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Reduced-scale experiments to evaluate performance of composite building envelopes containing phase change materials

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HIGHLIGHTS

- A new method is proposed to rapidly assess building envelope thermal performance.
- It was based on scaling analysis to design reduced-scale models of actual buildings.
- It was applied to PCM-composite envelopes than can reduce/delay building energy use.
- The new method requires less material, time, and space than previous studies.

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ABSTRACT

This study presents a convenient approach to rapidly assess the thermal performance of building envelopes containing phase change materials (PCMs) or other building materials. It establishes that the transient thermal behavior of full-scale building test structures featuring envelopes with PCMs can be represented by a reduced-scale test cell conveniently placed inside an environmental chamber. Indeed, PCM-composite envelopes have been considered for reducing and time-shifting the thermal load on buildings thanks to the latent heat associated with reversible transition between liquid and solid phases. First, a thermal model coupling outdoor, wall, and indoor temperatures and accounting for PCM latent heat was developed. It was validated against experimental temperature measurements within a reduced-scale test cell enclosure placed in an environmental chamber and subjected to a series of sinusoidal temperature cycles. Then, scaling analysis of the experimentally-validated thermal model was performed. It identified eight dimensionless numbers governing the transient thermal behavior of building structures with envelopes containing PCMs. The scaling analysis was validated using detailed numerical simulations for different enclosure geometries and outside diurnal climate conditions. Finally, the method was demonstrated on full-scale experiments reported in the literature. It can be used to assess building envelope thermal performance by designing representative reduced-scale experiments without requiring a significant amount of material, time, or space.

1. Introduction

Residential and commercial buildings accounted for 41% of primary energy consumption in the United States in 2015 [1]. Heating, ventilation, and air-conditioning (HVAC) systems are responsible for about half of the energy consumption in buildings [1]. Composite building envelopes containing microencapsulated phase change materials (PCMs) have received attention as a means of reducing space heating/cooling energy consumption [2–5]. Indeed, PCMs store large amounts of thermal energy in the form of latent heat associated with reversible liquid/solid phase change(s). Such latent heat storage increases the thermal mass of the building envelope. This can result in (i) a decrease in a building's heating and cooling loads and (ii) a time-shift of a building's heating and cooling loads to take advantage of time-of-use (TOU) electricity pricing. Such actions reduce energy costs for ratepayers and capital costs for peaker plants operated by utilities [2–6].

Several experimental studies [7–12] have investigated the effect of PCM embedded in cementitious building envelope materials on the thermal behavior of full-scale test enclosures subjected

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Nomenclature

Bi	Biot number
c_p	specific heat, J/(kg K)
C_r	heat capacity ratio
Fo	Fourier number
h	convective heat transfer coefficient, W/(m^2 K)
h_{sf}	latent heat of fusion, kJ/kg
k	thermal conductivity, W/(m K)
L	wall thickness, m
q''	heat flux, W/m^2
t	time, s or h
$T_a(t)$	inside air temperature, °C
$T_o(t)$	outside/chamber temperature, °C
$T_w(x,t)$	wall temperature, °C
$T_{o,max}, T_{o,min}$	maximum and minimum outside temperatures, °C
T_{pc}	PCM melting temperature, °C
x	spatial coordinate, m
w/c	water/cement ratio

Greek symbols

α	thermal diffusivity, m^2/s
ΔT_{pc}	PCM melting temperature window, °C
ϕ_j	volume fraction of material “j” in composite
ρ	density, kg/m^3
τ	oscillation period, h

Subscripts

a	refers to air
c	refers to core material in composite
$c+s$	refers to core–shell microcapsule
eff	refers to effective properties
l	refers to liquid phase
m	refers to matrix material in composite
q	refers to quartz
s	refers to solid phase or shell material in composite

Superscripts

$*$	refers to dimensionless quantity

to natural outdoor climates, for example, in southern Spain [7] or the continental United States [9]. These studies have demonstrated the ability of PCMs to reduce the magnitude of interior temperature fluctuations and/or to decrease the amount of energy required for space conditioning [7–10,12]. While insightful and comprehensive, such experimental efforts are highly cost, time, and resource intensive. For example, it is time-consuming to build such enclosures and to collect data over periods of days or months.

