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Research Paper

Development and experiment validation of variable-resistance-variable-capacitance dynamic simplified thermal models for shape-stabilized phase change material slab

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HIGHLIGHTS

- The Variable-resistance-variable-capacitance simplified model for SSPCM slab were developed.
- Parameter identification of simplified models using GA was proposed.
- A SSPCM slab containing 80 wt% RT28 and 20 wt% EG is prepared.
- Thermal performances of the SSPCM slab were measured to validate the simplified models.

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ABSTRACT

In recent years, shape-stabilized phase change material (SSPCM) slab arouses wide interests as a thermal storage media or thermal buffer in buildings for improving the thermal and energy performance. Traditional numerical models are widely used with low computational efficiency and low applicability of integration with conventional building thermal calculation package. Simplified model of SSPCM with good accuracy and high-efficiency is highly preferable for thermal performance prediction of building structures with SSPCM. This study presents variable-resistance-variable-capacitance simplified models with different orders (i.e., 2R1C, 4R2C and 6R3C model) for SSPCM slab. Parameters are identified using Genetic Algorithm. An experiment facility for measuring the dynamic thermal performance of SSPCM slab is established. The simplified PCM models are validated by comparing the model predictions and experiment measurements. Among these models, 4R2C model is more preferable since the parameters to be identified are less and the accuracy is also acceptable. The average error of surface temperature and heat flux are respectively 0.42 °C and 15%. The 4R2C model can represent the thermal dynamics of SSPCM with very simple structure. It can be easily integrated with conventional building simulation packages for thermal performance prediction of buildings with SSPCM as walls, roofs or ceilings etc.

1. Introduction

Energy is the prime mover and essential guarantee for all human daily activities. With the continuous development of urbanization and modernization, energy demand continues to grow, and the mismatch between energy supply and demand is becoming more prominent. Researches showed that the global energy consumption was increasing by 1.4% every year from 2007 onwards, and it would increase up to 30% between today and 2040 [1,2]. Moreover, the environmental pollution caused by excessive utilization of energy like fossil fuels is increasingly serious. It has been observed that many countries of the world are actively in searching renewable and efficient energy technologies to bridge the gap between energy supply and energy demand, to increase energy efficiency, and to reduce the greenhouse gas emissions.

Thermal energy storage technology has been an efficient energy usage method to match energy supply and demand. Phase change material (PCM) as a kind of latent heat storage media can absorb or

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Nomenclature

A	conversion coefficient of heat flux meter (mv·W^{-1}·m^2)
C	capacitance (J·m^{-2}·°C^{-1})
c_p	specific heat (J·kg^{-1}·°C^{-1})
h	convection coefficient (W·m^{-2}·°C^{-1})
L	latent heat of phase change (J·kg^{-1})
Q	heat flux (W·m^{-2})
R	resistance (°C·W^{-1})
T	temperature (°C)
t	time (s)
N	the number of reference data points
J	objective function
W	weighting factor
V	volume (m^3)

Greek symbols

α_i	*i*-th element of coefficient vector
β_i	*i*-th element of coefficient vector
λ	thermal conductivity (W·m^{-1}·°C^{-1})
ρ	density (kg·m^{-3})
δ	thickness (m)

Subscripts

s	solid phase
l	liquid phase
tot	total
al	aluminum
pred	predicted results
meas	experimental measurements
pcm	phase change material
upper	upper surface
bottom	bottom surface

release passively a large amount of thermal energy at a certain temperature range [3,4]. It has been widely used in HVAC and refrigeration systems [5–7], battery thermal management [8,9], solar energy systems [10–12] and building cooling/heating systems [13–20] due to the high energy storage density. Researches indicate that building energy consumption accounts for 30% of the global energy consumption and shows high potential applications of PCM for energy efficient buildings [2,14].

