Applied Thermal Engineering 128 (2018) 1331–1339

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Comparison of two numerical heat transfer models for phase change material board

Xing Jin [a,b,*], Huoyan Hu [c], Xing Shi [a,b], Xin Zhou [a,b], Xiaosong Zhang [c]

[a] *School of Architecture, Southeast University, No. 2 Sipailou, Nanjing 210096, PR China*
[b] *Key Laboratory of Urban and Architectural Heritage Conservation (Southeast University), Ministry of Education, No. 2 Sipailou, Nanjing 210096, PR China*
[c] *School of Energy and Environment, Southeast University, No. 2 Sipailou, Nanjing 210096, PR China*

HIGHLIGHTS

- Two numerical heat transfer models for PCM board was compared.
- The effective heat capacity model had inevitable calculation error.
- The effective heat capacity model with small phase change temperature range had large error.
- The effective heat capacity model needed less computing time than the enthalpy model.

ARTICLE INFO

Article history:
Received 12 April 2017
Revised 14 July 2017
Accepted 3 September 2017
Available online 6 September 2017

Keywords:
Phase change material (PCM)
Heat transfer
Numerical model
Enthalpy
Effective heat capacity

ABSTRACT

The effective heat capacity method and the enthalpy method are the two most common methods to build the numerical heat transfer models for phase change material (PCM) board. The objective of this research was to compare the PCM heat transfer models which were built by the effective heat capacity method and the enthalpy method respectively. Based on the numerical results of these two models, it was found that when the model was built with the effective heat capacity method, the calculation error was inevitable when the state (solid, molten or liquid) of PCM was changed during the calculation of one time step, while there was no such error when the model was built with the enthalpy method. The phase change temperature range could affect the magnitude of the calculation error when the model was built with the effective heat capacity method. When the phase change temperature range was very small, the calculation error of the model with the effective heat capacity method could be significant. However, the model with the effective heat capacity method needed less computing time than the model with the enthalpy method.

1. Introduction

The phase change materials (PCMs) have relatively high thermal storage density while requiring smaller masses and volumes of material, they can be used in many areas, such as thermal energy storage [1], building heating/cooling [2], thermal management [3], food preservation [4], etc. Because the thermal mass of building envelope can be enhanced greatly by the PCM, the PCM building envelope has attracted more and more researchers in the last decade [5–7]. Compared with the building envelope without PCM, the peak heat flux of the PCM envelope during a day is small, and the indoor air temperature fluctuations of the PCM envelope are also small. Accordingly, the indoor thermal comfort will be improved and the energy consumption for the space heating/cooling will be reduced [8–11].

The numerical models of the PCM walls or PCM boards have been studied for years. Because of the non-linear heat transfer in PCM, very few analytical solutions are able to be obtained, the numerical solutions are more available. There are several methods to build the numerical heat transfer model for the PCM board, such as the enthalpy method [12–19], the effective heat capacity method [20–26], and the heat source method [25,27,28]. According to the number of the papers published in the journals, the enthalpy method and the effective heat capacity method are the two most common methods.

In the enthalpy method, the latent heat and specific heat capacity are combined into an enthalpy term in the governing equation [29]. This method was proposed by Eyres [30] to deal with varia-

---

* Corresponding author at: School of Architecture, Southeast University, No. 2 Sipailou, Nanjing 210096, PR China.
E-mail addresses: x.jin@seu.edu.cn, jxining@163.com (X. Jin).

https://doi.org/10.1016/j.applthermaleng.2017.09.015
1359-4311/

tions of thermal properties with respect to temperature. For example, Biswas et al. [12] built a two-dimensional model for a nano-PCM enhanced wallboard using this method. Mankibi et al. [13] built a one-dimensional model for an active multi-layer living wall with the enthalpy method, and the model was validated. Another popular method is the effective heat capacity method, which is considered to be a versatile, convenient, adaptable and easily programmable method. The main advantage of this method is that the governing equations and the associated discretized equations have the general form of the heat conduction equation with a nonlinear heat capacity, namely the effective heat capacity. As a result, they can be solved with a standard heat transfer code. The key for accurate simulations lies in the appropriate selection of the nonlinear heat capacity curves [31]. For example, Kuznik et al. [20] built a PCM wall model using this method, and it was found that when the time step was 60 s and the mesh size was 0.001 m, the time discretization and spatial errors were both less than 1%. Zhou et al. [21] also built a one-dimensional model for a PCM board with this method, and the model was validated by the literature results.

