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Effect of inclined magnetic field on natural convection melting in a square cavity with a local heat source

Nadezhda S. Bondareva [a], Mikhail A. Sheremet [a,b,*]

[a] Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 634050 Tomsk, Russia
[b] Department of Nuclear and Thermal Power Plants, Tomsk Polytechnic University, 634050 Tomsk, Russia

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ABSTRACT

MHD natural convection melting in a square cavity with a local heater has been analyzed numerically. The domain of interest is an enclosure bounded by isothermal vertical walls of low constant temperature and adiabatic horizontal walls. A heat source of constant temperature is located on the bottom wall. An inclined uniform magnetic field affects the natural convective heat transfer and fluid flow inside the melt. The governing equations formulated in dimensionless stream function, vorticity 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, Stefan number, Hartmann number, magnetic field inclination angle and dimensionless time on streamlines, isotherms and Nusselt number at the heat source surface have been analyzed.

1. Introduction

Magnetic field plays a significant role for an external thermal control in many industries, associated to liquid metals and high-energy equipment [1,2]. The presence of magnetic field can reduce turbulent flows and fluctuations during the solidification process [3]. Because of strong effect of magnetic field on convective flows and heat transfer it uses in liquid metal blankets, crystal growth and other industries [1–3]. Analysis of MHD convective fluid flow and heat transfer is presented in many papers [4–10]. Thus, Sathiyamoorthy and Chamkha [4] have studied numerically natural convective flow and heat transfer of electrically conducting liquid gallium in a square cavity under the effect of inclined uniform magnetic field. It has been found that the average Nusselt number is a non-linear decreasing function of the Hartmann number regardless of the magnetic field inclination angle. Benos et al. [5] have analyzed steady two-dimensional MHD natural convection of an electrically conducting fluid in a horizontal internally heated shallow cavity. Numerical study has been carried out using a finite volume technique. They found that the fluid is decelerated by the magnetic field leading to the dominance of heat conduction and the heat transfer reduction. MHD natural convective flow and heat transfer in a laterally heated enclosure with a heat-conducting vertical partition on the basis of polynomial differential quadrature method has been investigated by Kahveci and Oztuna [6]. It has been found that the x-directional magnetic field is more effective in suppression of convection than the y-directional magnetic field. Jing et al. [7] have studied MHD natural convection of liquid metal in a cubical cavity using the projection method of second-order accuracy. It has been shown that three-dimensional effects on temperature are much stronger when the cavity walls are heat-conducting compared with the temperature distribution in the case of adiabatic walls. Numerical simulation of steady buoyant flow of liquid LiPb in a cubical cavity under the effect of magnetic field has been carried out by Wang et al. [8] using Fluent software. It has been shown that for high values of Hartmann number the control effects of magnetic field on convective motion become visible and the velocity profiles tend to become uniform. Numerical and experimental analysis of natural convection in a cubical cavity filled with a magnetic fluid under the effect of uniform magnetic field has been carried out by Yamaguchi et al. [9] and Krakov et al. [10]. The obtained results showed that a set of numerous convective structures exists in the cube and stability of these structures depends on the interaction between gravity and Lorentz forces. Bondareva and Sheremet [11] have analyzed laminar natural convection of metal melt ($Pr = 0.02$) in a three-dimensional enclosure under the effect of inclined uniform magnetic field. It has been shown that it is possible to utilize 2D data for an analysis of average Nusselt number when the aspect ratio (A) is grater than unit while the flow configuration in the mid-section of a 3D cavity differs insignificantly only than $A \geq 2$. Selimefendigil et al. [12] have studied natural convective heat transfer of ferrofluid in a partially heated square cavity. It has been

* Corresponding author at: Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 634050 Tomsk, Russia.
E-mail address: Michael-sher@yandex.ru (M.A. Sheremet).

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revealed that velocity profiles are very sensitive to the magnetic dipole source strength and the average heat transfer decreases with the magnetic dipole strength. Now many studies deal with analysis of MHD natural convection in nanofluids [13–15].

Not so many theoretical and even less experimental investigations are dedicated to the problem of natural convection regimes during phase transition under the influence of external magnetic field [16,17]. Thus, Bouabdallah and Bessaih [16] have analyzed the effect of magnetic field on three-dimensional natural convection solidification in a cubical cavity. The finite volume method with enthalpy formulation is utilized to solve the formulated boundary value problem. It has been found a strong dependence between the solid–liquid interface shape and the intensity and orientation of magnetic field. Zaidat et al. [17] have conducted experiments on control of melt convection by a traveling electromagnetic field. Some investigations have been carried out on melting of phase change material in various cavities [18–20] in the absence of magnetic field effects.

