenhouse gas emissions in the United States are caused by construction, operation, and maintenance of buildings. The search to find inexpensive and effective products and practices to achieve necessary reductions in energy consumption of the present and future building stock is an increasingly important problem to be solved.

The International Energy Conservation Code (IECC) lists minimum insulation values for commonly built exterior enclosure types such as wood-framed walls. Further tightening of the insulation standards is certainly likely in the future. Installation of additional insulation can be investment-intensive and impractical, especially in the case of refurbishments. Alternative energy conservation systems, including efficient interior thermal-energy storage using modern engineered materials, may provide valuable alternatives to insulation. How improved thermal insulation and added thermal storage compare directly and whether both alternatives could be combined to reduce energy usage are the focuses of this study.

## ALTERNATIVE: THERMAL STORAGE

This study focuses on buildings located in the southern regions of the U.S. where the outside temperatures predominantly fluctuate near the interior temperatures of the buildings. In the U.S., these regions are parts of Climate Zones 1, 2, and 3 (see *Graphs 1 and 2*). In these regions, the heat flux occurring through the building enclosures changes directions over the course of a day during much of the year.

An increase of thermal storage in the building enclosure itself results in reduced interior temperature fluctuations because a larger portion of the heat flux moving between interior and exterior is being stored in the building enclosure instead of being allowed to transfer through the enclosure into the interior space. The increase of ther-

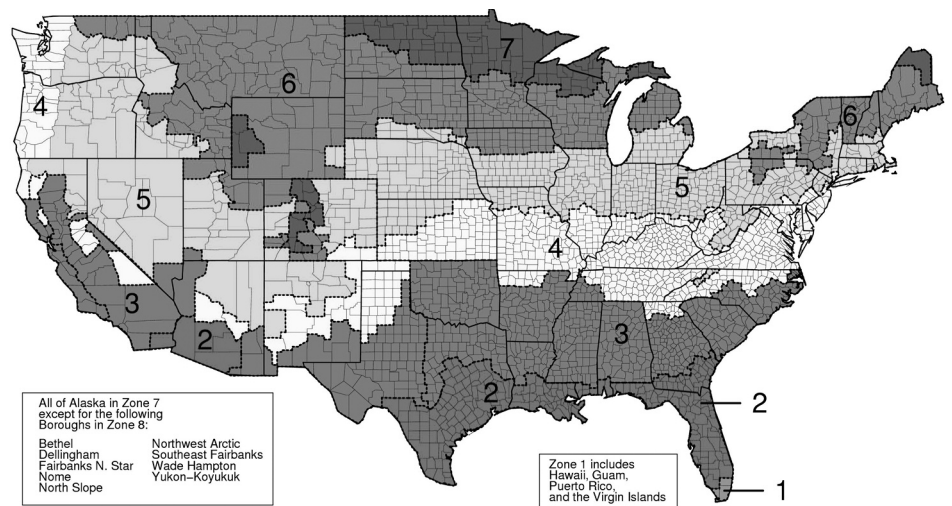
mal storage effectively acts as a heat flux buffer between the interior and the exterior of the building.

Traditionally, this additional thermal storage has been achieved by increasing the thermal mass within the building enclosure. This was done by installing materials with high heat capacity such as plaster, brick, or concrete. Due to the high heat-storage capacity of these materials, the installation of such layers in the building enclosure can soften exterior temperature

