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Laboratory assessment of residential building walls containing pipe-encapsulated phase change materials for thermal management

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ABSTRACT

To reduce the heat flow between building interior and exterior environments using thermal energy storage without causing problems related to moisture transfer, this paper presents residential building walls enhanced with pipe-encapsulated phase change materials (PCM). Experimental investigations are conducted to identify thermal performance of building walls with pipe-encapsulated PCM in typical summer conditions. A dynamic wall simulator was designed and built to reproduce residential building indoor and outdoor conditions in a laboratory setting. Two pipe sizes, based on diameter, installed in a horizontal arrangement and placed at various wall depths were investigated. The heat transfer through building walls with pipe-encapsulated PCM was evaluated based on peak heat flux reductions and peak heat flux time shift. The peak heat fluxes of the PCM-outfitted walls were reduced by a maximum of 22.5% for what was referred to as "next to wallboard" configuration and 36.5% for "middle depth" configuration, respectively, compared to standard walls. The corresponding daily energy savings were 27.4 W-hr/m^2 and 51.2 W-hr/m^2. PCM encapsulated in smaller pipes installed in the "middle depth" of the wall cavity is recommended to realize complete solidification and melting for larger peak flux reduction and energy savings.

1. Introduction

In 2016 buildings consumed about 40% (or about 4.1 × 10^4 TJ) of total U.S. energy consumption in the United States [1]. Most modern buildings provide a controlled internal environment conducive to the thermal comfort of its occupants. To provide this comfort air conditioning and ventilation equipment use a significant amount of energy, which tops the list of electric energy-consuming devices in buildings during the summer in most regions of the United States. A substantial amount of research related to either improving the efficiency of building energy systems or for the development of energy efficient building designs and components (e.g., envelopes) has been produced over the past several decades [2–7].

Building energy requirements for internal environmental control depend mainly on the building's intended use and the building enclosure; thus, the importance of research to develop energy efficient enclosure designs. For building enclosures to be energy efficient heat flow between the building interior and exterior environments must be reduced. One approach to reduce the heat flow without adding to its thickness of the enclosure is by exploiting the thermal energy storage (TES) potential of phase change materials (PCM), which can be integrated with the original layers of the wall. For example, experiments have shown that a 1.27 cm gypsum wallboard imbibed with PCM provides a comparable thermal resistance to a 15 cm concrete wall [8]. A significant increase in thermal resistance by using a thin layer of PCM, which can result in a temperature drop and heat flux reduction during summer and a temperature rise during the nighttime [9–12], [10,11]. The mechanism that makes PCM reduce the heat transfer through building walls is related to the PCM ability to hold the heat being transported through the wall cavity for longer periods of time during PCM phase change from solid to liquid. The liquid PCM is converted back to solid PCM during nighttime and early morning when the absorbed heat is released by the PCM. When integrated within

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building walls, the phase change (solid to liquid) of the PCM helps in reducing the heat transfer through the walls and to time-shift (i.e., delay) the peak heat fluxes. Delaying the peak heat fluxes reduces the demand on the electric grid at peak times of the day.

Methods used for integrating PCM into building materials generally fall into four categories: 1) direct incorporation, 2) immersion, 3) macroencapsulation, and 4) microencapsulation. Major drawbacks of the first two methods include the lack of containment of PCM that leads to leakage and oxidation [13,14]. To address this issue, macroencapsulation was proposed [15]. Lee et al. studied the heat transfer through building walls integrated with PCM encapsulated in polymeric bags [16] and panel-like layer [17]. A peak heat flux reduction of 51.3% for south-facing walls and 29.7% for west-facing walls using bag-encapsulated method and 27.4% and 10.5% for a south-facing and west-facing wall using panel-encapsulated method. Elnajjar [18] investigated the thermal performance of PCM encapsulated in bricks under a hot and arid climate, which produced a reduction in peak heat flux of 30%. Using panel-encapsulated method, Gounni and El Alami [19] found that the internal wall surface temperature was reduced by 2 °C; El Omari et al. [20] observed an increased performance during the summer when the mean outside air temperatures were 27 °C.

