EFFECT OF A MAGNETIC FIELD ON HEAT TRANSFER IN PHASE-CHANGE-MATERIAL-BASED THERMAL STORAGE DEVICE

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***Abstract:** To improve the efficiency of PCM-based thermal storage devices, various techniques are being used, such as, use of fins, use of multiple PCMs, use of heat pipes, and enhancing the thermal conductivity by adding nano-particles. In this work, 2D unsteady numerical simulations, using ANSYS-Fluent with the enthalpy-porosity formulation, are performed to study an effect of a uniform transverse magnetic field on heat transfer inside a cavity filled initially with a solid gallium. The horizontal walls of the cavity are considered insulated and vertical walls are, respectively, considered hot and cold. The magnetic field is characterized by the Hartmann number (Ha) and the results are shown for the Ha = 0, 30 and 50. It is observed that, with the increase in the transverse uniform magnetic field, the rate of melting of gallium and the heat transfer rate decreases.*

Index Terms* — *Magneto-hydrodynamics, PCM-based thermal energy storage devices, CFD simulations

I. INTRODUCTION

Thermal heat storage devices are frequently used to store and deliver energy for heat and power applications [1,2]. In these devices, thermal energy is stored as a latent or sensible heat. Among them, latent-heat based storage devices found to have higher heat transfer efficiency (storage capacity of PCM ranges from 50 to 150 kWh/t with the efficiency between 75-90%) [3]. This is achieved by the use of phase-change materials (PCMs), for example: gallium, sodium nitrate, potassium nitrate, etc. However, the heat transfer efficiency is less for the low thermal conductivity PCMs [3]. Therefore, it is necessary to improve the heat transfer performance, when low conductivity PCM is used, by using intrusive or non-intrusive means.

It is well-known that the efficiency can also be increased by enhancing the convection and rate of solidification and melting [4]. Magnetic fields have been found to have an effect on the fluid flow behavior and, therefore, on the heat transfer [5, 6]. However, to improve the efficiency of PCM-based thermal storage devices, current trend is to use various techniques, such as, fins [3, 7], multiple PCMs [3, 8, 9], heat pipes [3, 10], and addition of nano-particles [3, 11].

In PCM-based thermal storage device, during solidification and melting, steep gradients may occur near the interface also the dimensions could be so small that experimental method hardy provide accurate interface location and information of other flow variables. To understand the physics involving moving boundary phenomena, therefore, numerical methods play very important role to save time and cost for the problems.

In this work, a multi-scale model is developed using commercial software, ANSYS-FLUENT. A 2D unsteady numerical simulation, with the enthalpy-porosity formulation, is performed to study an effect of a uniform transverse magnetic field on heat transfer inside a cavity filled initially with solid gallium (PCM) to study possible heat transfer enhancement using externally applied magnetic field.

II. NUMERICAL METHODOLOGY

2.1 Problem and boundary conditions

A square cavity (i.e., aspect ratio unity), having length, L_x and height, L_y of 63.5mm each, is as shown in Figure 1. The left and right walls are maintained at isothermal temperature of 311.15K and 301.15K, respectively, whereas top and bottom walls are insulated. Figure 1 show a two-dimensional square cavity filled with solid gallium with fusion temperature 302.85K. The fluid flow inside the cavity is assumed as laminar throughout the simulation. In the current problem gravity force along with Lorentz force (due to the external magnetic field), is considered. Uniform magnetic field with varying strength (as characterized by the Hartmann numbers) has been applied normal to the right wall as shown in the figure. The magnetic field produced by the movement of liquid gallium has been assumed to be negligible as compared to externally applied magnetic field. The flow properties, except density, are assumed to be constants, as the maximum temperature difference (i.e., 10) is very small.