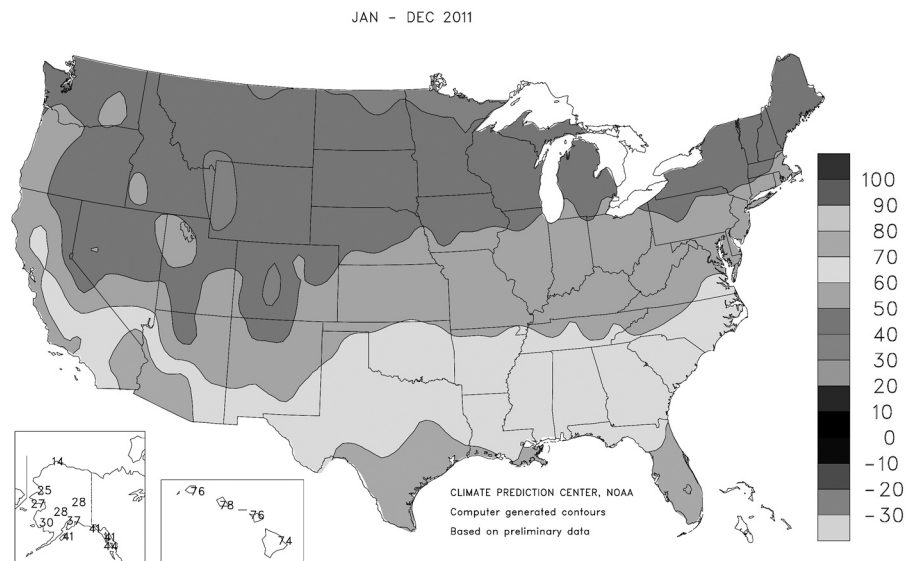
fluctuations by reducing the temperature swings transmitted to the interior. Additionally, the pass-through of temperature peaks is time-delayed and can be designed to coincide with opposing swings of the daily exterior temperature cycle.

## PHASE-CHANGE MATERIALS

Phase-change materials (PCM) store heat flux predominantly as latent heat by changing their physical state, similar to ice cubes that keep water temperatures at 32°F



**Graph 1 - Map of climate zones of lower 48 states per 2006 IECC.**



**Graph 2 - Average annual temperatures in the continental United States in 2011.**

during the time of melting. PCM take advantage of the characteristics of certain materials to function endothermically or exothermically at defined, constant temperatures during melting or solidification. PCM for use in building enclosures are engineered to change their physical state at typical interior temperatures of buildings. Materials with these characteristics can be manufactured by using paraffins made from hydrocarbon or natural oils. The introduction of PCM in lieu of high-thermal-mass materials has two significant advantages. Firstly, latent heat capacity is typically much greater than sensible heat capacity of these materials. Secondly, the latent heat storage occurs with no or very small change in temperature within the PCM.

The PCM data included in the analysis were based on proprietary PCM developed by a German chemical company. In the analysis, a layer of two 12.5-mm- (½-in.-) thick drywall boards infused with 20% PCM was included. This layer provides 140 kJ/m<sup>3</sup> latent heat capacity, which is activated between temperatures of 21°C and 24°C (70°F and 75°F) by melting and solidifying, respectively. Similar products are available from U.S.-based companies.

## DESCRIPTION OF WALLS ANALYZED

The study presented here directly compares three enclosure wall types with the purpose of comparing achieved energy conservation improvements—one insulated with glass-fiber batt insulation, the second a higher-insulated wall, and the third a PCM-infused wall. The wall systems analyzed are based on a commonly constructed wall type: stud walls with batt insulation within the stud cavity.

All walls were modeled with exterior acrylic stucco, exterior plywood sheathing, 3½-in. stud cavity, and interior gypsum board. The standard walls were insulated with glass fiber batt insulation in the stud cavity to achieve a total R-value as required by the 2006 IECC at the respective locale. The superior insulated walls were modeled with added exterior continuous insulation with expanded polystyrene board (EPS) to achieve a total R-value 1.5 times the standard wall's R-value. For the PCM-infused walls, the standard interior gypsum board was replaced by two layers of PCM-infused gypsum wall board. The R-value of the PCM-infused walls was not increased com-

pared to the standard wall's R-value.

## WUFI CHARACTERISTICS

These three different wall systems were modeled using the software package WUFI, a well-validated, hygrothermal software program developed by the Fraunhofer Institute for Building Physics in Germany.

The algorithm of the software package WUFI is based on a transient heat and moisture transfer model that can be used to assess the hygrothermal behavior of assemblies of a wide range of building material classes under dynamic climatic conditions. The numerical analysis performed by WUFI is based on findings by Künzle.<sup>1</sup> The analysis presented here utilized both standard exterior climate data and material data as supplied with WUFI.

