INFLUENCE OF VOID CAVITY DISTRIBUTION ON MELTING OF COMPOSITE PHASE CHANGE MATERIALS

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ABSTRACT

Most of phase change materials have an obvious density change during solid-liquid phase change, which is along with the volume change of phase change materials, and results in the formation or disappearance of the void cavities based on the encapsulation methods. Void cavities play ignorable roles in the phase-change process, while their influence in the composite porous phase change materials were hardly taken into account in the literatures. In this work, the effect of void cavities on the heat transfer of the porous phase change material has been studied for the first time by a two-dimensional lattice Boltzmann method. The high thermal diffusion coefficient and low conductivity of void cavities show significant influence on not only the temperature distribution but also the energy storage performance. This simulation model gets closer to the real application, which holds great promising for being applied in the guidance on the thermal management system design.

Keywords: phase change, metal foam, void cavity, lattice Boltzmann method

1. INTRODUCTION

Phase change materials (PCMs) attracts increasing attentions for thermal energy storage (TES) systems, due to their large latent heat and relatively stable operating temperature, which has been widely used in the thermal management of electronic devices, renewable energy and buildings. However, most of PCMs are composed of organic materials (e.g. paraffin), which suffer from their low thermal conductivities, leading to suppressed heat transfer efficiency [1]. To address this issue, composite porous PCMs have been explored, where porous structured frames with high thermal conductivity are introduced into the PCMs to provide 3D thermal conducting networks, such as metal foam and expanded graphite [2]. It can be found that the overall thermal conductivity could be improved by 3 to 130 times by introducing metal foam into PCMs [3].

Most of the PCMs that undergo liquid-solid phase changes (i.e. solidification or melting) have the obvious density change, which are along with the volume change of PCMs [4]. As the densities of the PCMs are changing when the liquid parts solidify (or the solid parts melt inversely), void cavities would be formed (or disappear) depending on the encapsulation methods. Assis et al. [5] reported the visual observation of void cavities during the phase change of paraffin, and the related numerical analyses were conducted to characterize the dynamic temperature evolution under different size of the open spherical enclosures. It can be concluded that void cavities during phase change play ignorable roles in the phase-change process. However, the influence of void cavities has been addressed in few literatures which are, moreover, for the pure PCM rather than the composite porous PCMs. Therefore, it is vitally important to investigate the distribution of void cavities and further explore their effects on the phase change behavior of composite porous PCMs.

The main purpose of this work is to better understand the effect of different distributions of void cavities on heat transfer performance and phase change behavior of composite porous PCMs. Considering the complex porous structure and dynamic melting interface during phase change, lattice Boltzmann model (LBM) is preferential for its mesoscopic model and easy treatment of boundary conditions [6]. A twodimensional LBM is developed to study the melting of composite porous PCMs in the presence of void cavities,

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and the effects of void cavities with different distributions are discussed.

2. MATHEMATICAL MODEL AND METHOD

2.1 Mathematical model

A schematic illustration of the physical problem in the present study is shown in Fig. 1. The composite porous PCM is filled into a square container, where the metal foam and the dodecane are adopted as the thermal conductivity enhancer and the PCM, respectively. The initial temperature in the square container is at the melting temperature of the PCM T_m , and the PCM is unactivated at the solid state. For the beginning of the heat transfer process, the temperature of the left hot wall goes up to T_h in an instant, and then the PCM starts to melt. During melting, the left hot wall remains constant T_h , the right cold wall remains constant T_m , and the other two walls are adiabatic.

During the melting of PCM, heat conduction exists among the metal foam, solid and liquid PCM, where the evaporation and condensation of the saturated vapor in void cavity also happen simultaneously. For these multiple complex physical processes, some assumptions are made as follows:

(1) Heat conduction is the dominate heat transfer mechanism while natural convection of liquid PCM is negligible.

(2) The evaporation and condensation of void during melting are ignored.

(3) The location and shape of the void cavity are fixed.

To explore the influence of the void cavities on the melting of the composite porous PCM, two different distributions are studied and compared. The Case 1, all void cavities locate the region close to the left hot wall with high temperature, designed based on the Marangoni effect as shown in Fig. 1 (a). The Case 2 is that the void cavities are randomly distributed in the square cavity, which is based on the experimental research [7] composite porous PCM, shown Fig. 1 (b). The volume fractions of the void cavities are 10.0% and 9.9% for the Case 1 and Case 2, respectively, hence the influence of volume fraction of void cavities could be left out.

