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Application of phase change materials in gypsum boards to meet building energy conservation goals

Naser P. Sharifi*, Ahsan Aadil Nizam Shaikh, Aaron R. Sakulich

Department of Civil and Environmental Engineering, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA, 01609-2280, USA

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ABSTRACT

Energy consumption in buildings has increased drastically during the last two decades. Reducing the energy demand in buildings by improving their thermal performance has therefore been the subject of many governmental plans and building codes. This study aims to evaluate the efficiency of PCM-impregnated gypsum boards on improving the thermal performance of buildings in order to achieve such energy reduction goals. Computational simulations using Typical Meteorological Year data were conducted to study the performance of PCM-incorporated walls subjected to the real temperature profiles of different cities. Four different criteria were considered and a simplified cost analysis was performed. Utilizing PCM-incorporated gypsum boards was shown to be a promising strategy to achieve energy reduction goals for buildings. The results show that using a PCM with a melting point near the occupant comfort zone delays and reduces the inside peak temperature, increases the duration of time during which the inside temperature stays within the comfort zone, and decreases the cost and energy required by HVAC system to keep the inside temperature in this range. However, the efficiency of PCMs is completely dependent on the input temperature profile, and increasing the amount of the utilized PCM leads to diminishing returns on efficiency.

1. Introduction

Worldwide energy consumption has been increasing significantly during the last two decades [1,2]. Between only 1998 and 2009, global energy consumption increased by more than 30% [3]. This energy is mostly obtained from fossil fuels, which contribute CO_2 to the atmosphere that can intensify the greenhouse effect and promote global warming [4]. A large portion of the generated energy is consumed in residential and commercial buildings. In the European Union and the United States, up to 40% of all energy is used by buildings [4,5]. The energy consumption of Chinese buildings has also doubled between 1998 and 2009 [6]. Therefore, decreasing the energy consumption of buildings has been the topic of many governmental plans and building codes [7].

For instance, in the United States, the state of California is implementing strategies to achieve Zero-Net-Energy (ZNE) residential buildings by 2020, and ZNE commercial buildings by 2030 [8]. The Washington State Building Code Council has developed energy codes to achieve a 70% reduction in building energy use by 2030 compared to 2006 levels [9]. Improving the energy efficiency in existing buildings, as well as new buildings, was recognized as one of the main strategies to reduce energy consumption and reach ZNE buildings.

The share of space heating and cooling in the buildings' total energy consumption in the world was reported to be 34% in 2010 [10]. This share was slightly higher in the U.S. [11]. These statistics show that reducing the energy required for the air conditioning of buildings is one of the key elements to achieve the aforesaid goals. Thus, significant research has been done during the last two decades to improve energy efficiency of buildings [12,13]. Different methods, such as utilizing polystyrene insulation boards [14] and lightweight insulating concretes [15], have been introduced to reduce the energy lost through the walls, floors, and roofs of buildings. These methods also address changes in the interior temperatures of buildings and suggest different methods for keeping that temperature in the comfort range and reducing HVAC energy consumption [16,17]. Implementing these strategies not only improves occupant comfort, but also reduces the electricity demand and the associated emission of gasses such as CO_2 [18].

The incorporation of Phase Change Materials (PCMs) in construction materials has been proposed as a promising method to address energy consumption concerns [19–21]. PCMs are substances with relatively high latent heats of fusion. When the

* Corresponding author.
E-mail addresses: npourakbarsharif@wpi.edu (N.P. Sharifi), arsakulich@wpi.edu (A.A.N. Shaikh), ashaikh@wpi.edu (A.R. Sakulich).

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Nomenclature

T	Temperature (°C, K, °F, and R)
Q	Heat energy (J and BTU)
h	Heat transfer coefficient (W/m^2 K and BTU/h ft^2 R)
λ	Thermal conductivity (W/m K and BTU/h ft R)
C_p	Specific heat at constant pressure (J/g K and BTU/lb·R)
L	Latent heat of fusion (J/g and BTU/lb)
ρ	Density of the solid material (kg/m^3 and lb/ft^3)
σ	Stefan-Boltzmann constant (W/m^2 K^4 and BTU/h ft^2·R^4)
ε	Surface emissivity
θ_g	Volume fraction of gypsum in the gypsum board
β	Volume fraction of PCM in phase 1
ϕ	Time lag
f	Decrement factor
PCM	Phase change material
EEF	Energy efficiency factor
CEF	Cost efficiency factor

ambient temperature rises above its melting point, a given PCM absorbs heat and turns to the liquid phase while remaining at an almost constant temperature. When the ambient temperature falls below the melting point, the PCM begins to release heat and solidify, again remaining at an almost constant temperature [22]. A large number of PCMs with different melting points, from roughly −33 °C to 800 °C (−27 °F to 1472 °F), and different latent heats of fusion, are industrially available [23].

Using PCMs in buildings prevents rapid changes in the inside temperature and saves energy by reducing heating/cooling demands [24]. Laboratory tests have shown that using PCM in construction materials increases the heat storage capacity and decreases thermal conductivity [25–28]. The results of an experiment in Montreal, Canada, showed that utilizing PCM-impregnated boards over existing walls kept an inside temperature 6 °C (10.8 °F) cooler during the day and 4 °C (7.2 °F) warmer during the night [29]. Another laboratory test conducted in Tianjin, China, showed that using PCM panels in a building can reduce interior peak temperatures by 2.46 °C (4.43 °F) during the summertime [30]. PCMs can also be used in the air conditioning systems in buildings. The results of a small scale experimental study showed that up to 90% of a daily cooling load could be stored each night in a system in which a 30 mm (1.18") thick packed bed of granular PCM was employed [31]. In addition, PCMs coupled with energy storage units such as solar-aided cylindrical tanks can act as space heating systems [32]. Extensive reviews have been published focusing on the application of PCMs in thermal energy storage units [33,34], and glazing and shading of buildings [35].

In addition to laboratory studies, many numerical and computational studies can be found in the literature, indicating that PCMs can improve the thermal performance of buildings [36–39]. The results of a study on a passive house duplex located in Oregon State showed that using PCM in a building can reduce the annual overheated hours, the total hours in a year that the inside temperature is above the occupant comfort level of 26 °C (78.8 °F), by 50% [40]. Another simulation showed that PCMs can also be used in combination with underfloor heating systems in buildings to improve their efficiency. The latent heat of the utilized PCM can efficiently provide a uniform heat energy for the underfloor heating system by shifting the energy from the peak hours to off-peak hours, i.e. from days to nights [41].

Although the ability of PCMs to decrease the energy usage in buildings has been evaluated by different studies, few studies have investigated the changes in temperature of a structural element under specific, realistic temperature profiles. Since the performance of PCMs is completely dependent on the input profile temperature, it is necessary to evaluate their efficiency when real temperature profiles are applied to the structural elements. Such an investigation using laboratory experiments would be very time consuming, expensive, and in some cases impractical, therefore, this investigation was carried out using computational simulations.

In first step, artificial sine function temperature profiles were applied to the wall models to find the most efficient location for the PCM-impregnated gypsum board in the wall's cross-section. Then, using the same temperature profiles, the effect of the PCM percentage on the decrease and delay in the maximum inside temperature, the increase in the duration that the inside temperature stays within the comfort zone, and the decrease in the energy required by HVAC system to keep the inside temperature in this range, were studied. Finally, the efficiency of utilizing PCM-impregnated gypsum boards to improve the thermal performance of buildings was investigated for various U.S. cities with different climates using real temperature profiles extracted from Typical Meteorological Year databases. As two specific examples, a three-month summer period and a full year were simulated for two cities in California and Washington, in order to determine whether the use of PCM-impregnated gypsum boards in walls is an efficient approach to governmental plans being pursued in these two states.