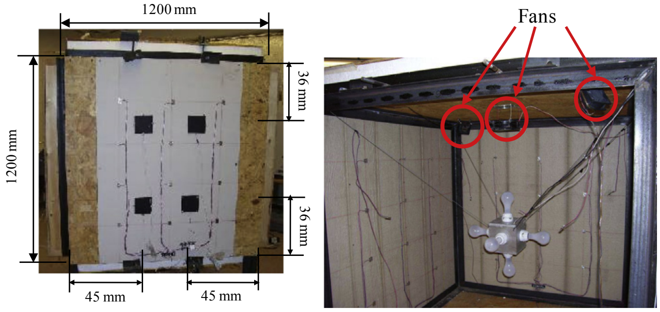
To be summarized, macroencapsulation method was effective to reduce peak heat flux and produce peak heat flux time lag. However, the heat flux reduction and time lag were affected significantly by the PCM location. Jin et al. [21,22] studied the optimal location of macroencapsulated PCM within a depth, L, of the wall. The parameter L measured the distance of the wall cavity taking as reference the exterior surface of the innermost layer of the wall. That is, $L = 0$ at the interface between the external surface of the wallboard and the wall cavity. It was reported that when the PCM layer was located at a distance of 1/5 L, the PCM-enhanced wall produced the largest reductions in peak heat flux. Fateh et al. [23] examined the optimal location of a PCM panel within a wall for winter applications using numerical simulations. A maximum reduction of about 15% of total space heat consumption was obtained when the PCM panel was placed toward the middle of the wall cavity. A peak heat flux time delay of about two hours was also reported.

Moreover, since the PCM container was totally sealed to prevent leaks, there may be problems related to moisture transfer [24]. This paper presents a pipe-encapsulated method to reduce the moisture problem. Pipes were placed within walls with spaces, where moisture could transfer through walls. A dynamic wall simulator was designed and built to reproduce residential building indoor and outdoor conditions in a laboratory setting. Two pipe sizes, based on diameter, installed in a horizontal arrangement and placed at various wall depths were investigated in terms of heat flux reduction and time lag. In experimental test, the focus was on the thermal performance of building walls with pipe-encapsulated PCM in typical summer conditions. The influence of outdoor temperature, pipe location, and pipe size on heat flux reduction and time delay was discussed. This article will give an understanding into how to utilize PCM in residential buildings to realize energy savings.

2. Experimental set-up

2.1. Dynamic wall simulator

A dynamic wall simulator was designed and built as a cubic box made up of six equally sized removable wall panels with dimensions of 1.2 m × 1.2 m, as shown in Fig. 1. The simulator was located in an air-conditioned laboratory room, in which the indoor room air temperature was kept at 24 °C all year round. Inside the simulator, six 200-W light bulbs were used as heat sources to simulate solar radiation. Thus, the inside of the simulator represented the warm outside environment while the air-conditioned laboratory room represented the air-conditioned indoor space. Consequently, its vertical frame wall panels were installed in an "inside out" configuration. Three fans were installed inside the simulator to stir the air and reduce stratification effects. An opening equipped with a small exhaust fan located at the bottom of the simulator evacuated hot inside air when a quick internal temperature drop was required. Three timers and two dimmers were installed to control the light bulbs and the exhaust fan.



(a) Exterior

(b) Interior

Fig. 1. Dynamic wall simulator.

Type T thermocouples were used to measure wall surface temperatures, indoor air temperatures, and the temperatures around the PCM encapsulation pipes. All thermocouples were shielded with aluminum tape to reduce radiation effects on the temperature measurements. Four heat flux sensors were attached on each of the four walls to measure the heat fluxes through the walls. Table 1 shows the sensors and their corresponding accuracies. A data logger and a computer collected the data at an interval of 10 s. The 10-s data were averaged to yield one reading per hour.

2.2. Temperature control inside the simulator

Li et al. [25] recommended that PCM melting temperature selection should be made based on west-facing walls data. This is the case because temperature fluctuations and heat flows through these walls are larger. As a result, hourly surface temperature changes of a west-facing wall exposed to full weather conditions were used to program the controls of the simulator. Based on observed surface temperature histories of a west-facing wall under full weather conditions, it was found that these temperatures increased gradually in the morning. Then, after the noon hour, the temperature increased at a faster rate because of the direct solar radiation. After sunset, the wall surface temperature decreased rapidly.

To create artificial wall surface temperature changes that closely resembled real outer surface temperatures on west walls under full weather conditions, one timer first turned on the light bulbs to create the slow temperature increase in the early morning. This period lasted 6.5 h. Then the second timer turned on more light

Table 1
Sensors and their accuracy.

Sensor	Range	Accuracy (% deviation)
Type T T/C	−18–93 °C	0.6 °C
Heat Flux Meter	0–3.1 × 10^5 W/m^2	2%