The previous researches show that the relationship between enthalpy and temperature is very important to the enthalpy method, while the relationship between effective heat capacity and temperature is very important to the effective heat capacity method. Both of the two methods have high accuracy and could satisfy the calculation requirements [32,33]. However, because the enthalpy method and the effective heat capacity method have different governing equations and different solving methods, the numerical results of these two methods may be different. Especially when the state of the PCM is about to be changed, the calculation error may exist. Do the models have the inevitable errors? Which parameters could affect the calculation errors? Which model needs less computing time? Therefore, to figure out these questions, two numerical heat transfer models of the PCM board were built with the enthalpy method and the effective heat capacity method, respectively. The objective of this research was to compare these two models and find out the calculated error which may exist during the calculations.

2. Numerical models

A thin board which was made by PCM was chosen as the research object in this paper. Compared with the length and the width of the board, its thickness was relatively small, it was assumed the heat transfer process in the PCM domain was one-dimensional [8]. In addition, the natural convection effect in the molten PCM was neglected [16].

2.1. Effective heat capacity method

When the model is built with the effective heat capacity method, the governing equation is:

$$\rho c_p(T)\frac{\partial T}{\partial t} = \lambda\frac{\partial^2 T}{\partial x^2} \tag{1}$$

where ρ is the density, $c_p(T)$ is the specific heat capacity, λ is the thermal conductivity, T is the temperature, t is the time, and x is the coordinate.

The effective heat capacity is usually calculated by the following equations.

$$c_p = \begin{cases} c_{ps} & T < T_c - \Delta T \\ \frac{L}{2\Delta T} + \frac{c_{ps}+c_{pl}}{2} & T_c - \Delta T \leqslant T \leqslant T_c + \Delta T \\ c_{pl} & T > T_c + \Delta T \end{cases} \tag{2}$$

where L is the heat of fusion, c_{ps} and c_{pl} are the heat capacities of solid PCM and liquid PCM, respectively. ΔT is the half of the phase change temperature range, T_c is the center temperature of the phase change temperature range.

The boundary conditions of the governing equation are:

$$T(0,t) = T_1 \tag{3}$$

$$T(\delta,t) = T_2 \tag{4}$$

where δ is the thickness of the board, T_1, T_2 are the surface temperatures of the board.

The initial condition is:

$$T(x,0) = T_2 \tag{5}$$

The governing equation along with the boundary conditions was discretized using the finite difference method (FDM). Central difference was applied in space and fully implicit method was applied in time. The whole equations system was solved by the tridiagonal matrix algorithm (TDMA).

2.2. Enthalpy method

When the model is built with the enthalpy method, the governing equation is:

$$\rho\frac{\partial H}{\partial t} = \lambda\frac{\partial^2 T}{\partial x^2} \tag{6}$$

The PCM enthalpy is calculated by the following equation.

$$H = \int_{T_0}^{T_c-\Delta T} c_{ps}dT + \int_{T_c-\Delta T}^{T_c+\Delta T} c_{pc}dT + \int_{T_c+\Delta T}^{T} c_{pl}dT \tag{7}$$

where T_0 is the temperature where the enthalpy is 0 kJ/kg, c_{pc} is the heat capacity of PCM when the PCM temperature is in its phase change temperature range.

The boundary conditions and the initial condition are the same as Eqs. (3)–(5).

The governing equation along with the boundary conditions was solved using the Gauss-Seidel method. A fully implicit finite-difference scheme was applied. The maximum difference between successive elements of the solution was less than 10^{-6}.

2.3. Comparison of the effective heat capacity method and the enthalpy method

When the model was built with the effective heat capacity method, the discretized equation for an inner node was:

$$T(i,j) - T(i,j-1) = \frac{\lambda}{\rho\cdot c_p(T(i,j-1))}\cdot\frac{d}{h^2}(T(i+1,j) - 2T(i,j) + T(i-1,j)) \tag{8}$$

where i is the ith space node, j is the jth time node, d is the time step size, and h is the space step size.

When the model was built with the enthalpy method, the discretized equation for an inner node was:

$$H(i,j) - H(i,j-1) = \frac{\lambda}{\rho}\cdot\frac{d}{h^2}(T(i+1,j) - 2T(i,j) + T(i-1,j)) \tag{9}$$

If the specific heat capacity of the material was constant in Eqs. (8) and (9), the numerical results of these two models should be the same. However, as shown in Eqs. (2) and (7), the specific heat capacity of the PCM was changed with its temperature.

When the model was built with the specific heat capacity method, as shown in Eq. (8), because $T(i,j)$ was unknown, the effective heat capacity value in the equation was dependent on $T(i,j-1)$, while it was not affected by the value of $T(i,j)$ during the calculation. Assume that the PCM was heated, and the temperature of a space node was T_A in Fig. 1. In other words, $T(i,j-1) = T_A$. d sec-