The WUFI algorithm for the hygrothermal calculation considers thermal transport, vapor diffusion, and liquid flow. It is based on equations for energy transfer and moisture transfer through a defined section of the building element. The left side of each equation represents the storage terms, while the other side of the equation represents the fluxes dependent on temperature and relative humidity located at the element. The software (WUFI) segments the various layers of the enclosure into small increments to allow for a numerical calculation. Both equations have to be solved individually for each element within the building enclosure. The boundary conditions for the systems of wall elements are provided by the conditions of the interior and exterior climate, respectively. The calculations are typically performed for each hour within the time frame analyzed.

The analysis requires complete and realistic material data for all parts of the assembly, including geometric and material properties. This includes initial material data, such as temperature and moisture content, of each layer. The geometry of the building is factored into the analysis by specifying factors such as cardinal direction and inclination of the surface. The analysis further requires interior and exterior climate conditions, including air temperatures and relative humidity. On the exterior of the enclosure, these factors also include solar radiation, rain intensity, and wind speeds. Standard interior and exterior transfer coefficients for heat and moisture are considered.

It can be assumed that the hygrothermal state of the building has only infinites-

imal influence on the temperature and humidity of the surrounding area. However, due to the limited size of the enclosed interior system, there is an efficient temperature and moisture exchange between the interior enclosure surface and the interior climate. The interior climate is furthermore dependent on factors such as the HVAC system and the behavior of the occupants.

The temperature as part of the interior climate is connected to the total of all heat fluxes. In addition to the heat flux occurring through the enclosure, the heat fluxes include passive solar gains, internal thermal gains, and the thermal energy added by air exchanges.

The moisture budget at the interior of the building is governed by the total of the moisture fluxes over the interior surfaces, the moisture production, the infiltration by ventilation, as well as sources and sinks due to the mechanical systems.

## EXTERIOR AND INTERIOR CLIMATE

The focus of the research was the southern states of the U.S. as the goal was to analyze the potential of installing PCM in regions with high temperatures. WUFI includes climate data for numerous cities throughout the U.S., which have been derived from long-term climate data supplied by ASHRAE. Three locations in the southern part of the U.S. with hot-humid, warm-humid, and hot-dry conditions were selected. These were Miami, FL; Charleston, SC; and Las Vegas, NV.

In an effort to make the modeling as realistic as possible, interior climate conditions derived from real-time analysis according to ASHRAE Standard 160P, *Criteria for Moisture Control Design Analysis in Buildings*, were selected. This new standard dynamically calculates interior hygrothermal data based on usage, exterior climate, size of rooms, HVAC systems, etc.

## METHODOLOGY

The modeling with the WUFI software analyzes the dynamic relationship between the interior and exterior climate connected by the wall system. The results of the calculations provide large amounts of hygrothermal data that can be shown in graphs, exported, and postprocessed using external software. This includes temperature and heat-flux data at any location of

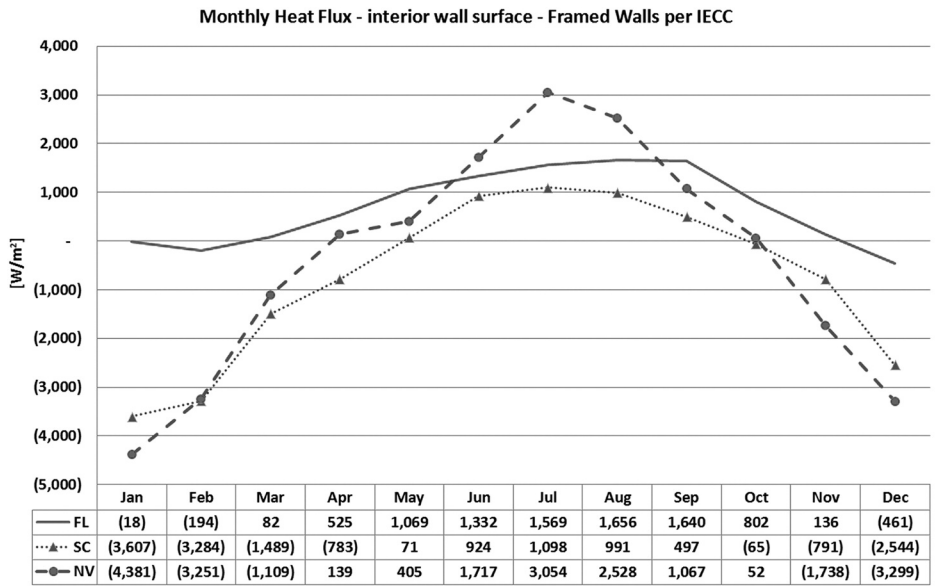
the enclosure system, in time increments of one hour throughout the span of the calculation. WUFI, however, does not include information on energy demands within the building required to keep the interior temperature regulated between the temperature maxima for the interior climate chosen in the WUFI calculations. Therefore, the results provided by WUFI had to be further analyzed. The hourly WUFI results data, including temperatures, heat flux, relative humidity moisture flux, etc., were exported into external spreadsheets for further analysis in ways suitable for this research project.

