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3D natural convection melting in a cubical cavity with a heat source

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Three-dimensional natural convection melting in a cubical cavity with a local heater has been analyzed numerically. The considered region is an enclosure bounded by two isothermal opposite vertical surfaces of low constant temperature and adiabatic other walls. A heat source of high constant temperature is located on the bottom wall. The governing equations formulated in dimensionless vector potential functions, vorticity vector and temperature with corresponding initial and boundary conditions have been solved using implicit finite difference method of the second-order accuracy. The effects of the Rayleigh number ($5 \cdot 10^4 \le Ra \le 5 \cdot 10^7$) and dimensionless time for Prandtl number ($Pr = 48.36$) and Stefan number ($Ste = 5.53$) on streamlines, isotherms, profiles of temperature and velocity as well as mean Nusselt number at the heat source surface have been analyzed.

1. Introduction

Nowadays, development of modern electronic devices, energy apparatus, and thermal insulation of buildings demands a creation of effective cooling systems [1]. Thereupon, a usage of phase change materials (PCM) for the abovementioned purpose has essential advantages against conventional materials [2]. It should be noted that PCM have large latent heats of fusion at a constant temperature. At the same time, PCM release or gain isothermal energy during phase transitions and have a heat storage capacity about 5–14 times higher than the conventional thermal storage materials. Phase change materials have wide engineering applications including not only electronic cooling technology and thermal comfort in dwellings but also waste heat recovery; textiles; heating, ventilation and air conditioning; and thermal energy storage (containers for temperature sensitive food, isothermal water bottles, medical devices) [2–6]. Analysis of heat transfer processes in PCM is conducted using experimental [7–12] and numerical [12–20] techniques. Thus, Fan et al. [7] have analyzed experimentally the effects of melting temperature and internal fins on flow and heat transfer in phase change material for thermal management of electronics. It has been found, that the use of PCM with a high melting temperature can extend a longer time of protection from overheating. Kandasamy et al. [8,9] have studied an influence of different governing parameters on heat transfer and flow structures in PCM package for thermal management of portable electronic devices. The authors have revealed that an inclusion of PCM in the cavities of the heat sinks can increase the cooling performance in comparison with the cavities without PCM in the case of high input power level. Natural convection melting of PCM in an inclined rectangular enclosure has been investigated by Kamkari et al. [10]. The authors have analyzed thermo-hydrodynamic structures of lauric acid ($Pr \approx 100$) during the melting process under an influence of temperature differences and inclination angle. It has been found, that reduction of an inclination angle from vertical to the horizontal position of the cavity leads to formation of irregular interface shapes and increases the strength of vortices. Sharifi et al. [11] have examined melting of PCM induced by a heated rod within a cylindrical cavity. The authors have shown that for the considered system the strong three-dimensional effects become apparent even at modest inclination angle of the domain of interest. Ben-David et al. [12] experimentally and numerically have studied gallium melting in a rectangular container with a heated side face. Numerical analysis has been conducted using COMSOL Multiphysics software. It has been shown that three-dimensional analysis allows to obtain results with an acceptable fit with experimental data and can be exploited as an effective instrument

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for the prediction of the liquid–solid interface dynamics and melt flow features.

It is worth noting that numerical analysis of PCM melting processes usually is conducted using two-dimensional approach without any local heat sources. For example, Fuentes et al. [13] have proposed a hybrid numerical technique for natural convection melting of PCM in a cavity where lattice Boltzmann method is used for definition of velocity field, while finite difference method is used for solution to the energy equation. The authors have shown an opportunity to use such approach for numerical simulation of melting processes in PCM. Numerical analysis of melting process within a finned rectangular cavity filled with a phase change material has been conducted by Taghilou and Talati [14] using lattice Boltzmann method. The authors have found that natural convection through the fixed solid phase raises the melting rate due to an increasing the heat transfer coefficient. Latent heat thermal energy storage with internal fins and thick walls has been investigated numerically using lattice Boltzmann method by Ren and Chan [15]. It has been shown that using internal fins could enhance the heat transfer process in the PCM cavity while the PCM melting speed increases with the length of the internal fins. El Qarnia et al. [16] have studied numerically 2D melting with natural convection in a rectangular cavity filled with PCM in the presence of discrete heat sources. Computations have been conducted in dimensionless primitive variables using finite volume method. The authors have shown an essential effect of PCM on the cooling capacity of the PCM-based heat sink. Omari et al. [17] have numerically analyzed a passive cooling system using enclosures with different geometries filled with PCM. The authors have used primitive variables and finite volume method for numerical simulation. It has been found that the use of rounded corners has a slight positive effect on the heat transfer efficiency. Three-dimensional MHD solidification from a melt in a cubical cavity has been examined numerically by Bouabdallah and Bessaih [18]. The finite volume method has been used for numerical solution to the formulated governing equations. The authors have found that for high values of the Hartmann number the convective flow is suppressed and the solid-liquid interface becomes regular. Here we would like to note some interesting papers [19,20] on nano-enhanced phase change materials that can be used for an intensification of physical process in different fields of power engineering, electronics and others.