2. Computational simulation

Computational simulations were conducted by applying artificial sine function temperature profiles and real temperature profiles to the models. The real temperature profiles were extracted from Typical Meteorological Year (TMY) databases. TMY is a collection of selected weather data for a specific location and for a specific period of time. The National Renewable Energy Laboratory's latest TMY collection (TMY3) was based on data for 1020 locations in the U.S. between the years of 1991 and 2005 [42]. TMY2 provides the same set of data for fewer locations from 1961 to 1990 [43]. These two different TMY datasets were used to provide a wide range of temperatures available for the simulations.

The investigation time period for each of the simulations was selected to be either one week or three months. The temperature profile of a location provided by the TMY data contained 168 datapoints in a week; 2232 datapoints in three months, and 8760 datapoints in a year; however, the experimental apparatus, a programmable cold plate, had limited programming capability. Also, the thickness of the walls and the PCM percentage in the gypsum board were meant to be changed to have a parametric study. Thus, a computational procedure was chosen, because conducting this study by laboratory experiment was found to be very time consuming, expensive, and, impractical. COMSOL Multiphysics software[1] was used to conduct this study.

To simplify matters, architectural features such as windows and doors were not taken into account. Although such features affect the overall thermal behavior of a building, along with factors such as the presence, or lack thereof, of exterior foliage or neighboring structures, the goal of this study was to identify general trends regarding the use of PCMs.

[1] This software is identified and explained in this study in order to specify the simulations and modeling procedures adequately. However, such identification is neither intended to imply recommendation or endorsement, nor is it intended to imply that this software is necessarily the best available for the purpose.

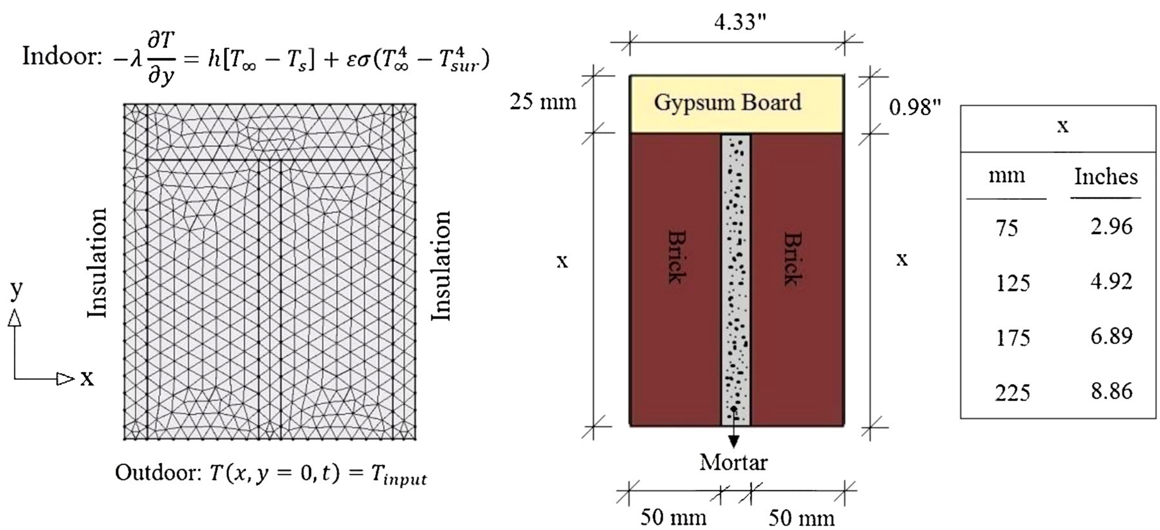

Fig. 1. Boundary conditions of the COMSOL heat transfer model and the geometry of the modeled walls.

2.1. Formulation and modeling in COMSOL

A 2D heat transfer model was generated by using the COMSOL Multiphysics software package to simulate the temperature changes in structural elements under real temperature profiles. The physics involved in this problem were heat transfer by conduction, convection, and radiation. The cross-sections of the modeled wall consist of two halves of bricks on the sides with a layer of mortar between them, and a layer of gypsum board (Fig. 1). Since the heat transfer in the wall is one-directional, two insulating layers with a thermal conductivity two orders of magnitude lower than the thermal conductivity of the rest of the materials used in the media were placed on the two sides of the model. The conduction heat transfer equation for a system without a heat source is described by [44]:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

where λ is the thermal conductivity of the material (W/m K), T is temperature (K), ρ is the density of the material (kg/m^3), and C_p is the specific heat of the material (J/kg K). For constant thermal conductivities of each material, the equation is reduced to:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{\rho C_p}{\lambda}\frac{\partial T}{\partial t} \quad (2)$$

Eq. (2) is second order in the spatial coordinates in the x and y directions and first order in time; therefore, two boundary conditions in each direction and one initial condition need to be specified. The first boundary condition in the y-direction was the heat load (external temperature) that was applied to the bottom layer of the model as:

$$T(x, y = 0, t) = T_{input} \quad (3)$$

The other three boundary conditions were based on the conservation of thermal energy at the sides of the model:

$$-\lambda\frac{\partial T}{\partial x} = h[T_\infty - T_s] + \varepsilon\sigma\left({T_{sur}}^4 - {T_s}^4\right) \quad (4)$$

$$-\lambda\frac{\partial T}{\partial y} = h[T_\infty - T_s] + \varepsilon\sigma\left({T_{sur}}^4 - {T_s}^4\right)$$

where λ is the thermal conductivity of the material (W/m K), T is temperature (K), h is the heat transfer coefficient (assumed to be 5 W/m^2 K for free air [44]), T_∞ is the temperature at infinity (assumed to be room temperature, i.e., 296.15 K),T_s is the temperature of the material surface (K), ε is the surface emissivity of the material, σ is the Stefan-Boltzmann constant, and T_{sur} is the surrounding temperature (assumed to be room temperature, i.e., 296.15 K).

For the initial condition, the entire system was assumed to be at room temperature before the heat load was applied. Therefore:

$$T(x, y, t = 0) = T_R \quad (5)$$

where T_R is the room temperature and assumed to be 296.15 K.

The gypsum board was modeled as a porous medium with PCM in its porosity. Eq. (2) describes heat transfer in solid media, but for a model with a porous medium, more equations are involved. The volume fraction of gypsum in the gypsum board was defined as θ_g, and thus the volume fraction of the porosity (the volume fraction filled with PCM) was equal to $\left(1-\theta_g\right)$. Therefore, the effective thermal conductivity of the media was defined as:

$$\lambda_{eff} = \lambda_g\theta_g + \lambda_{PCM}\left(1-\theta_g\right) \quad (6)$$

The subscript g stands for gypsum. Similarly:

$$\left(\rho C_p\right)_{eff} = \rho_g C_{p,g}\theta_g + \rho_{PCM}C_{p,PCM}\left(1-\theta_g\right) \quad (7)$$

The volume fraction of PCM at Phase 1 was specifies as β; therefore, the effective density of PCM was equal to:

$$\rho_{PCM} = \rho_{Phase1}\beta + \rho_{Phase2}\left(1-\beta\right) \quad (8)$$

Similarly:

$$\lambda_{PCM} = \lambda_{Phase1}\beta + \lambda_{Phase2}\left(1-\beta\right) \quad (9)$$

$$C_{p,PCM} = \frac{1}{\rho_{PCM}}\left(\rho_{Phase1}C_{p,Phase1}\beta + \rho_{Phase2}C_{p,Phase2}\left(1-\beta\right)\right) + L\frac{\partial\alpha_m}{\partial T} \quad (10)$$

where Cp is the specific heat (J/kg K), L is the latent heat of fusion (J/kg), and α_m is:

$$\alpha_m = \frac{1}{2} \times \frac{\rho_{Phase2}\left(1-\beta\right) - \rho_{Phase1}\beta}{\rho_{Phase2}\left(1-\beta\right) + \rho_{Phase1}\beta} \quad (11)$$

In Eq. (11), α_m presents the mass percentage of PCM that is transferred from Phase 1 to Phase 2. Also, in Eq. (10), the term $L\frac{\partial\alpha_m}{\partial T}$ represents the effect of the latent heat of fusion on the specific heat of PCM as a function of the mass percentage of PCM that is transferred from Phase 1 to Phase 2. This term will be equal to zero when the temperature is not close to the PCM's melting point; however, when the temperature gets closer to the PCM's melting point, the phase of PCM starts to change, and because of its latent heat of fusion, the PCM starts to either absorb or release heat energy. This phenomenon instantaneously changes the specific heat of the PCM.

