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Low-cost phase change material as an energy storage medium in building envelopes: Experimental and numerical analyses ☆

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ABSTRACT

A promising approach to increasing the energy efficiency of buildings is the implementation of a phase change material (PCM) in the building envelope. Numerous studies over the last two decades have reported the energy saving potential of PCMs in building envelopes, but their wide application has been inhibited, in part, by their high cost. This article describes a novel PCM made of naturally occurring fatty acids/glycerides trapped into high density polyethylene (HDPE) pellets and its performance in a building envelope application. The PCM–HDPE pellets were mixed with cellulose insulation and then added to an exterior wall of a test building in a hot and humid climate, and tested over a period of several months. To demonstrate the efficacy of the PCM-enhanced cellulose insulation in reducing the building envelope heat gains and losses, a side-by-side comparison was performed with another wall section filled with cellulose-only insulation. Further, numerical modeling of the test wall was performed to determine the actual impact of the PCM–HDPE pellets on wall-generated heating and cooling loads and the associated electricity consumption. The model was first validated using experimental data and then used for annual simulations using typical meteorological year (TMY3) weather data. This article presents the experimental data and numerical analyses showing the energy-saving potential of the new PCM.

1. Introduction

According to the 2009 residential energy consumption survey (RECS)[1] of the United States Energy Information Administration (EIA), about 48% of the total residential end-use energy consumption is due to space heating and air conditioning. The U.S. Department of Energy (DOE) has set a goal of developing high-performance, energy-efficient buildings, which will require more cost-effective and energy-efficient building envelopes. Phase change materials (PCMs) have been widely investigated for thermal storage in a range of applications, including integrated collector storage solar water heater [1], spacecraft thermal control in extreme environments [2], phase change slurries for active cooling [3], thermal management of building integrated photovoltaic panels [4], etc. Application of PCMs to building envelopes to take advantage of their latent heat capacities in reducing the envelope-generated heating and cooling loads has received a lot of attention in the last two decades [5].

PCMs in building envelopes operate by changing phase from solid to liquid while absorbing heat from the outside and thus reducing the heat flow into the building, and releasing the absorbed heat when it gets cold outside to reduce the heat loss through the building envelope. Different approaches to PCM applications in building envelopes have been investigated: PCM wallboards [6,7], PCM mixed in concrete and brick [8,9], PCM mixed with loose-fill insulation [10,11], rigid polyurethane foam incorporating fatty acid ester based PCM [12], and macro-packaged PCM in plastic pouches [13,14]. Recent experimental and numerical studies have shown the potential of PCMs in reducing indoor temperature fluctuations under different weather conditions [15–17], reducing energy consumption and providing peak-load shifting [18], and also providing internal humidity control [16].

The energy saving potential of PCMs for buildings has been demonstrated, but the traditionally high PCM prices have precluded their extensive application in the building industry. This

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[1] http://www.eia.gov/consumption/residential/data/2009/index.cfm?view=consumption.

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0196-8904/

Nomenclature

c_p	specific heat (kJ/kg/K)
F	view factor
$h(T)$	enthalpy (kJ/kg)
h_{ext}	exterior surface convective heat transfer coefficient ($W/m^2/K$)
h_{int}	interior surface heat transfer coefficient ($W/m^2/K$)
k	thermal conductivity (W/m/K)
L_f	latent heat of melting/freezing (kJ/kg)
q	heat flux (W/m^2)
q_{solar}	solar irradiance (W/m^2)
T	temperature (K)
α	solar absorptance
ε	infrared emittance
ρ	density (kg/m^3)

Subscripts

ext	exterior
int	interior
l	fully molten state of PCM
s	fully frozen state of PCM

Abbreviations

LWR	long wave radiation
NET	natural exposure test
OSB	oriented strand board
PCM	phase change material
RH	relative humidity

article is related to the evaluation of thermal performance of a new low-cost bio-PCM, with the end goal being the commercialization of the low-cost PCM. The production process of the bio-PCM involves two components: (1) on-purpose production of C16–C18 paraffins from low cost bio-renewable feedstock, and (2) low-cost encapsulation using under-water pelletizers. Bio-renewable feedstock such as low-value fats and greases, which do not compete with food crops, have been shown to be both sustainable and profitable feeds for production of biofuels – ester “biodiesel” and paraffinic “renewable diesel” [19,20], whose cost is similar to petroleum diesel. This new bio-based PCM is the intermediate product in the renewable diesel production process. Furthermore, the current petrochemical PCM paraffins (hexadecane and octadecane) command significantly higher prices than diesel fuels (bio-based and petroleum). Given the petrochemical PCM-vs-diesel price differential, the new bio-based paraffinic PCMs are indeed a sustainable, low-cost alternative to current PCMs.