In our analysis, the interior air temperature was being held between 21.1°C and 23.9°C (70°F and 75°F) to model the climate typically found in many buildings. To keep the temperature between these two set points, either heating or cooling energy has to be expended. To measure the cumulative amount of both heating and cooling, the following method was used:

For heating, the heat flux through the interior wall surface was summed up during any time the interior surface temperature was below the heating set point (70°F). This assumes that heating energy is necessary during all hours when the interior surface temperature is below the set temperature in order to keep the air temperature from falling below the set temperature.

For cooling, the summation of heat flux was done during all hours when the interior surface temperature was above the cooling set point (75°F). This assumes that cooling energy is necessary during all hours when the interior air temperature is above the set temperature.

This heating and cooling energy was tracked and used for the comparative analysis of energy demands of the various wall systems. For total HVAC energy demands, the cooling and heating energy demands were simply combined. The cumulative hourly heating and cooling energy was used to determine monthly and annual energy demands for each wall system.



Graph 3 – Heat flux, interior wall surface, standard framed walls for Florida, South Carolina, and Nevada.

**RESULTS**

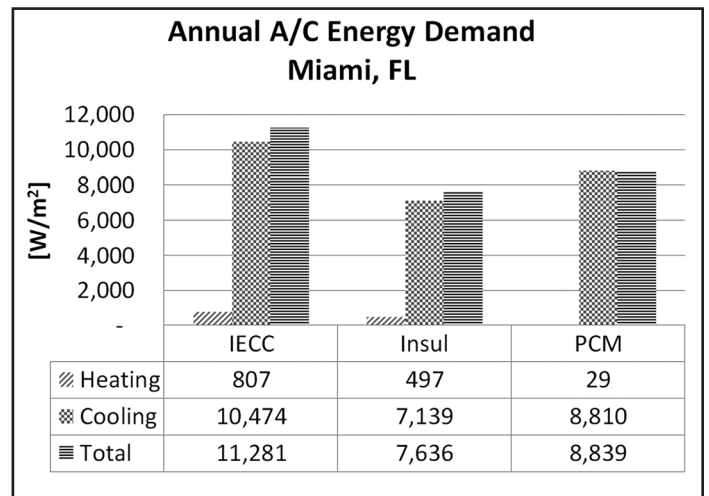
Graph 3 shows the monthly heat flux at the interior surface of the different walls. The graph shows the results for the walls built per minimum requirements of the IECC. This gives an impression of the general variations between the seasonal heat fluxes at the three different climate locations. Positive values show heat flux into the interior building space; negative values show a loss of thermal energy from the interior space.

The results show an almost constant influx of thermal energy into the building at the Miami climate. The maximum heat flux in Florida is reached at the end of August. In both Charleston and Las Vegas, the maximum heating demands are higher than the cooling demands. In Las Vegas, these maxima are higher than in Charleston. The large heating and cooling demands in winter and summer in Las Vegas explain why the PCM have reduced value in Nevada.