The purpose of the present study is to analyze three-dimensional fluid flow and heat transfer structures during natural convection with melting in a cavity with a local heat source. Calculations have been performed for a cubical enclosure filled with paraffin heated from the local source and cooled from two opposite vertical surfaces while other surfaces are thermally insulated. The present paper is an extension of natural convection melting papers [21,22] to the three-dimensional case. To authors best of knowledge this problem has not been studied before and the reported results are new and original. The main novelty of the present paper is a three dimensional analysis of natural convection melting in cavity with a local heater. Such domain of interest allows to analyze heat transfer in an electronic cabinet with a heater that can be cooled using PCM. Moreover, for 3D numerical analysis an in-house computational code using vector potential functions and vorticity vector components has been developed. Therefore, the present paper demonstrates new features of the numerical technique for simulation of melting in a cubical cavity with a heater. At the same time, the obtained 3D results have been compared with 2D data [21,22]. Such comparison allows to use 2D approach for numerical simulation of the analyzed processes in an appropriate range of the governing parameters.

2. Mathematical formulation

Transient natural convection with melting is analyzed within a cubical cavity of length L in the presence of heat source of constant temperature T_h located on the bottom wall (Fig. 1). At the beginning of the process, the phase change material (paraffin) of the cavity has solid state with a fusion temperature T_m. Two vertical surfaces ($x = 0$ and $x = L$) have low constant temperature $T_c < T_m$. Other surfaces are considered to be adiabatic. The flow is laminar, three-dimensional and time-dependent. The effect of buoyancy force is described by the Boussinesq approximation. The thermophysical properties of the material are constant.

The governing partial differential equations can be written as follows in Cartesian coordinates for the liquid state of material:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\rho_l\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu_l\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\rho_l\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu_l\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\rho_l\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu_l\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g\beta(T-T_m) \tag{4}$$

$$\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}+w\frac{\partial h}{\partial z}=k_l\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

For the solid material we used the transient heat conduction equation in the enthalpy formulation:

$$\frac{\partial h}{\partial t}=k_s\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{6}$$

Here $h=\begin{cases}\rho_s c_s T, & T<T_m,\\ \rho_s c_s T_m+\rho_l c_l(T-T_m), & T\geq T_m\end{cases}$ is the enthalpy; x, y, z are the Cartesian coordinates; t is the time; g is the gravity acceleration; ρ_s and ρ_l are the densities of solid and liquid phases, respectively; μ_l is the dynamic viscosity of liquid phase; β is the thermal expansion coefficient of liquid phase; u, v, w are the

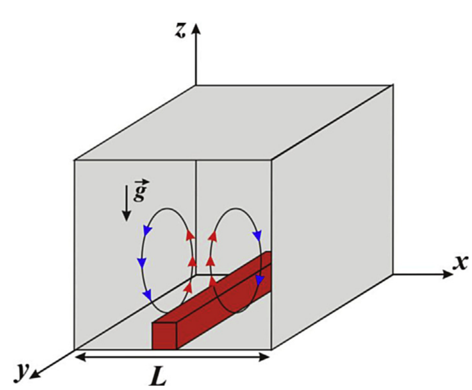

Fig. 1. Schematic diagram of the physical system.