2.2 Governing equations

The governing equations of continuity, momentum and energy conservation are solved numerically by ANSYS-FLUENT software. The equations are:

1. Continuity equation $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$
2. Momentum in x-direction: $\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + S(T)u$

   Momentum in y-direction: $\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + g\beta(T_l - T_f) + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \left(\sigma {B_0}^2\right)v + S(T)v$ where $S(T) = A_{mush}\,(1-\gamma)^2/(\gamma^3 + \in)$, $A_{mush} = 10^5$, $\in$ is a small number (0.001), $\rho = \rho_{ref}[1 - \beta(T - T_{ref})]$, liquid fraction $\gamma = 0$, if $T < T_{solidus}$, $\gamma = 1$, if $T > T_{liquidus}$ and $\gamma = (T - T_{solidus})/(T_{liquidus} - T_{solidus})$.
3. Energy equations: $\frac{\partial H}{\partial t} + u\frac{\partial H}{\partial x} + v\frac{\partial H}{\partial y} = \frac{k}{\rho C_p}\left(\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2}\right)$ where $H = h + \Delta H$, and $h = h_{ref} + \int_{T_{ref}}^{T} C_P T$.

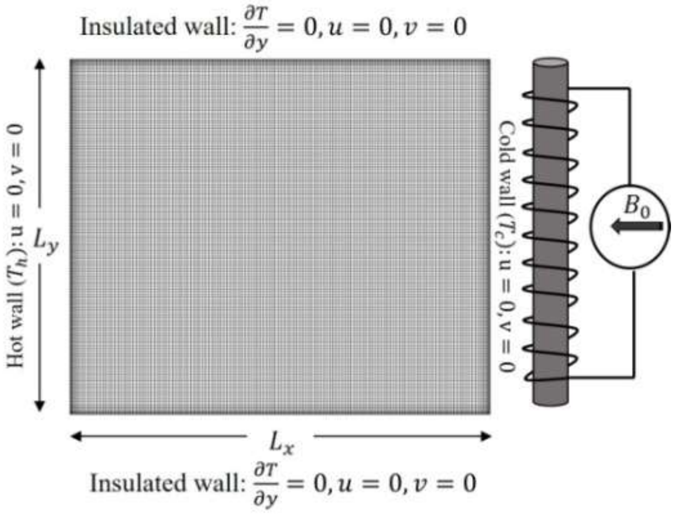


FIGURE 1. Computational domain with grid and boundary conditions.

Table 2.1: Thermo-physical properties of pure gallium [6, 12]

Prandtl number (P_r)	0.0216	Fluid dynamic viscosity (μ)	0.00181 $kg/\,m-s$
Stefan number (S_{te})	0.039	Fluid kinematic viscosity (ν)	1.375 × 10^{-7} m^2/s
Rayleigh number (R_a)	6× 10^5	Thermal diffusivity (α)	1.375× 10^{-5} m^2/s
Density (ρ)	6322 – 0.678 T kg/m^3	Electrical conductivity (σ)	7.1× 10^6 S/m
Thermal conductivity (K)	32 $W/\,m-K$	Magnetic permeability of free space (μ_0)	1.257× 10^{-6}
Latent heat of fusion (h_f)	80160 J/kg	Solidus temperature	302.85 K
Specific heat (Cp)	381.5 $J/kg\ K$	Liquidus temperature	302.85 K

The governing equations are solved by the SIMPLE method and the discretization scheme used to discretize momentum and energy conservation equations is the second-order upwind, and for the pressure is PRESTO!. The convergence criterion for the energy, momentum and continuity, respectively, is 10^{-6}, 10^{-4} and 10^{-4}. The thermo-physical properties of pure gallium used in the numerical simulation are presented in Table 2.1. It is noted that, in case of pure metal (for example, pure gallium), the solidus and liquidus temperature are same and are taken as the fusion temperature of the pure liquid gallium. The dimensionless parameters are defined as: the Rayleigh number: $R_a = \left(\rho^2 C_p\ g\beta L_y^3\right)/(\mu k)$; the Stefan number: $St_e = \left(C_p(T_h - T_c)\right)/\left(h_f\right)$; the Prandtl number: $P_r = \left(\mu C_p\right)/(k)$; the Hartmann number: $Ha = B_0 L_y\sqrt{\sigma/\rho\nu}$, the Fourier number, $Fo = \alpha t/L_y^2$, a dimensionless time, $\tau = St_e \times Fo$, the Nusselt number, $(Nu)_{avg} = (q' \cdot \Delta Y)/(\Delta T \cdot k)$ and a melting rate = $\left(X_{avg}^{t_{n+1}} - X_{avg}^{t_n}\right)/\Delta t$.