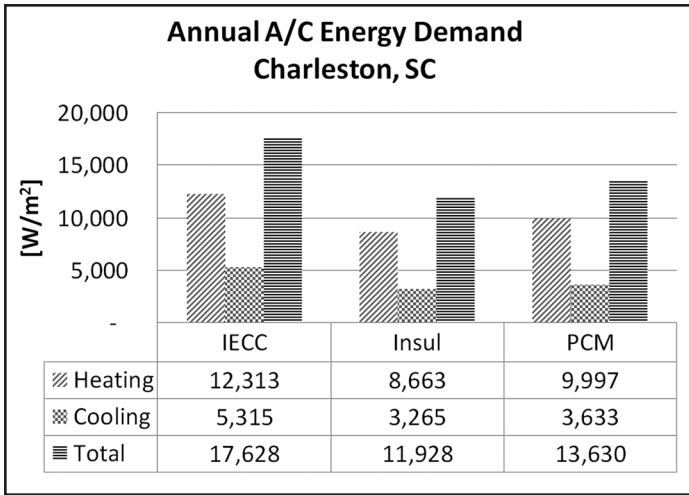
Graphs 4, 5, and 6 show the annual energy demand for

air-conditioning the buildings in the three different cities. In particular, it shows the heating, cooling, and total air-conditioning energy demands to keep the interior between the temperature set points at 70°F and 75°F. Energy demands are shown for all three types of walls: standard, highly insulated, and PCM-infused walls. A summary of energy savings is shown in Graph 7.

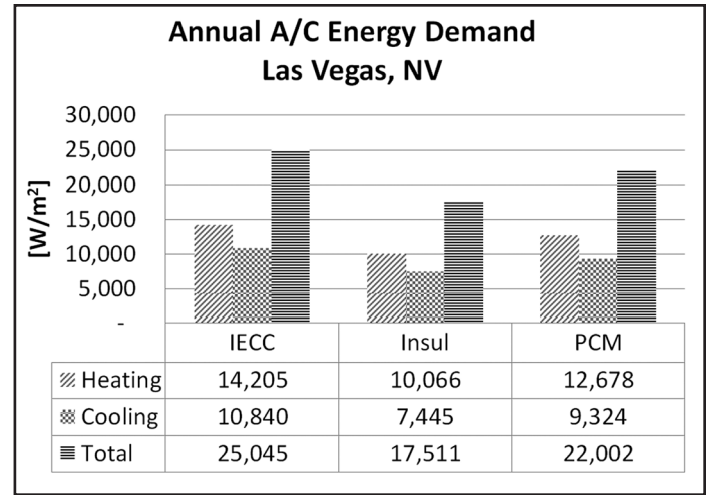
The results for the walls analyzed in the climate of Miami show an improvement for framed walls by using additional thermal-energy resistance in the walls as well as additional thermal-energy storage. Additional insulation in framed walls yielded



Graph 4 – Annual air-conditioning energy demand for Miami, FL.



**Graph 5 – Annual air-conditioning energy demand for Charleston, SC.**



**Graph 6 – Annual air-conditioning energy demand for Las Vegas, NV.**

improvements of about one third over the IECC walls. Please note that an additional R-value of 6.5 was necessary for framed walls to increase the standard IECC R-value by 50%.

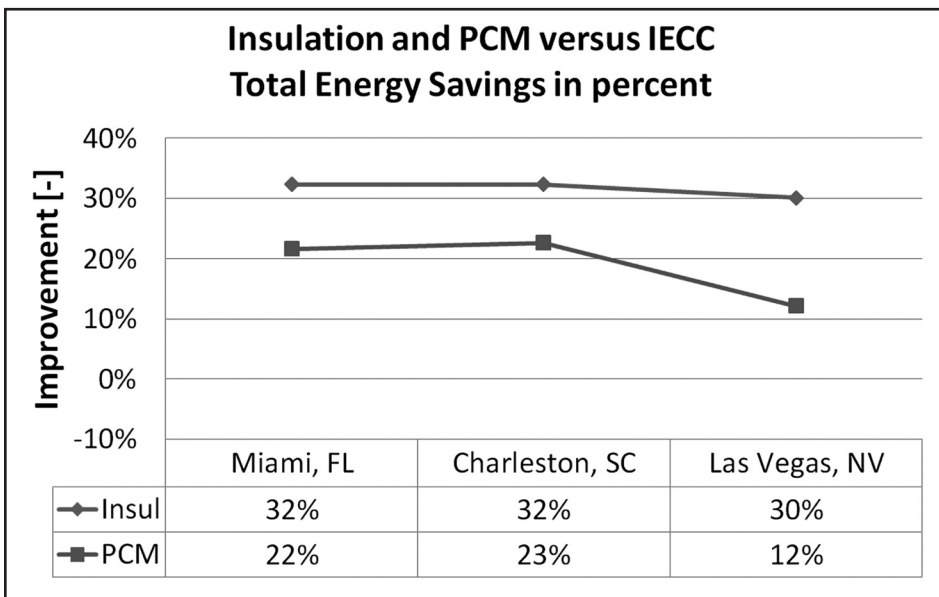
The installation of PCM wall board resulted in energy conservation improvements of about 22%. Considering the minor modification to the traditional construction work due to this installation, the energy conservation benefits should be considered significant. Due to the short time periods of cold temperatures in Miami and the capability of PCM to store greater amounts of energy, the graph shows that the required heating energy for PCM-infused walls is almost zero.