Shape-stabilized phase change material (SSPCM) slab is the one of present encapsulation technologies of PCM applying to building envelopes. It can solve the leakage and volatilization problems and maintain the shape constant undergo a phase change process. Thus, SSPCM slabs were widely incorporated into walls, ceilings and floors to save energy consumption and improve thermal performance in rooms. Zhang and Lin et al. [16] discussed the preparation of the SSPCM and proposed the potential applications of SSPCM as wallboard or floor in energy efficient buildings. Kim and Mae et al. [17] found that the construction incorporated with the SSPCM layer can improve the indoor temperature stabilization effect. They examined three identical huts under heating conditions. Compared with the reference hut without SSPCM sheet (i.e., hut A), the total energy consumption for heating decreased by 9.2% and 18.4% in hut B (four layers of SSPCM sheets were applied to the floor) and hut C (one layer of SSPCM was applied to the floor, walls and ceiling) respectively. Yao and Kong et al. [18] prepared a novel SSPCM wallboard by paraffin and expanded perlite. This wallboard was used in buildings, and the indoor thermal comfort was experimentally studied. Results showed that the SSPCM wallboard used in the building can maximally reduce the indoor temperature of 2.53 °C. Zhou and Yang et al. [19] investigated the thermal performance and energy consumption of a hybrid space-cooling system using SSPCM plates combined with night ventilation. Simulations results indicated that the indoor thermal comfort was obviously improved, and the daytime cooling energy consumption was decreased by 76% by using the hybrid system.

To improve the thermo-physical property and mechanical stabilization of SSPCMs, various PCMs and supporting materials have been widely investigated [21–26]. Among these PCMs, paraffin has higher latent heat and higher crystallization rate with ignorable undercooling and precipitation. It is stable, nontoxic, non-corrosive and low-cost. However, paraffin will appear as liquid when temperature exceeds the melting temperature, and its thermal conductivity is low, generally below 0.4 W/(m·°C) [27,28]. Expanded graphite (EG) is an alternative supporting material for paraffin to improve the thermal conductivity. It also has good adsorption capability, less surface free radicals and unique network structure showing good stable performance [7,29,30]. Zhang and Zhang et al. [31] produced EG by microwave irradiation performed at room temperature. The composite PCM was prepared by absorbing liquid paraffin into the porous structure of EG, which possessed the advantages of relatively high latent heat and enhanced thermal conductivity. The composite PCM can solve the leakage problem, and it is effective and economical to prepare SSPCM layer by physical means using the composite PCMs (paraffin/EG).

It is essential to estimate the thermal performance and energy saving benefits in the design and optimization of PCMs. To predict the thermal performance accurately, the thermal models for PCMs have been increasingly studied in recent years [32–37]. Alawadhi [32] and Kant and Shukla et al. [33] developed a two-dimensional thermal model for PCM in building brick wall with the effective heat capacity method. The model was solved by using finite element analysis method and showed good effectiveness. Gracia and Navarro et al. [34] developed a numerical heat transfer model for a ventilated facade with PCM by using enthalpy method. The application and influence factors of this model for PCM board were further analyzed. Sun and Zhang et al. [35] presented a mathematical model of PCM used in building envelopes based on the moving heat-source method. The model accurately predicted the position of the solid-liquid interface and the thermal performance of PCM board. The optimal melting temperatures of PCM board for different regions in China was discussed by using the model.

Although these numerical models can predict the characteristics of PCMs accurately, its computational efficiency is low, and it is too complicated to be integrated with conventional building thermal and energy calculation package for simulation. Numerical PCM model needs meshing the SSPCM slab with many nodes or computational domain, and each node or computational domain needs one or more formula (equations) to present its heat transfer process. It requires a lot of calculation time to solve the whole numerical model (usually several hours or days) [34,38]. Tabares-velasco and Christensen et al. [39] established a one-dimensional finite difference numerical model for PCM plates by using explicit specific heat method and integrated it into EnergyPlus. The author found that the time step need to be small enough to ensure the convergence and accuracy of calculation by using this one-dimensional numerical model. The small step greatly increases the computation cost.

Fast and efficient simplified models for the application of SSPCM are more favorite. It is also necessary for system performance prediction and optimization design of buildings with SSPCM to develop the applicable simplified models. Mirzae and haghighat [40] proposed a new one-dimensional analytical model for PCM plate based on a RC-circuit