The temperature transition interval between Phase 1 and Phase 2 of the PCM was selected to be 3 °C (5.4 °F). This number was selected based on the results of Differential Scanning Calorimetry tests conducted in another study [45]. Modeling the temperature changes was a time dependent problem. The time intervals and the relative tolerance were selected to be 1 s and 0.01, respectively; however, they were modified depending on the problem. For the cases with high percentages of PCM, both of them were reduced to a smaller number in order to obtain more accurate results and smoother graphs. The thermal properties of the materials used are provided in Table 1.

2.2. Verifying the validity of the COMSOL model

The accuracy of the results produced by the COMSOL model were validated by comparing them with results generated by a laboratory experiment. In the laboratory experiment, two different temperature profiles were applied to samples that contained PCMs with melting points of 6 °C (42.8 °F) and 28 °C (82.4 °F), referred to as PCM6 and PCM28, respectively, by using a programmable cold plate apparatus; and the temperature at different points of the sample were recorded by an array of thermocouples over the course of the experiment. Properties of the utilized PCMs are provided in Table 2, A full description of the cold plate apparatus and its operation can be found in [46]. A COMSOL model with the same geometry and the same materials were generated and the same temperature profiles were applied to them.

To have a quantitative criterion, the Coefficient of Determination (R^2) was calculated for different cases. This number indicates how well the modeling results fit the experimental results [47]. The Coefficient of Determination can be calculated by:

$$R^2 = 1 - \frac{\sum (T_i - t_i)^2}{\sum \left(T_i - \bar{T}\right)^2} \tag{12}$$

where for each temperature profile, T_i is the temperature at each time step obtained from laboratory experiments, $\bar{T}$ is the laboratory average temperature, and t_i is the temperature at each time step calculated by the COMSOL model. An R^2 of one would indicate that the COMSOL temperature profile perfectly fits the temperature profile obtained from the laboratory experiment, while an R^2 of zero would indicate that the two sets of temperature profiles do not fit at all. R^2 for the samples containing PCM6 and PCM28 were equal to 0.97 and 0.96, respectively. This shows that the computational model can accurately calculate changes in temperature both due to the gradual temperature changes and the phase transition of PCMs. The details of the validation process are explained in detail in another study [48].

2.3. Four criteria and cost analysis

Four different criteria, including Time Lag (ϕ), Decrement Factor (f), duration of being in the comfort zone, and the energy required to keep the inside temperature in the comfort zone were used to evaluate the efficiency of PCMs to improve the thermal performance of buildings. Time lag represents the difference between the times that the peak temperature occurs inside and outside of the wall. The decrement factor can be calculated by [49]:

$$f = \frac{A_{x=0}}{A_{sa}} \tag{13}$$

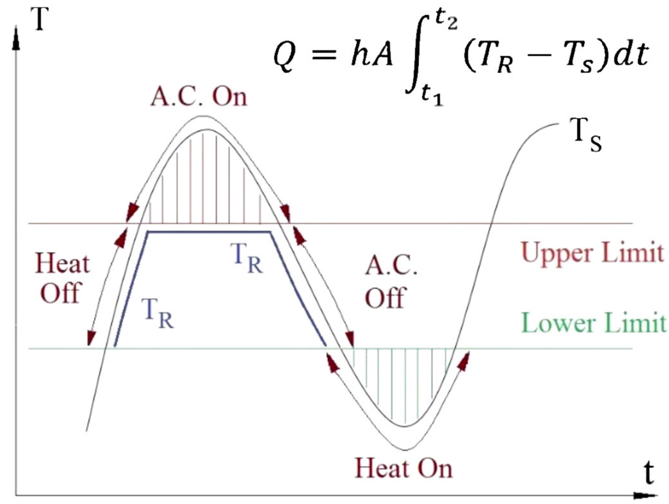

Fig. 2. The area outside the comfort zone.

where $A_{x=0}$ is the difference between the maximum and the minimum indoor wall surface temperature, and A_{sa} is this difference for the outside of the wall.

The third criterion was the time duration that the inside temperature stays in the occupant comfort zone. For that, two comfort levels were introduced; for level 1, the comfort zone was the reference temperature ±1.5 °C (±2.7 °F), and for level 2, the comfort zone was the reference temperature ±3.0 °C (±5.4 °F). The reference temperature was selected to be equal to 22 °C (71.6 °F); however, it is an arbitrary number and using another reference temperature does not change the results. The melting temperature of the PCM was set equal to the reference temperature, and its heat of fusion was selected to be equal to 161 J/g (69 BTU/lb), which is equal to the heat of fusion of commercially available PCM28 that has previously been used by the authors [45].

The fourth parameter was the energy required by an HVAC system to keep the room temperature in the comfort zone. The inside of the wall is in contact with the room air, therefore the heat energy can be transferred from the wall to the air by convection [44]:

$$\frac{dQ}{dt} = hA(T_R - T_s) \rightarrow Q = hA\int_{t_1}^{t_2}(T_R - T_s)\,dt \tag{14}$$

where Q is the heat energy (J), h is the heat transfer coefficient (assumed to be 5 (W/m^{2}K) for free air [44]). A is the area of the wall in contact with the air (m^2), T_R is the room temperature, andT_s is the temperature of the inside of the wall (K). The integral term in Eq. (14) presents the area under the temperature-time curve, and has a unit of h·K. If the room temperature is in the occupant comfort zone, the HVAC system will not be engaged. But if the room temperature falls outside this zone, the HVAC system needs to use energy to adjust the temperature. Therefore the mentioned area is an index of the energy that is used by the HVAC system to bring the room temperature back to the comfort zone. This area was calculated by Simpson's trapezoidal integration method (Fig. 2).

2.4. Temperature profiles

2.4.1. Sine function temperature profiles

To study the optimum location of the PCM-impregnated gypsum board, and the effect of utilizing different percentages of PCM on the time lag and decrement factor, the wall was studied under sine function temperature profiles. Three sine temperature profiles with amplitudes of 10 °C, 20 °C, and 30 °C (18 °F, 36 °F, and 54 °F, respec-

Table 1
COMSOL material properties inputs.

Material	Density kg/m^3 (lb/ft^3)	Specific heat J/g K (BTU/lb °F)	Thermal conductivity W/m K (BTU/h ft °F)	Surface emissivity
Mortar	2200 (137)	0.88 (0.21)	1.4 (0.809)	0.94
Brick	1920 (120)	0.84 (0.20)	1.0 (0.578)	0.75
Gypsum	1380 (86)	1.09 (0.26)	0.25 (0.144)	0.93
Insulation	24.8 (1.5)	1.30 (0.31)	0.0025 (0.001)	0.95

Table 2
PCM properties [45].