The results for walls in Charleston follow generally the same trends seen for the walls in the Miami, FL, climate. Significant differences are that the total thermal energy required to condition the building is over 50% higher for any of the framed walls. Due to the cooler climate in Charleston, it is easy to see that the cooling load is lower than in Miami. However, it is remarkable to find the heating load to be two to three times as great as the energy demand for cooling. The walls equipped with PCM are just as competitive in Charleston, SC, as they are in Miami, FL.

Due to the more extreme continental desert climate with extreme heat and cold winters, the total energy demand in Las Vegas, NV, is about 50% higher than in Charleston, SC, even though both cities are within the same IECC climate zone. The advantages for increased thermal resistance are significant for framed walls. However, the energy demand reduction of PCM-infused walls over standard walls is coming in at only around 10%. However, as shown below, the ability of PCM to effectively regulate interior temperatures still applies.

The reason for the reduced effectiveness of the PCM appears to be the presence of larger temperature extremes in the warm and cold season. With average monthly mean temperatures as low as 41°F and as high as 77°F, it becomes clear that the energy storage capacity of the PCM with switching temperatures between 70°F and 75°F becomes exhausted. After all particles have changed their state, the wall board begins to act similar to traditional wall board, having relatively small thermal resistance.

A summary of energy savings produced by the use of increased insulation and PCM layers, respectively, compared to walls insulated as required by IECC, is shown in Graph 7.



**Graph 7 – Total energy savings for highly insulated walls and PCM-infused walls compared to insulated walls, according to IECC.**

As previous research by Katz *et al.*<sup>2</sup> and Medina *et al.*<sup>3</sup> has shown, important and valuable characteristics of PCM are the dampening of temperature fluctuations, the mitigation of temperature spikes, and the

delay of daily temperature cycles.

The results of the present analysis clearly confirm the previous findings. *Graph 8* shows an example of the temperature variations, which is representative for other wall systems. It shows temperature fluctuations at the three wall variations located in Miami, FL. Again, the variations included follow:

1. The wall with minimum insulation as required by the IECC ("IECC"),
2. The wall with 50% increased insulation ("Insul"), and
3. The wall with minimum insulation per IECC plus added PCM wallboard at the interior ("PCM").

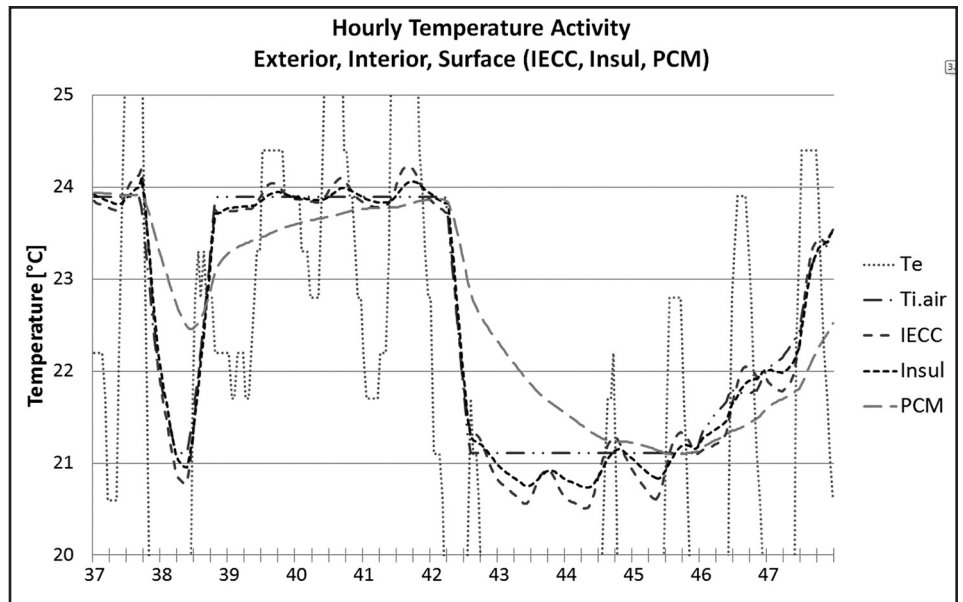
The graph shows the exterior air temperature ("T.e"), the interior air temperature ("Ti.air"), and the interior surface temperatures of each wall ("T.IECC," "T.Insul," and "T.PCM," respectively).