To overcome such challenges without sacrificing the quality and nature of insights obtained, the present study demonstrates how scaling analysis can be used to extend the results of a reduced-scale experimental test cell placed within an environmental chamber to full-scale experimental enclosures analogous to real buildings. Such scaling analysis permits rapid, accurate parametric investigations of the ability of PCMs or of other approaches to reduce and delay space conditioning (HVAC) energy needs within energy-efficient buildings.

2. Background

2.1. Previous experimental studies

Numerous experimental studies have been conducted to compare the thermal behavior of test rooms with and without PCM-composite envelopes. Cabeza et al. [7] constructed a pair of large outdoor cubicles (2 m × 2 m × 3 m) with a conventional concrete envelope or with a composite concrete envelope containing 5 wt% microencapsulated PCM with a melting temperature around 26 °C in the south, west, and roof walls. The cubicles were subjected to the climate of Puigverd de Lleida, Spain over a period of three summer months. The authors found that the cubicle containing PCM featured smaller interior wall temperature fluctuations and smaller inner wall heat flux (heat load). Castell et al. [8] performed similar experiments on concrete and alveolar brick cubicles with and without macroencapsulated PCM. Here, the authors included an active cooling system within the cubicles. They found that the inclusion of PCM decreased the cooling energy requirement by about 15% over a summer season.

Zhang et al. [9] constructed two 1.83 m × 1.83 m × 1.22 m test rooms featuring wooden frame walls without and with PCM featuring a melting temperature window between 20 °C and 30 °C. The PCM was macroencapsulated in copper tubes embedded in the insulation layer of the wall. The test rooms were exposed to summer conditions in Lawrence, Kansas, and the indoor temperature of the test rooms was controlled by an air conditioning system. The authors found that the space cooling energy requirement for a summer day was reduced by 8.6% for a wall with 10% PCM by weight and by 10.8% for a wall with 20% PCM by weight.

Kuznik and Virgone [10] constructed an experimental setup consisting of a large test room (3.1 m × 3.1 m × 2.5 m) adjacent to a climatic chamber on one side. An array of heat lamps was also used to simulate incident solar radiation. The outdoor temperature and solar radiation flux corresponding to a summer, mid-season, and a winter day were imposed at the outer surface of the test room wall. The authors found that when the test room walls were modified to include an additional 5 mm-thick wallboard layer with 60 wt% microencapsulated PCM with melting temperature around 20 °C, the amplitude of the indoor temperature oscillation was reduced by 21–27% for all days simulated. They also found that the maximum indoor temperature was reduced by up to 4 °C in the summer.

Fang and Zhang [11] constructed three test cells with dimensions 0.7 m × 0.7 m × 0.7 m. Each test cell had five ordinary gypsum board walls and a ceiling wall containing either 0, 20, or 50 wt% of impregnated PCM with a melting temperature around 23 °C. The authors used a tungsten heat lamp placed at various vertical distances above the top wall to simulate solar radiation. In the experiments, the lamp was switched on and the resulting transient change in the interior test cell temperature was recorded. The maximum temperature attained by the interior air was reduced by 5°C and 9 °C for wall panels containing 20 wt% and 50 wt% of PCM, respectively. Note that the authors did not measure the response of the test cells to periodic exterior temperature fluctuations.

Overall, previous experimental studies of diurnal thermal response of building enclosures with envelopes made of PCM-composite walls have been limited to full-scale test rooms placed in various actual or simulated outdoor climates. Unfortunately, such experiments are time-consuming and resource-intensive to build, operate, and optimize. The objective of the present study is to demonstrate that a reduced-scale test cell subjected to faster