PCM	Type	Density kg/m^3 (lb/ft^3)	Melting Point °C (°F)	Specific heat J/g K (BTU/lb °F)	Heat of fusion J/g (BTU/lb)
PCM6	Organic, Paraffin blend	880 (54.9)	6.0 (42.8)	2.08 (0.50)	160 (68.8)
PCM28	Organic, Paraffin blend	880 (54.9)	28.0 (82.4)	2.11 (0.50)	151 (64.9)

Table 3
One week duration of six selected cities.

City (State)	Period of Time (week of)	Minimum Temperature °C (°F)	Average Temperature °C (°F)	Maximum Temperature °C (°F)
Portland (OR)	First/Jun. 1989	10.1 (50.1)	19.54 (67.1)	31.1 (87.9)
San Antonio (TX)	Second/Aug. 1990	21.7 (71.1)	28.5 (83.3)	34.4 (93.9)
Miami (FL)	Third/May 2000	22.1 (71.7)	25.9 (78.6)	33.1 (91.6)
Concord (NH)	Third/Aug. 1985	8.9 (48.1)	20.1 (68.2)	33.3 (91.9)
Minot (ND)	Second/Jun. 1980	10.6 (51.1)	21.2 (70.2)	32.9 (91.1)
Elko (NV)	Second/Jun. 2004	2.2 (54.1)	15.1 (59.1)	28.3 (82.9)

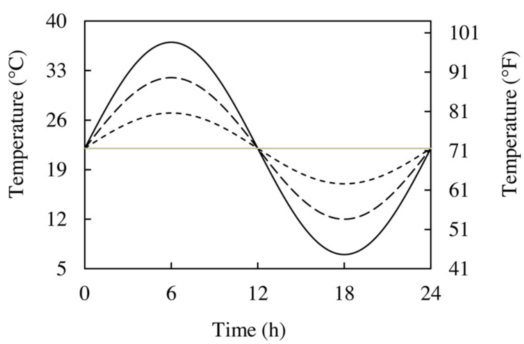

Fig. 3. Sine function temperature profiles.

tively), a reference temperature of 22 °C (71.6 °F), and a period of 24 h, were applied to the models. These temperature profiles were named T10, T20, and T30, respectively (Fig. 3). Utilizing different amplitudes makes it possible to study the effect of the difference between the peak and the lowest temperature (the amplitude of the applied temperature) on the efficiency of PCMs. The melting point of the PCM was selected to be equal to the reference temperature.

The gypsum board can be located in the inner or outer side of the wall. In some previous studies, the gypsum board was located in the inner side of the wall [50–54], and in some of them, the board was set to be a middle layer of the wall [55,56]. However, it has been demonstrated that the most efficient location of the gypsum board depends on parameters such as the thickness of the layer and the thermal properties of the utilized PCM [57]. To explore the most effective location of the gypsum board, two models were generated and their performances were compared. For the first model, the board was located in the inner side of the wall, and for the second model, it was located in the outer side of the wall.

Different percentages of PCM were used in the gypsum boards. To have a parametric study, 10 vol.%, 30 vol.%, and 50 vol.% of the gypsum board was replaced by PCM. It should be mentioned that the practical side of incorporating these amounts of PCM in the gypsum board is beyond the scope of this study.

It is obvious that by increasing the thickness of the wall, the thermal inertia of the system will increase, and thus, the time lag of the wall increases and the decrement factor decreases. However, to compare the effectiveness of the increase in the thickness of the wall with an increase in the PCM percentage in the gypsum board, sine temperature profiles were also applied to the walls with different thicknesses and no PCM in their gypsum boards. Including the thickness of the gypsum board, the total thicknesses of the models were 100 mm (3.94”), 150 mm (5.91”), 200 mm (7.87”), and 250 mm (9.84”) (Fig. 1).

2.4.2. Real temperature profiles

2.4.2.1. One-week period of six cities. In addition to walls subjected to sine temperature profiles, a wall with a total thickness of 250 mm (9.84”) was studied under real temperature profiles. One-week profiles for six cities (Portland, Oregon; San Antonio, Texas; Miami, Florida; Concord, New Hampshire; Minot, North Dakota; and Elko, Nevada.) were selected and applied to the model as thermal load. These cities are located in different parts of the US, and their temperature parameters, such as peak temperature, lowest temperature, and the difference between day and night temperatures, differ significantly. Using a longer period of time yields more comprehensive and reliable results; however, the goal of this study is to demonstrate how PCM works in different climates and how the optimum percentage of PCM in different cases can be calculated. The dates of the weeks selected to describe the applied thermal load, along with the minimum, average, and maximum temperatures therein, are provided in Table 3.

Since the time lag and the decrement factor are defined only for sine functions, only the two criteria of duration of being in the comfort zone and the energy required to keep the inside temperature in the comfort zone were used to evaluate the efficiency of the PCM. Based on the ASRAE standard, the occupant comfort zone was defined as the range of 22.2 °C (72 °F) to 24.4 °C (76 °F) [58], and thus, the melting point of the simulated PCM was selected to be 23.3 °C (74 °F). The heat of fusion of the simulated PCM was set to be equal to that of PCM28, as above.

A simplified cost analysis was also conducted for the walls equipped with PCM-incorporated gypsum boards under real tem-

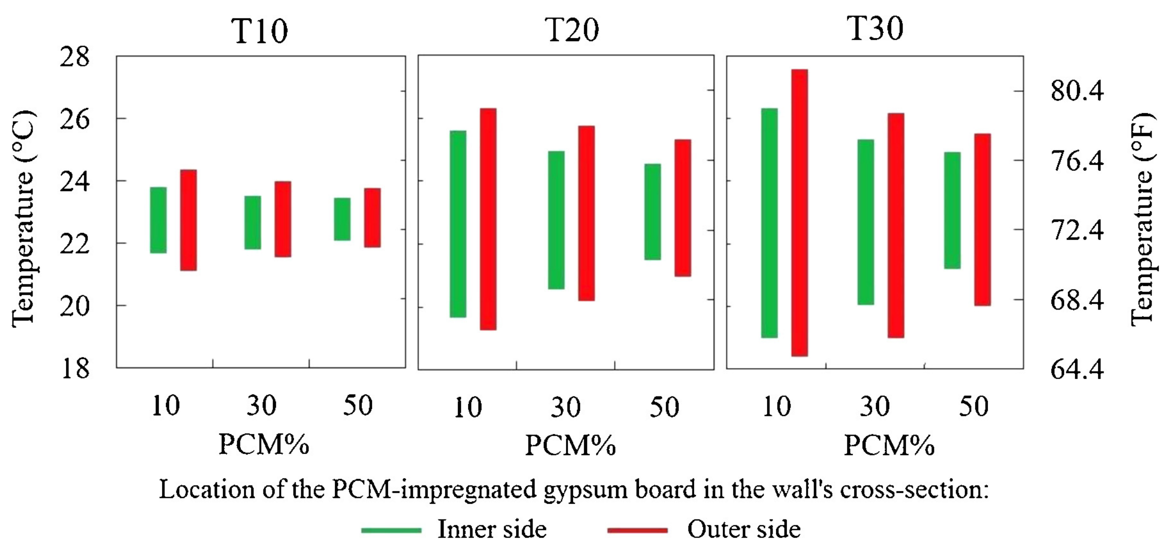

Fig. 4. Comparison of the inside temperature oscillation range for the walls with the gypsum board on the inner side vs. the walls with the gypsum board on the outer side.