III. RESULTS AND DISCUSSIONS

A numerical simulations on a computational domain of 63.5mm × 63.5mm, with grids generated using ICEM-CFD, are perform using the enthalpy-porosity formulations as described in the previous section. The problem of melting of pure gallium is considered and grid size of 150 ×150= 22500 cells and time-step of 0.1 is used, which is also found to be optimum grid-size by [6]. The effect of uniform magnetic field is characterized by the Hartmann number (Ha) of 0, 30 and 50. The results are plotted at various non-dimensional time (τ) and Ha = $\{0, 30, 50\}$ in terms of contours of liquid fraction and temperature. Finally, a comparison between the average Nusselt numbers (at the hot wall) and melting rate at various Hartmann number are studied.

Figure 2 shows results of validation study has been performed comparing the present data with [6] at Ha = 0. The study showed a reasonably good match with the experimental data. The discrepancy, between the present data and the data of [6], at larger times may be due to the three-dimensional nature of the problem [12].

Figure 3 shows the contours of liquid mass fraction at various Hartmann numbers at fixed non-dimensional steady-state time (τ) of 0.08. It can be seen that the movement of melting-front of gallium, inside a computational domain, is slow at higher Ha for the fixed flow-time. It is, therefore, can be concluded that the effect of natural convection near the interface is getting reduced.

Figure 4 shows the contours of temperature at various Hartmann numbers at fixed non-dimensional steady-state time of 0.08. It can be seen from the figure that, at smaller Hartmann numbers the temperature contours are wavy indicating the additional change in the direction of temperature gradient. This, further, indicates the presence of conduction in the region close to the interface. It is sufficient, therefore, to conclude that the natural convection is dominance at lower Ha numbers.

It was observed from the Figures 3 and 4 that the dominance convection activity gets reduced at higher Ha numbers. To further clarify this, therefore, Figure 5(a) shows the melting rate and Figures 5(b-c) show the average Nusselt number (at the hot wall), respectively, as a function of τ and Ha. It can be seen in Figure 5 that the melting rate as well as the average Nusselt number decreases with increase in Ha numbers.

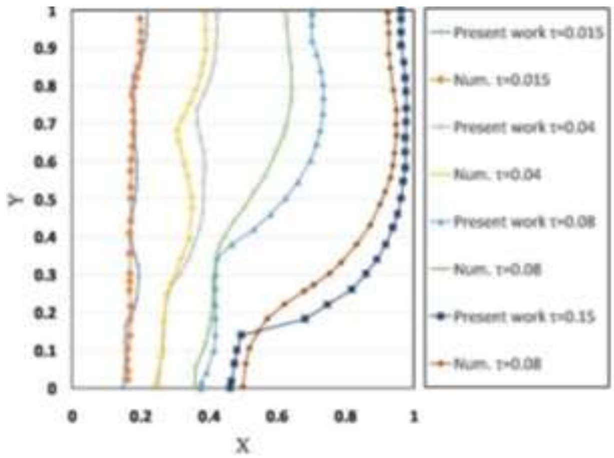


FIGURE 2. Results of validation study at Ha = 0 (comparison with the data of [6]).

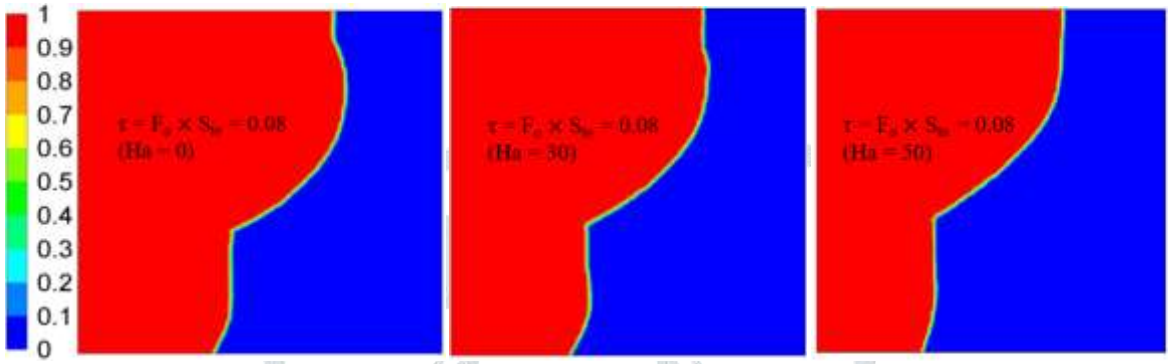


FIGURE 3. Contours of liquid mass fraction at various Hartmann number, Ha $=\{0, 30, 50\}$ at fixed dimensionless steady-state time.