The purpose of the present study is to examine the influence of inclined magnetic field on natural convection melting in a cavity with a local heater. Calculations have been performed for a square enclosure filled with pure gallium heated from the local source and cooled from two vertical side walls. The present paper is an extension of natural convection melting without magnetic field [20]. To authors best of knowledge this problem has not been studied before and the reported results are new and original.

2. Mathematical formulation

Consider a square cavity of length L with a square heat source of size$l$having high constant temperature T_h mounted on the bottom wall. At initial time the cavity is filled with a phase change material (pure gallium) in solid state having fusion temperature T_m. Two opposite vertical walls are kept at low constant temperature T_c. Uniform magnetic field affects the natural convective melt flow and heat transfer under the inclination angle α. The schematic diagram of the physical system with temperature boundary conditions is presented in Fig. 1.

The flow is assumed to be laminar, two-dimensional and time-dependent. The buoyancy force is defined by the Boussinesq approximation. The thermophysical properties of the material are constant. Viscous dissipation and pressure work are neglected. Under the abovementioned assumptions the governing equations can be written as follows in Cartesian coordinates for the liquid state of material:

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

$$\rho_l\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu_l\nabla^2 u + \left(\bar{j}\times\bar{B}\right)_x \tag{2}$$

$$\rho_l\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu_l\nabla^2 v + \left(\bar{j}\times\bar{B}\right)_y + \rho g\beta\left(T - T_m\right) \tag{3}$$

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = k_l\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

For the solid state of analyzed material we utilized the heat conduction equation in following form

$$\frac{\partial h}{\partial t} = k_s\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{5}$$

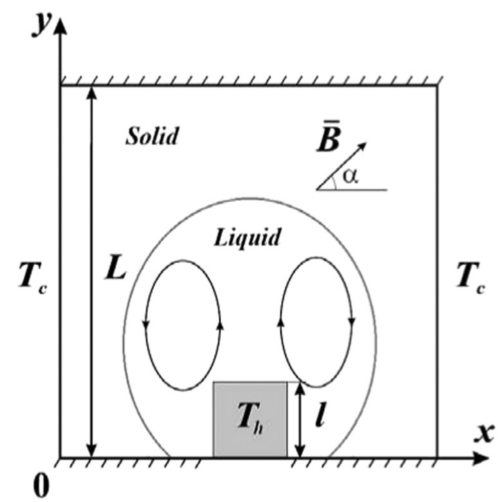

Fig. 1. Schematic diagram of the physical system.

Here $h = \begin{cases} \rho_s c_s T, & T < T_m, \\ \rho_s c_s T_m + \rho_l L_m + \rho_l c_l (T - T_m), & T \geq T_m \end{cases}$ is the enthalpy; x, y 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 are the velocity components in x- and y-directions, respectively; p is the pressure; $\bar{j} = \sigma\left(\bar{V}\times\bar{B}\right)$ is the current density; $\bar{V}$ is the velocity; $\bar{B}$ is the magnetic field intensity; σ is the electrical conductivity; T is the temperature; T_h is the heat source temperature; T_m is the melting temperature; k_s and k_l are the thermal conductivities of solid and liquid phases, respectively; L_m is the latent heat; c_s and c_l are the specific heats of solid and liquid phases, respectively.

To associate the both energy equations for solid and liquid phases and to remove the jumps of enthalpy function on the phase transition line the following smoothing function was introduced:

$$\varphi = \begin{cases} 0, & T < T_m - \eta \\ \dfrac{T - \left(T_m - \eta\right)}{2\eta}, & T_m - \eta \leq T \leq T_m + \eta \\ 1, & T > T_m + \eta \end{cases} \tag{6}$$

The formulated dimensional partial differential Eqs. (1)–(5) have been written in non-dimensional form using the following dimensionless variables

$$X = x/L,\ Y = y/L,\ U = u/\sqrt{g\beta\left(T_h - T_m\right)L},\ V = v/\sqrt{g\beta\left(T_h - T_m\right)L},\ \tau = t\sqrt{g\beta\left(T_h - T_m\right)/L},\ \Theta = \left(T - T_m\right)/\left(T_h - T_m\right)$$

and new dependent dimensionless functions such as stream function $\Psi\left(U = \frac{\partial\Psi}{\partial Y},\ V = -\frac{\partial\Psi}{\partial X}\right)$ and vorticity $\Omega = \frac{\partial V}{\partial X} - \frac{\partial U}{\partial Y}$. Therefore the governing Eqs. (1)–(5) using the abovementioned variables can be written as follows

$$\frac{\partial^2\Psi}{\partial X^2} + \frac{\partial^2\Psi}{\partial Y^2} = -\Omega \tag{7}$$