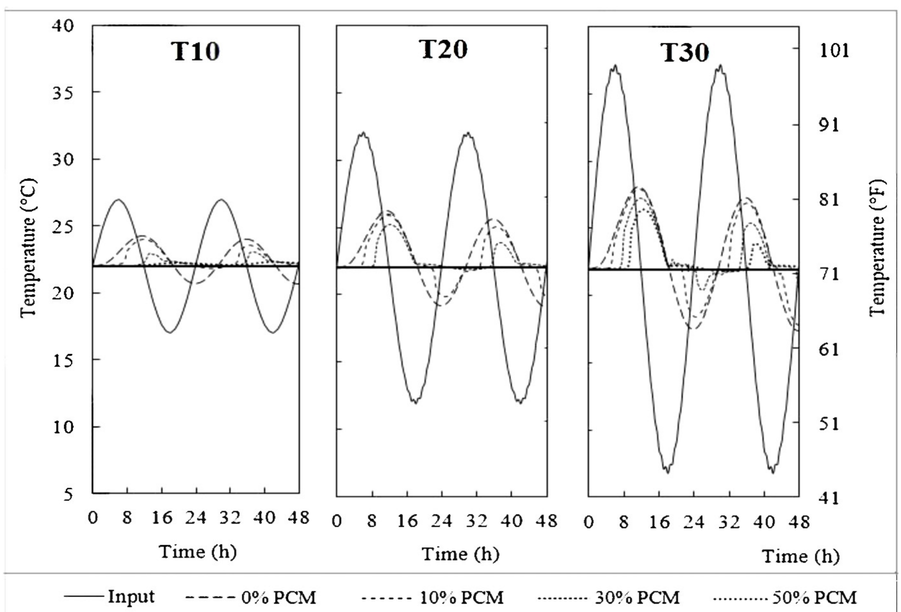

Fig. 5. Temperature changes in 250 mm (9.84") wall with 0 vol.%, 10 vol.%, 30 vol.%, and 50 vol.% of PCM in its gypsum board under sine function temperature profiles with different amplitudes.

Table 4
Electricity rates for different cities.

City (State)	Residential Rates (cents/kW h)			Source
	On-peak hours	Off-peak hours	Ratio	
Portland (OR)	26.900	6.700	4.0	[59]
San Antonio (TX)	21.900	9.200	2.4	[60]
Miami (FL)	17.392	2.885	6.0	[61]
Concord (NH)	13.299	1.940	6.9	[62]
Minot (ND)	13.634	2.220	6.1	[63]
Elko (NV)	37.594	4.329	8.7	[64]

perature profiles. This cost analysis was based on the electricity rates reported in governmental catalogs provided for each state (Table 4). The electricity rates are divided into on-peak hours and off-peak hours for all cities. The ratio between these two tariffs is also presented in the table.

For each case, the cost of energy used by the HVAC system to keep the inside temperature in the comfort zone was calculated by multiplying the used energy obtained from Equation (14) by the electricity rates provided in Table 4. The on-peak hours and off-peak hours are allocated to different parts of a day in different states. Therefore, a MATLAB code was developed to multiply the energy used in each part of the day by the electricity rate specified for that part of the day for that case. The assumptions and considerations of the cost analysis were:

- The absolute total cost for each case was not calculated; rather, the percentage reduction in energy and cost was determined. Since the actual area of the building would be required for calculating the total cost, the problem was solved for one square meter (or one square foot) of the described wall, and the percentage of change was calculated.
- In some states, the on-peak hours and off-peak hours are allocated to different parts of a day in different months of the year.

However, for these states, the rates that are presented in Table 4 belongs to the months of the year that match those used in the simulations.
- For each state, there is a monthly service fee in addition to the cost of the used electricity. This extra fee was not included in cost analysis and only the costs related to the power usage were considered.
- For some states, there is an extra charge for usage over a specific limit. This fee was not included in the calculations.

2.4.2.2. Summer period and a full year of two cities in California and Washington. The states of California and Washington are following strategies to reduce the energy consumption in their buildings. Two cities in these states (Bishop and Hanford, respectively) were selected for further study. Both a three-month summer period (21 June–21 September), and a full year were simulated using the COMSOL model. The daily temperature fluctuation of the summer time in these two locations were close to the comfort zone, and thus close to the melting point of the utilized PCM – as specified below. It was therefore expected that the PCM would have the highest efficiency in this period of time, however, to have a more comprehensive assessment, a full year period of these cities was studied to evaluate the effectiveness of PCM-impregnated gypsum in meeting energy reduction goals.

The temperature profiles of these time periods were applied to a wall with a total thickness of 250 mm (9.84”). The highest PCM percentage (50 vol.%) was incorporated in the gypsum board. The occupant comfort zone was defined as the range of 22.2 °C (72 °F) to 24.4 °C (76 °F), the melting point of the simulated PCM was selected to be 23.3 °C (74 °F); and the heat of fusion of the simulated PCM was set to be equal to that of PCM28.

3. Results and discussion

3.1. Sine function temperature profiles

PCM-impregnated gypsum board can be located on the inner or outer side of the wall. To find the arrangement that has the better performance, the sine function temperature profiles (T10, T20, and T30) were applied to wall models in each configuration (Fig. 4). The results for the case of T10 and for the board with 10 vol.% of PCM located on the inner side of the wall show that the inside temperature oscillates between 21.8 °C (71.2 °F) and 23.8 °C (74.8 °F); whereas for the board located on the outer side of the wall, the inside temperature oscillates between 21.2 °C (70.2 °F) and 24.2 °C (75.6 °F). When the PCM percentages increases, the oscillation range in each case reduces, however, these ranges are smaller for cases where the board is on the inner side of the wall.

The same results can be reached for cases where the models were subjected to sine temperature profiles with larger magnitudes, i.e. T20 and T30. This suggests that regardless of the amplitude of the applied temperature and the PCM percentage incorporated in the gypsum board, the efficiency of the board is higher when it is installed in the inner side of the wall. Therefore, the rest of the simulations were conducted on models with the gypsum board on their inner side.

The temperature changes in the 250 mm (9.84”) wall with different percentages of PCM incorporated in gypsum board subjected to T10, T20, and T30 are shown in Fig. 5. As the temperature rises, the PCM absorbs the applied heat energy and turns to liquid, and reducing the peak temperature. When the applied temperature drops below the melting temperature, the PCM releases the heat energy that was absorbed initially and thus increases the minimum temperature. This suggests that PCMs can be used as passive heat storage units in the walls that smooths the inside temperature profile. This effect increases by incorporating more PCM; however,

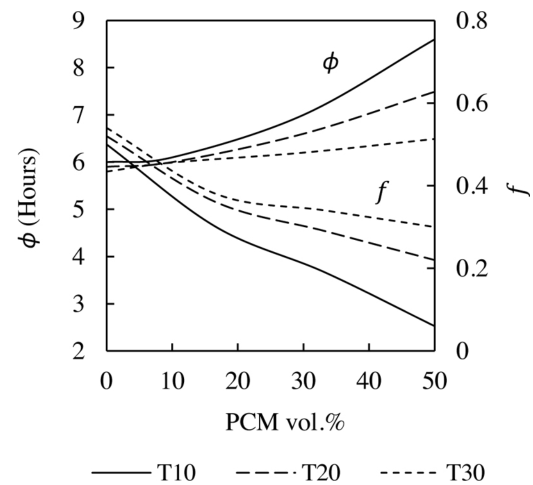

Fig. 6. Time Lag and Decrement Factors for 250 mm (9.84”) wall with different PCM percentages in its gypsum board and under sine function temperature profiles with different amplitudes.

PCM has a limited latent heat of fusion and therefore it cannot completely eliminate changes in temperature.

The results of the effects of different percentages of PCM on the Time Lag and Decrement Factor show that by increasing the PCM percentage, the time lag increases (Fig. 6). This increase is larger when the applied temperature has a smaller amplitude. This is because of the limited latent heat of fusion of the PCM. The decrement factor decreases as the PCM percentage increases. When 50 vol.% of the gypsum board volume is replaced with PCM and for the input temperature profile with a magnitude of 10 °C (18 °F), this factor can be as low as 8% which means more than 90% of the peak temperature is damped. The effects of the latent heat capacity of PCM on the time lag and the decrement factor have been studied elsewhere, where it was reported that there is an exponential relationship between time lag and heat capacity and an inverse exponential relationship between decrement factor and heat capacity [49].

