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Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management ☆

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HIGHLIGHTS

- A thin PCM layer was evaluated using experimental test houses.
- The thin PCM layer produced lower heat fluxes through residential building walls.
- The thin PCM layer produced a time delay in heat transfer.
- The optimal location of the thin PCM layer in the wall cavities was found.

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ABSTRACT

The thermal performance of building walls integrated with phase change materials (PCM) was evaluated in terms of heat flux reduction and heat transfer time delay. To fully melt and solidify over daily cycles, PCMs must be incorporated as thin layers placed longitudinally within the walls. The thin PCM layer was integrated into the wall via a thermal shield, whereby the PCM was contained in thin sealed polymer pouches, arranged in sheets laminated with aluminum foil on both sides. This system is herein referred to as "PCM thermal shield (PCMTS)". The optimal location of the PCMTS within the wall cavities is critical for heat transfer reduction and management. The thermal performance of south and west facing walls with and without PCMTS was evaluated experimentally using two identical test houses. The PCMTS was installed at various depths, one at a time, within the wall cavities. Each location depth was numbered from 1 to 5 starting at next to the wallboard surface facing the wall cavity (location 1) and proceeding to the exterior side of cavity at intervals of 1.27 cm. The results showed that the optimal location for a PCMTS in the south wall was location 3 (2.54 cm from the wallboard), while the optimal location for a PCMTS in the west wall was location 2 (1.27 cm from the wallboard). At these locations, the peak heat flux reductions were 51.3% and 29.7% for the south wall and the west wall, respectively. The maximum peak heat flux time delays were 6.3 h for location 1 in the south wall and 2.3 h for location 2 in the west wall. The maximum daily heat transfer reductions were 27.1% for location 3 in the south wall and 3.6% for location 5 in the west wall.

1. Introduction

In recent years, climate change, which in part is the result of increased energy-related CO_2 emissions, mostly from fossil fuels, has become a major environmental issue worldwide [1]. As part of a global action, 191 countries have put forth various efforts to reduce greenhouse gas emissions. Such efforts include, but are not limited to, developing renewable energy technologies and energy efficiency strategies, including those for buildings [2]. In the U.S., buildings consume about 40% of total energy used in the country [3] and about 40% of greenhouse gas emissions are attributed to building energy consumption [4]. Space cooling and heating energy use tops the list of energy consumption in buildings at roughly 50% [3]. For this reason, energy savings in building space cooling and heating would produce a significant reduction in total energy consumption, which in turn would reduce greenhouse gas emissions.

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In buildings, enclosure thermal storage, which is related to building thermal mass, has gained importance in energy management and energy conservation [5,6]. In general, thermal mass is achieved by constructing massive structures, which is expensive and old-fashioned. The principle of thermal mass can be significantly assisted by the integration of latent heat storage technologies. This can be achieved by the use of phase change materials (PCM), which absorb and release heat in greater amounts than conventional building materials. This is the case because conventional building materials store heat energy in a sensible rather than in a latent manner. PCM integration in building enclosures helps with wall thermal management (e.g., peak heat flux reduction and time delay) as well as in reducing building energy consumption [7–13]. The peak heat flux reduction would translate to a size reduction in space cooling equipment. A peak heat flux time delay implies that electricity generating utilities may be able to attend to this new peak without having to run extra equipment. This may potentially reduce their operating costs and increase their load factors during the cooling season. A load factor is the ratio of the averaged load over a designated period of time to the peak load occurring during the same period [14]. Electricity generating utilities are required to meet their peak loads at all times. In the summer time, however, these peaks occur for only several hours in the afternoons and are mainly the result of increased air conditioning use [15]. By shifting a portion of the peak demand from air conditioning usage to off-peak times, the peak loads would be reduced. Thus, utility companies would run their power plants more efficiently and at higher load factors. Also, residents and businesses may save on their electricity bills by consuming a part of the electricity for air conditioning during off-peak times rather than on-peak. Utility companies usually charge lower rates for electricity use during off-peak times [16]. Furthermore, it is required that PCM applications be practical, reliable, and cost effective. Therefore, it was necessary to investigate several approaches for the optimization of the thermal performance of building enclosures containing PCMs.