The time period selected runs from calendar day 37 to 48, which equals approximately the second week of February to the beginning of the fourth week of February. The time period, because it is typified by strong temperature fluctuations, was chosen in order to gain insight into the temperature characteristics of the three wall types.

The curves show strong correlation between the interior air temperature and the surface temperature of the IECC wall. The surface temperature of the Insul wall follows, with a small time and temperature delay. A significant difference between the characteristics of these two walls is presented by the PCM wall. Its surface temperature reacts with considerably greater time and temperature delay relative to the interior air temperature.

The graph also shows the considerably smaller influence of the exterior air temperature on the interior surface temperature of PCM walls than on the interior surface temperatures of IECC and Insul walls. This is obvious, for instance, between Day 42 and Day 46 of the graph, where the surface temperatures of the non-PCM walls vary 0.5°C over less than 12 hours, and the interior air temperature is stable. The surface temperatures of the PCM-infused wall do not show any short-term fluctuations. Instead, the temperature is falling slowly from the highs that had occurred on the previous day.

The delayed change in surface temperatures at PCM-infused walls will help protect the surface from dropping below the dewpoint temperature when the exterior tem-



**Graph 8 – Sample of temperatures over several days for exterior air, interior air, and interior surface temperatures of standard, highly insulated, and PCM-infused walls.**

peratures fall rapidly, as occurred between Days 42 and 46. On these days, the interior air temperature fell about 2.75°C within nine hours as a result of falling exterior temperatures. The surface temperatures of the IECC and Insul walls fell almost in lock-step. However, both of these surface temperatures continue to fall significantly past the mechanically regulated interior air temperature. This rapid temperature fall and the below air-surface temperatures could lead to condensation at the wall surfaces. The surface temperature of the PCM wall, however, takes approximately three days to decrease the same 2.75°C, drastically reducing the possibility of condensation.


The modest pace of the temperature change increases the thermal comfort level of the interior climate by allowing the human body to adjust its skin temperatures. The operative temperature of a room is the arithmetic mean of interior temperature and average surface temperature. Reducing operative temperature fluctuations is of considerable benefit to thermal comfort for the inhabitants.

### SUMMARY

The installation of PCM in building enclosures near the interior surface can have significant benefits for buildings in the southern regions of the U.S. These benefits include increased energy efficiency, reduced surface-temperature fluctuations, stabilized operative temperatures, reduced humidity

fluctuations, and a reduced likelihood of condensation. Additionally, the installation of PCM reduces the influence of thermal bridging problems by adding a continual thermal storage layer on the inside of wall studs that can act as thermal bridges. On the other hand, thermal bridging by wall studs or roof joists is often made worse when installing additional insulation in the enclosure cavities.

These hygrothermal advantages are combined with practical advantages; since the PCM layer is best installed at the interior surface of the walls, the installation of interior layers of PCM are often easier and more cost-effective to perform than installing additional insulation layers near the exterior of the buildings. This is especially true for retrofits of existing buildings. Since retrofitting buildings is more common than new construction, especially in the current economic times, having this additional tool to improve energy efficiency could have a significant impact on improving the overall building stock in the southern part of the U.S.

The results of the current study provide good reasons to perform additional research in the field of PCM for building applications. This should include further comparative field studies to verify the findings in energy efficiency, as well as to determine the longevity and practicality of installing and maintaining PCM layers in buildings. 

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