The increase in the length of time spent in the comfort zone for the 250 mm (9.84”) wall, with different percentages of PCM incorporated in its gypsum board under different temperature profiles, is presented in Table 5. For T10 and for the first comfort level, by using 30 vol.% PCM, the inside temperature stays in the comfort zone for the entire time, therefore increasing the PCM content has no effect.

For the second level, without using PCM, the entire graph falls inside the comfort zone; therefore, using PCM does not increase the comfort duration. For all of the input temperatures, the ability of PCM to increase the comfort duration is higher for the first level of comfort, because when the temperature tolerance is larger, even without PCM a relatively large portion of the inside temperature stays within the comfort zone. This suggests that PCM are more applicable when a narrower range of comfort zone is desired (Table 5).

It is obvious that by increasing the thickness of the wall, the thermal mass will be increased, and thus, the decrement factor of the wall decreases and the time lag increases. However, to compare the effectiveness of the increase in the thickness of the wall and increase in the PCM percentage in the gypsum board, the sine temperature profiles were also applied to the walls with different thicknesses and no PCM in their gypsum boards. Unlike the cases where PCM was incorporated, the inside temperature profiles have sine-shaped behavior (Fig. 7).

The results of these simulations are summarized in Fig. 8. The graph shows that the increase in the time lag is the same for all

Table 5
The effect of PCM on the comfort duration and the area out of the comfort zone for sine function temperature profiles.

Input	PCM vol.%	Percentage increase in the comfort time duration		Percentage decrease in the area out of the comfort zone	
		22 ± 1.5 °C (71.6 ± 2.7 °F)	22 ± 3.0 °C (71.6 ± 5.4 °F)	22 ± 1.5 °C (71.6 ± 2.7 °F)	22 ± 3.0 °C (71.6 ± 5.4 °F)
T10	10	29	0	82	100
	30	41	0	100	100
	50	41	0	100	100
T20	10	69	18	43	63
	30	181	29	88	95
	50	202	33	98	100
T30	10	75	26	26	35
	30	208	97	73	84
	50	323	118	92	93

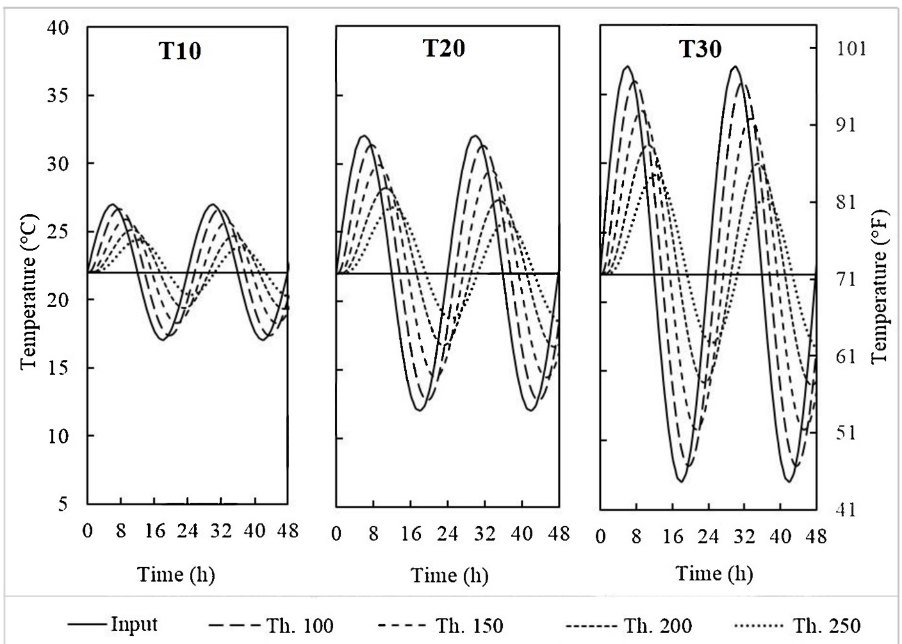

Fig. 7. Temperature changes in walls with the thicknesses of 100 mm (3.94"), 150 mm (5.91"), 200 mm (7.87"), and 250 mm (9.84") and with 0 vol.% of PCM under sine function temperature profiles with different amplitudes.

the temperature profiles. This means that for a wall with a specific thickness, the time lag is independent of the amplitude of the input sine function temperature profile; because this amplitude will appear as a constant number in the solution of the heat transfer differential equation, and the arguments of the exponential and sine functions in the solution will not be a function of this amplitude. By increasing the wall thickness, the increment factor decreases for all the temperature profiles. This decrease is greater for the sine function with a larger amplitude.

Comparing Figs. 6 and 8 show that, for instance, to increase the time lag of the wall by 2 h for the case of T10, the thickness of the wall should be increased by 100 mm (3.94"); however, by incorporating 42 vol.% of PCM in the gypsum board, the same increase in the time lag can be reached. As another example, to decrease the decrement factor by 0.2 for the case of T30, the thickness of the wall should be increased by 65 mm (2.56"); however, by incorporating 40 vol.% of PCM in the gypsum board, the same decrease in the decrement factor can be reached. These results suggest that instead of increasing the thickness of the walls, PCMs can be incorporated in order to reach the desired thermal performance. In addition to economic advantages, this is also important from the architectural point of view; because using PCMs in the walls leads to saving space in buildings.

3.2. Real temperature profiles

3.2.1. One-week period of six cities

To evaluate the efficiency of PCM-incorporated gypsum board at increasing the comfort duration under real temperature inputs, the real temperatures of six cities were applied to the model. The results show that by increasing the PCM percentage, the duration of being in the comfort zone increases for all the cities but this increase is not consistent (Table 6). For the cases of Concord and Minot, this duration was increased by up to 38% and 30%, respectively, when 50% of the gypsum board volume was replaced by PCM; however, with the same amount of PCM for the case of San Antonio, this increase was as low as 4%.

For the cases of Concord and Minot, on average, the outside temperature fluctuation was close to the defined comfort zone; therefore, the PCM was able to absorb a considerable amount of the applied heat energy during the days and release it during the nights, and make the inside temperature fluctuation smoother. In

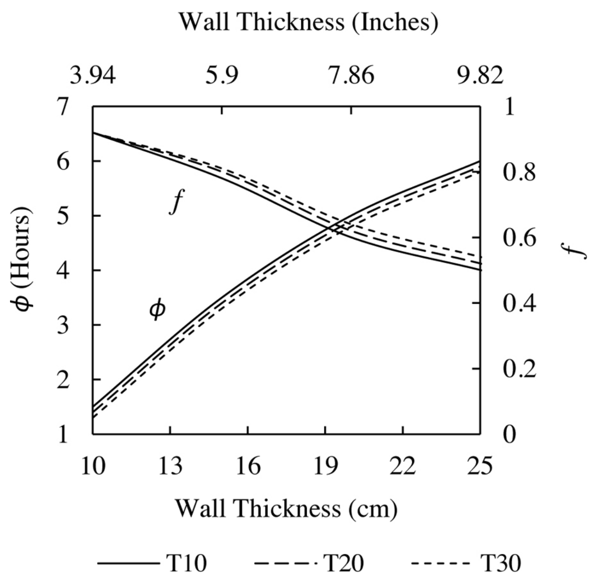

Fig. 8. Time Lag and Decrement Factors for walls with different thicknesses and with 0 vol.% of PCM in their gypsum boards and under sine function temperature profiles with different amplitude.

contrast, the outside temperature fluctuation was far from the comfort zone for the case of San Antonio. The average temperature for this case was 5.2 °C (9.4 °F) higher than the comfort zone average temperature, i.e. 23.3 °C (74 °F). As the latent heat of fusion of PCM is limited, it was not able to absorb a considerable portion of the applied heat and thus, the duration of being in the comfort zone was not efficiently increased. This shows that the efficiency of PCM is completely dependent on the outside temperature profile.