2.2 Lattice Boltzmann model

To characterize the dynamic melting of composite porous PCM with the void cavities, LBM combined with the enthalpy method is applied in the present study. The porous structure established in Fig. 1 is based on the real porous geometrical features of metal foam. The twodimensional nine-velocity discrete model is applied. Evolution equation for temperature distribution function



Fig 1 Schematic of melting of composite porous PCM in a square cavity (a) Case1 - void cavity close to the hot wall; (b) Case 2 - random distribution of void cavity

including the streaming process and collision process is carried out to simulate the temperature field during melting, as given by

$$g_i(\mathbf{r} + \mathbf{e}_i \delta t, t + \delta t) - g_i(\mathbf{r}, t) = -\frac{1}{\tau} [g_i(\mathbf{r}, t) - g_i^{eq}(\mathbf{r}, t)] + \delta t S_i \quad (1)$$

here, $g(\mathbf{r},t)$ is the temperature distribution function of the lattice at position \mathbf{r} , at time t. The relation of the dimensionless relaxation time τ and the thermal diffusivity α is shown as

$$\alpha = c_s^2 (\tau - 0.5) \delta t \tag{2}$$

S is the local latent heat term, which is calculated by the gradient of liquid fraction (*fl*)

$$S_{i} = -w_{i} \frac{La}{c_{p}} (fl(\mathbf{r}, t) - fl(\mathbf{r} + \mathbf{e}_{i}\delta t, t + \delta t))$$
(3)

The non-equilibrium mirror reflection scheme is used for the thermal boundary conditions of the square container. The harmonic mean of the interfacial thermal diffusion is applied for handling the conjugate heat transfer between the PCMs, metal foams, void cavities and the heated wall.

3. RESULTS AND DISCUSSION

3.1 Model validation

The present LBM is established incrementally to simulate the multiple physical processes of composite porous PCM including the dynamic phase change and the conjugate heat transfer between PCMs, void cavities and metal foams. Considering that there is almost no numerical solutions or experimental results related to these complex processes, the validation of the present LBM consists of two different tests. One is for melting process of pure PCM; the other is for the conjugate heat conduction among PCMs, void cavities and metal foams. The accuracy and facility of the present LBM have been

validated successfully in our previous work [6] by comparing the Nusselt number and dynamic melting interface with the numerical results where Gallium is chosen as the PCM. The detail validation results are not shown here due to the limited space. The other validation test is for the heat conduction of void cavity, metal foam and PCM. The effective thermal conductivity coefficient of composite porous PCM with different volume fraction of void cavities are compared with the public numerical results [8], as presented in Fig. 2. The similar trend of influence of void cavities on effectivity thermal conductivity can be obtained. In addition, the higher effectivity thermal conductivity in the present model can be interpreted by the porosity (0.946) used here is lower than that in the literature (0.949) [8], taking from the experimentally observed by X-ray microcomputed tomography (X-ray CT) of metal foam.



Fig 2 Comparison of effective thermal conductivity with the public numerical results under differetn volume fraction of void cavities

3.2 Influence of void cavities distribution on melting of composite porous PCM

The dimensionless parameters Fourier number *Fo* and Stefan number *Ste* are adopted to describe the transient melting process, as given by:

$$Fo = \frac{\alpha t}{H^2}; Ste = \frac{c_p (T_h - T_m)}{L_a}$$
(4)

Stefan number Ste = 0.099 are kept constant for PCM.

3.2.1 The transient temperature fields and phase fields of composite porous PCMs with void cavities

The effects of different void cavities distribution on the evolutions of temperature fields and phase fields during melting of composite porous PCMs are discussed. As characterized in Fig. 3, dimensionless temperature fields and phase fields with different void cavities

distributions are presented at a certain time, where the void cavities are depicted by grey area and metal foam by dark. Firstly, from the Fig. 3 (a), it is obvious to find that the isothermals are distorted by void cavities during melting of composite porous PCMs, compared with the vertical isothermal lines in the pure PCM melting dominated by heat conduction. Both for random distribution and distribution close to the heated wall, the more homogeneous temperature distribution can be found in the void cavities, where the temperature inside the void cavities is very similar with the temperature at the left-side interfaces of void cavities, as depicted in Fig. 3 (a). The reason for this phenomenon is that although the thermal conductivity (λ) of the void cavity is much lower than that of the PCM, the void cavity with the low heat capacity (ρc) and high thermal diffusion coefficient endow it with the ability to easily increase its own temperature when close to a high-temperature heat source.