The study of PCM integration methods in building materials started from direct incorporation methods, such as imbibing [17–21]. The imbibing technique consisted of the immersion of the construction materials, such as gypsum boards, bricks, or concrete blocks into PCM baths where the PCM was absorbed into their pores. Direct incorporation was practical; however, in this method the PCM-filled materials suffered from leakage and created moisture transfer problems across the enclosure [6,21]. Then, macroencapsulation methods were suggested, which entailed encapsulating PCMs in tubes or other containers where leakage and moisture transfer problems would be eliminated [22]. These methods, however, proved not practical for the integration of PCMs into building walls because these containers had to be fastened to a part of the wall cavity and there is no building trade in charge of such task. Later, another approach of direct incorporation of PCM in building walls was investigated in which direct mixing of PCM with blown-in insulation, such as cellulose, was used [23,24]. Unless the PCMs were micro-encapsulated, direct mixing of PCM with insulation presented problems dealing with PCM water absorption, in the case of inorganic PCMs, and PCM evaporation, degradation, and eventual dematerialization, in the case of organic PCMs [24]. With micro-encapsulation, improper mixing of the PCM with the insulation was a potential problem. Improper mixing included volumes of heavier concentrations of PCM, volumes containing no PCM at all, and volumes containing evenly distributed PCM. In the case of evenly distributed PCM there existed the potential for partial melting and solidification of the PCM, mainly because of the location of part of the PCM. That is, PCMs located further away from the heat source would tend to not melt or PCMs located towards the middle of the wall cavity would tend to not solidify [25].

In the previously mentioned integration methods, the issue of partial melting and/or partial solidification represented a problem; therefore, to fully melt and solidify over daily cycles, PCMs must be incorporated as thin layers placed longitudinally within the walls [25]. A proposed method was a thermal shield [26], whereby the PCM was contained in thin sealed polymer pouches, arranged in sheets laminated with aluminum foil on both sides and perforated around the PCM pouches. The proposed PCM thermal shield (PCMTS) would eliminate leakage of PCM, moisture transfer related problems, evaporation, degradation, water absorption, improper mixing, and the issue of impracticality presented by the previous methods. The use of shields would make it easier to integrate PCMs within the inside cavities of building walls. However, the optimal location of the shields within the wall cavities must still be found [25–27].

The objective of this study was to assess the thermal performance of residential building walls outfitted with PCMTSs and to determine the optimal locations of the PCM shields within the wall cavities. The field tests were carried out using two identical test houses during two cooling seasons under full weather conditions. The PCMTSs were installed at five locations, one at a time, at various depths within the wall cavities of the south and west facing walls. One test house was used as a control while the other was used as a retrofit house. The thermal performances of the south and west facing walls outfitted with the PCMTSs at each location were compared with those walls without the PCMTSs by measuring their wall heat fluxes, wall temperatures, and cavity temperatures. Differential scanning calorimeter (DSC) tests were also carried out to determine the properties of the PCM contained in the PCMTS, which included the melting temperature range and the heat storage capacities during phase transition. These results were used to define the degree of PCM melting at each PCMTS location within the south and west facing walls cavities.

2. Experimental set-up for field-testing of the PCMTSs

2.1. Test houses

The field tests were performed using two 1.83 m × 1.83 m × 1.22 m identical test houses located in Lawrence, KS, USA. The houses featured conventional North American residential construction and were air conditioned using scaled down space cooling and heating systems. The test houses are shown in Fig. 1. One house was used as the control and the other house was used as the retrofit house. The south and west walls of the retrofit house were outfitted with the PCMTS. The wall assemblies were made of 0.95-cm plywood siding, 5.08-cm × 10.16-cm studs, and 0.95-cm wallboards. Five layers of rigid foam insulation board, each with a thermal resistance of 0.53 m^2 K/W and thickness of 1.27 cm, were installed in the cavities of the walls.

Fig. 1. Test houses (southeast view).