There is not a linear relationship between the utilized PCM percentages and the percentage increase in the duration of being in the comfort zone. For the case of Minot, when the amount of utilized PCM was tripled (from 10 vol.% to 30 vol.%), the effectiveness of the PCM was also roughly tripled (from 8% to 23%). However, when the amount of utilized PCM was quintupled (from 10 vol.% to 50 vol.%), the effectiveness of the PCM increased by less than four times. The results suggest that by increasing the PCM percentage, its efficiency decreases.

The same pattern was observed for the decrease in the area out of the comfort zone (Table 6). This area is important because it is an index of the energy required by the HVAC system to keep the inside temperature within the comfort zone. For all cases, the percentage of the area out of the comfort zone was decreased when the amount of utilized PCM was increased. In the case of Concord, this area was decreased by 45% when 50 vol.% of PCM was used; however, this number was as low as 10% for the case of San Antonio.

Similar to the duration of being in the comfort zone, there is not a linear relationship between the utilized PCM percentages and decrease in the area out of the comfort zone. As an example, for the case of Miami, the decrease in the area out of the comfort zone increased by 67% (from 6% to 10%) when the PCM percentage was increased from 10 vol.% to 30 vol.%; however, it was increased by 100% (from 6% to 12%) when the PCM percentage was increased from 10 vol.% to 50 vol.%. Therefore, an Energy Efficiency Factor (EEF) was introduced to find the energy-wise optimum percentage of PCM for each case. This factor was calculated by dividing the value of the percentage decrease in the area out of comfort zone by the value of the PCM percentage (Table 6).

The results show that for all the cases, by increasing the amount of utilized PCM, the EEF was decreased, representing diminishing returns as more PCM is applied. For the case of Portland, the PCM efficiency was dropped from 2.4 to 0.83 and 0.7 when the PCM percentage was increased from 10 vol.% to 30 vol.% and 50 vol.%, respectively. Concord had the lowest and Portland had the highest drop in PCM efficiency when the PCM content was increased from 10 vol.% to 50 vol.% (25% and 71%, respectively).

These results agree with those presented by Pieppo *et al.* [65] and Feldman *et al.* [66] where the energy savings in buildings utilizing PCM wallboards with approximately the same percentages of PCM were reported to be between 5% to 20% and about 22%, respectively, depending on the climate and temperature profile of the location. Based on the investigation of Bejan and Catalina, incorporation of PCM-impregnated panels with latent heat storage of 574 W h/m^2 (45.9 kcal/ft^2) can decrease the cooling energy by 48% and heating energy by 11% [67]. Also, Hittle reported that by incorporating PCMs in floor tiles, the annual heating costs of a building can be greatly reduced [68].

Athienitis et al. also reported that the utilization of PCM-impregnated gypsum wallboard was shown to reduce maximum room temperatures by about 4 °C (7.2 °F) during the day and can significantly reduce the heating load at night [29]. The results of an outdoor test room experiment indicated that the peak temperature in PCM-impregnated wallboards can be as much as 10 °C (18 °F) lower than the peak temperature in the control test room during sunny days [69]. However, the reults of this study suggests that the effciency of PCMs was overestimated in that research. As the effectiveness of PCM is compelately dependent of the input temperature, studies that use artificial temperature profiles or have short durations will not yield realistic results regarding the efficiency of PCMs.

Cost analysis was also conducted to evaluate the efficiency of PCM-equipped gypsum boards to reduce the electricity costs regarding air conditioning in buildings. If the electricity rates were the same for all parts of a day, the percentage of reduction in costs for each case would be exactly the same as the reduction percentage in the energy required by the HVAC system to keep the inside temperature in the comfort zone. However, the electricity rates for the on-peak hours and off-peak hours are not the same.

The results show that by increasing the PCM percentage, the electricity costs of the HVAC system were reduced in all cases (Table 7). In the Minot simulation, air conditioning costs were reduced by one quarter when 50 vol.% PCM was used. For the same case, 10% of the costs were reduced by incorporating 10 vol.% of PCM. However, this reduction in costs was as low as 7% and 3% for both Miami and San Antonio when 50 vol.% and 10 vol.% of PCM were used, respectively.

Similar to the Energy Efficiency Factor, a Cost Efficiency Factor (CEF) was used to find the economic-wise optimum percentage of PCM for each case. This factor was calculated by dividing the value of the percentage decrease in the costs by the PCM percentage. The results show that similar to EEF, CEF was also decreased when the PCM percentage was increased, that is, CEF was at a maximum when only 10 vol.% of PCM was used. Comparing the results of Table 6 with Table 7 shows that CEF is always smaller than EEF. This means that the effectiveness of PCM in reducing the energy used by the HVAC system is smaller than the effectiveness of PCM in reducing the cost of air conditioning. This is because the electricity rates were lower during the off-peak hours, and a considerable amount of the total energy was used by the HVAC system during these hours. In other words, a portion of the energy that was used by the HVAC system had a lower tariff.

3.2.2. Summer-period and a full year of two cities in california and washington

The temperature changes at the inner side of a wall containing 0% or 50% PCM, in the city of Bishop, during the 93 days of summer, are shown in Fig. 9.a. For the case in which no PCM is used, the inside temperature frequently falls out of the comfort zone, below

Table 6
The effect of PCM on the comfort duration and the area out of the comfort zone for walls equipped with PCM-impregnated gypsum boards under real temperature profiles.

City (State)	Period of Time (week of)	PCM vol.%	Percentage of increase in the comfort time duration	Percentage of reduction in the area out of comfort zone	Energy Efficiency Factor
Portland (OR)	First Jun. 1989	10	7	24	2.40
		30	16	25	0.83
		50	29	35	0.70
San Antonio (TX)	Second Aug. 1990	10	1	5	0.50
		30	2	7	0.23
		50	4	10	0.20
Miami (FL)	Third May 2000	10	2	6	0.60
		30	3	10	0.33
		50	5	12	0.24
Concord (NH)	Third Aug. 1985	10	8	12	1.20
		30	32	31	1.03
		50	38	45	0.90
Minot (ND)	Second Jun. 1980	10	8	17	1.70
		30	23	39	1.30
		50	30	43	0.86
Elko (NV)	Second Jun. 2004	10	8	12	1.20
		30	14	28	0.93
		50	20	36	0.72

Table 7
Costs analysis for walls equipped with PCM-impregnated gypsum boards under real temperature profiles.

City (State)	Ratio	PCM vol.%	Percentage of reduction in costs	Cost Efficiency Factor
Portland (OR)	4.0	10	15	1.5
		30	17	0.6
		50	21	0.4
San Antonio (TX)	2.4	10	3	0.3
		30	4	0.2
		50	7	0.1
Miami (FL)	6.0	10	3	0.4
		30	5	0.2
		50	7	0.1
Concord (NH)	6.9	10	6	0.6
		30	14	0.5
		50	20	0.4
Minot (ND)	6.1	10	10	0.9
		30	21	0.7
		50	25	0.5
Elko (NV)	8.7	10	5	0.5
		30	12	0.4
		50	16	0.3

the lower limit during the nights and above the upper limit during the days. However, when PCM is incorporated, for the first 60 days, the inside temperature does not fall below the lower limit. Since the outside temperature is much higher than the melting point of the PCM, the PCM cannot keep the interior temperature below the upper limit. For the final 15 days, the inside temperature for the case of no PCM falls both above the upper limit and below the lower limit.