Fig 3 Temperature field and phase field during melting with different void caivties distributions

3.2.2 Evolution of heat storage of composite porous PCMs with void cavities

Despite the void cavities possesses a high thermal diffusion coefficient (α) and can rapidly drive the high temperature from the hot-side to the cold-side, less heat energy can be transferred from the void to PCM due to its lower thermal conductivity and lower heat capacity, leading to a lower heat transfer efficiency. To further investigate the influence of void cavities distribution on energy storage performance, a gap factor is defined to indicate the difference of the amount of heat storage

during melting, as described in the Eq. 5. q is heat flux per unit width near the left hot wall, subscript i = 1 and i = 2 represent the Case 1 and Case 2, respectively.

$$q_{i} = \frac{1}{H} \int_{x=0}^{\infty} \lambda_{i} \frac{\partial T_{i}}{\partial x} dy; \quad \eta = \frac{\int q_{1} dt}{\int q_{2} dt}$$
(5)

As evidenced in Fig. 4, the heat storage in Case 1 is always less than that in Case 2, and the difference of the input energy becomes larger with the development of melting process. This result indicates the integral heat energy grows slowly when the voids accumulates together and interrupt the direct contact between the PCM and the heat source, precisely presenting the weaker heat storage capability. For this porous PCM system, the total stored energy during the melting process can be divided into two parts: 1. Energy introduced by the temperature increasing (influenced by the heat capacity of the materials); 2. Latent energy of the PCM. The existence of the voids takes up the volume of the PCM, which certainly decreases the available stored energy of the porous PCM.

In the end, the interesting phenomenon caused by the void cavities which has the weak thermal conductivity while high thermal diffusion coefficient, is the paradox between their rapid "temperature transfer" and low-efficient "heat storage" properties. Its mechanisms cannot be completely disclosed until the influence of the void cavity on the melting process are systematically studied, which may expand a new direction for studying the void cavity effects on the PCM melting.



Fig 4 The evolution of gap factor about the ratio of heat storage of Case 1 to Case 2

4. CONCLUSIONS

A lattice Boltzmann model combined with enthalpy method was successfully established for characterize the liquid-solid phase change with composite porous phase change materials, and the influence of void cavities distribution is documented by comparing the temperature filed, phase field, and heat storage during melting. Results showed that the temperature distributions were significantly adjusted due to the introduction of the voids, which possessed a high thermal diffusion coefficient. However, the heat stored during melting are apparently depressed, due to the low thermal conductivity of the void cavities, influencing the heat flux. This work opens the door of the study on the void effects in porous PCM during the melting process, which may guide the design of the thermal management systems in a fine-grained way.

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REFERENCES

[1] JankowaskiN Nicholas R., McCluskey F. Patrick. A review of phase change materials for vehicle component thermal buffering Appl Energy 2014;113:1525-61.

[2] Yang XH, Bai QS, Zhang QL, Hu WJ, Jin LW, Yan JY. Thermal and economic analysis of charging and discharging characteristics of composite phase change materials for cold storage. Appl Energy 2018;225:585-99.
[3] Mills A, Farid M, Selman JR, Al-Hallaj S. Thermal conductivity enhancement of phase change materials using a graphite matrix. Appl Therm Eng. 2006;26:1652-61.

[4] Archibold AR, Gonzalez-Aguilar J, Rahman MM, Goswam DY, Romero M, Stefanakos EK. The melting process of storage materials with relatively high phase change temperatures in partially filled spherical shells. Appl Energy; 2014;116:243-52.

[5] Assis E, Katsman L, Ziskind G , Letan R. Numerical and experimental study of melting in a spherical shell. Int J Heat Mass Tran; 2007;50:1790-804.

[6] Li XY, Ma T, Liu J, Zhang H, Wang QW. Pore-scale investigation of gravity effects on phase change heat transfer chracteristics using lattice Boltzmann method. Appl Energy 2018;222:92-103.

[7] Yao YP, Wu HY, Liu ZY, Gao ZS. Pore-scale visualization and measurement of paraffin melting in high porosity open-cell copper foam. Int J Therm Sci 2018;123:73-85.
[8] Yao YP, Wu HY, Liu ZY. Pore Scale Investigation of Heat Conduction of High Porosity Open-Cell Metal Foam/Paraffin Composite. J Heat Transfer 2017;139:1-11.