Hexadecane ($C_{16}H_{34}$), heptadecane ($C_{17}H_{36}$), and octadecane ($C_{18}H_{38}$) are three paraffins that melt/freeze between 20 °C (64 °F) and 28 °C (82 °F), and have latent heats ranging between 152 and 244 kJ/kg [21]. The temperature range of 20–28 °C is considered the comfort zone for most people. High latent heat and a suitable phase change temperature range make these paraffins attractive as PCMs for building applications. Animal fats and vegetable oils contain 97% or higher C_{16} and C_{18} fatty acids, and can be converted to C_{16}–C_{18} paraffins using a reaction called hydrodeoxygenation. Further, studies have shown that paraffins can be trapped into high density polyethylene (HDPE) by co-crystallizing a paraffin/HDPE melt. Up to 70% paraffin can be trapped in the HDPE matrix such that molten paraffin does not seep out of the solid HDPE matrix. Under-water pelletizers have been successfully used to convert molten polymer systems to pellets of various sizes, including <1 mm pellets. The combination of C_{16}–C_{18} paraffin production from low-cost fats and waste vegetable oils, combined with a low-cost encapsulation method, is expected to result in a significant reduction in PCM production costs. Kosny et al. [22] performed an economic analysis to evaluate the cost effectiveness of PCM-enhanced building envelopes and determined the target cost levels at which PCMs can be cost competitive with conventional building thermal insulation materials. For a payback period of 10 years, assuming 30%-by-weight dispersed PCM in wall insulation, Kosny et al. [22] estimated cost targets of \$3.30–8.80/kg (\$1.50–4.00/lb) for PCMs with latent heats varying between 120 and 220 kJ/kg. The cost of the current PCM with a latent heat of 116 kJ/kg [23] is projected to be about \$4.40–6.60/kg (\$2–3/lb) or less, when manufactured at a commercial scale.

As mentioned earlier, there are several studies evaluating building applications of PCMs [5–18]. Al-Saadi and Zhai [24] reviewed the modeling of PCMs in building enclosures and highlighted the issues needing further research, with one of the research needs being quantification of PCM modeling performance under different climatic and operating conditions [24]. Recently, Biswas et al. reported a combined experimental and numerical evaluation of a nano-PCM containing gypsum board [25]. The PCM–gypsum board was tested in a natural exposure test (NET) facility in a hot and humid climate over a period of several months. Finite-element models of the test wall were built and validated against the test data (temperature and heat flows), and then used to evaluate the energy-saving potential of the PCM–gypsum board through annual simulations [25].

This article describes another test wall, tested at the same NET facility, containing the new low-cost bio-PCM. The PCM-containing HDPE pellets were dispersed in cellulose insulation for filling in wall cavities. The primary difference between the previous nano-PCM study [25] and the current study is the manner of incorporating PCMs in the building envelope. Similar to the nano-PCM study, two-dimensional finite element models of wall assemblies were created and validated against data from the NET building, and then used for annual simulations of the PCM–HDPE pellets mixed with cellulose insulation (or ‘PCM–cellulose insulation’ in further discussions). In the following sections, the test wall is briefly described, followed by descriptions of the experimental testing and numerical modeling methodology, and finally, the performance of the PCM–cellulose insulation is compared to regular cellulose insulation. The test facility and the simulation methodology are the same as described by Biswas et al. [25], but for convenience, the details have been repeated in this article.

2. Test facility and test wall details

The NET facility is located in Charleston, South Carolina and is used for testing building envelope assemblies by exposing them to natural weathering. Fig. 1 shows the southeast wall of the Charleston NET facility, which houses multiple side-by-side test walls. Also shown is a weather station on the southwest gable end of the building. Fig. 2 shows the test wall construction. The test wall was divided into four sections, indicated by A–D in Fig. 2. Section ‘A’ was filled with regular cellulose insulation and ‘B’ contained the PCM–cellulose insulation. The regular cellulose insulation section was used as a baseline. Two additional sections were created: section ‘C’ containing a mixture of cellulose and HDPE pellets without the paraffin, and section ‘D’ containing a sandwiched