For the case of Hanford, it can be seen that the PCM makes the temperature profile smoother (Fig. 9b). For the times during which the outside temperature is not extremely high or low, the PCM is effective at keeping the inside temperature in the comfort zone. For example, on the 36th to 40th and 44th to 50th days the temperature is high enough to melt all the PCM and thus, the PCM is not able to modify the inside temperature because it never re-solidifies.

The total duration of the three months of summer is 2232 h. For Bishop, without PCM, the total duration that the inside temperature is out of the comfort zone is 1717 h. However, when 50 vol.% of PCM was used, this duration was reduced by 45% to 947 h (Table 8). This percentage was higher for the times that PCM was supposed to keep the inside temperature above the lower limit (during nights) than the time that it was supposed to keep the inside temperature below the upper limit (during days). The results also show that for this city, up to 39% of the energy that is required by the HVAC system to keep the inside temperature within the comfort zone can be reduced when 50 vol.% of PCM is incorporated in the gypsum board. The

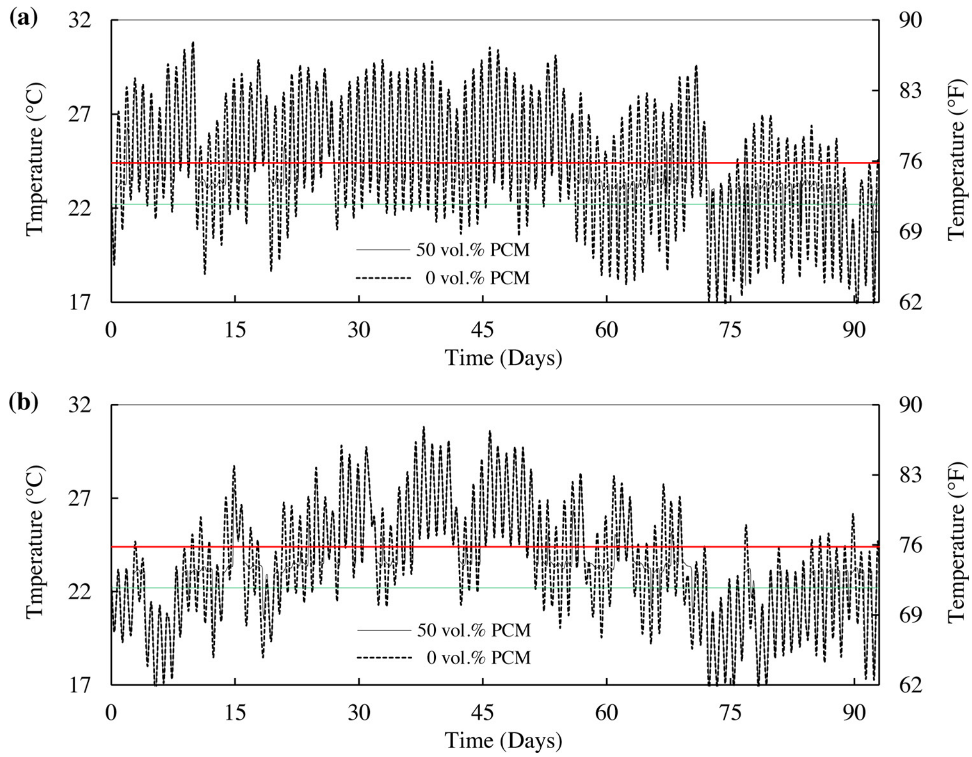

Fig. 9. Inside temperature changes of walls with and without PCM in their gypsum boards during summer. a) Bishop, CA, and b) Hanford, WA.

Table 8
Effectiveness of utilizing PCM-impregnated gypsum boards to improve the thermal performance of buildings, three-month summer period of two cities.

City (State)	PCM	Out of comfort zone duration (h)			Out of comfort zone area (h K)		
		Below	Above	Sum	Below	Above	Sum
Bishop (CA)	0 vol.%	576	1141	1717	1106	2902	4008
	50 vol.%	194	752	947	456	1989	2445
	Reduction%	66	34	45	59	31	39
Hanford (WA)	0 vol.%	809	838	1647	1540	1751	3291
	50 vol.%	505	581	1085	1159	1368	2527
	Reduction%	38	31	34	25	22	23

Table 9
Effectiveness of utilizing PCM-impregnated gypsum boards to improve the thermal performance of buildings over a full year in two cities.

City (State)	PCM	Out of comfort zone duration (h)			Out of comfort zone area (h K)		
		Below	Above	Sum	Below	Above	Sum
Bishop (CA)	0 vol.%	6541	1326	7867	4886	3190	8076
	50 vol.%	5521	820	6341	4589	2075	6664
	Reduction%	16	38	19	6	35	17
Hanford (WA)	0 vol.%	7066	949	8015	63,934	1955	65,889
	50 vol.%	6275	803	7078	57,787	1780	59,567
	Reduction%	11	15	12	10	9	10

PCM decreases the heating demand by 59% and the cooling demand by 31%.

Roughly the same results can be reached for the case of Hanford. For this city, incorporating PCM reduces the duration of time spent outside the comfort zone from 1647 h to 1085 h, which is a 34% reduction. In this case, the efficiency of PCM is higher at night, when it is supposed to keep the interior temperature warm. Also, incorporating PCM can reduce the HVAC system energy demand by 23%; 25% of the heating demand and 22% of the cooling demand.

To have a more comprehensive study, the simulation period was expanded to a full year for these cities. In the case of Hanford, the efficiency of PCM to keep the inside temperature above the lower limit and below the upper limit was 11% and 15%, respectively (Table 9). Compared to the summer-period, this efficiency was lower because during the seasons of winter and spring, the temperature oscillation was far from the melting point of the utilized PCM, and thus, the phase transition did not take place frequently. As a result, the efficiencies of the PCM in decreasing the heating and cooling demands were 10% and 9%, respectively.

For Bishop, the duration of being out of the comfort zone was decreased by 19% over a full year when the PCM-impregnated boards were used. The effectiveness of PCM in keeping the indoor temperature above the lower limit was low (16%), because the daily temperature oscillation was mostly below the PCM's melting point, and thus, not enough heat energy was stored in the PCM. However, the effectiveness of PCM to decrease the duration above the upper limit was as high as 38%. Also, incorporating PCM reduced the HVAC system energy demand by 17% for a full year; 6% of the heating demand and 35% of the cooling demand.

These results show that utilizing PCM-impregnated gypsum boards in new or existing buildings could be an effective strategy to achieve the thermal performance desired by governmental plans and building codes. Existing buildings were mostly built before the recognition and implementation of thermal efficiency in buildings codes. For instance, more than half of California's 13 million residential units and over 40% of the commercial buildings were built before 1978, when the first building energy efficiency standards were implemented [8]. Thus, most of these buildings do not meet the current energy code requirements. Adding a layer of PCM-impregnated gypsum board, or replacing conventional wall layers with these boards, could have a significant contribution to achieving the desired level of thermal performance of the buildings.

4. Conclusion and future work

Utilizing PCM-incorporated gypsum boards was shown to be a promising strategy to achieve governmental plans to decrease the energy consumption in buildings. These boards not only can be used in new buildings, but also can be added to existing buildings to improve their thermal performance. However, the efficiency of PCMs is completely dependent on the applied temperature. PCMs do not have high efficiency in areas with high temperature fluctuations. Also, increasing the amount of the utilized PCM leads to diminishing returns on efficiency. Generating more comprehensive computational models, which can take into account the effects of the existence of windows and solar radiation, and addressing practical considerations such as long-term thermal behavior of PCM-impregnated wallboards, their durability and fire rating, are suggested for future work.

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