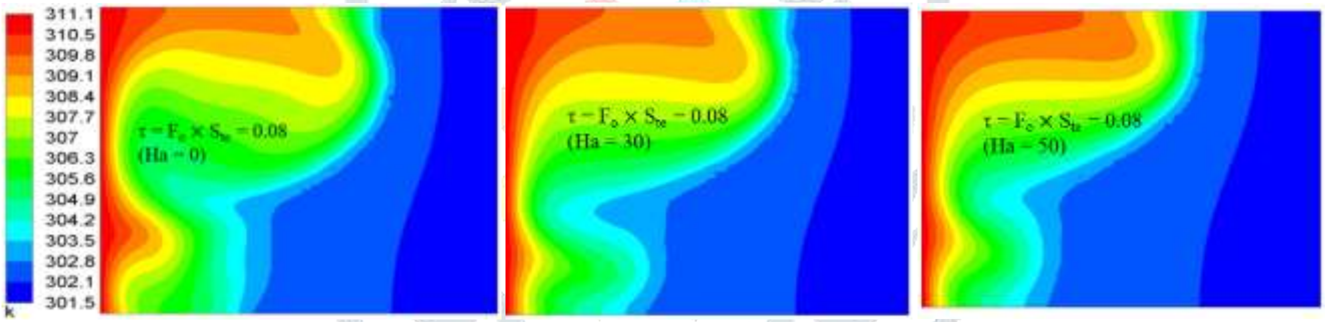
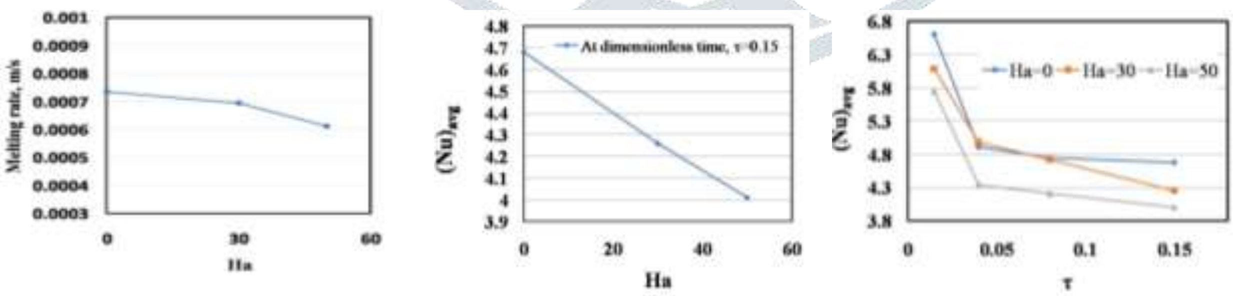


FIGURE 4. Contours of temperature at various Hartmann number, Ha $=\{0, 30, 50\}$ at fixed dimensionless steady-state time.



(a) (b) (c)

FIGURE 5. (a) Melting rate as a function of Ha (b) Average Nusselt number as a function of τ at various Ha (c) Average Nusselt number as a function of Ha.

IV. CONCLUSIONS

The 2D unsteady numerical simulations of melting, using ANSYS-Fluent with the enthalpy-porosity formulation, are performed to study an effect of a uniform transverse magnetic field on heat transfer inside a cavity filled initially with solid gallium. The horizontal walls of the square cavity are considered insulated and vertical walls are, respectively, considered hot and cold. The magnetic field is characterized by the Hartmann number (Ha) and the results, in terms of the contours of liquid fraction and temperature and melting rate and the averaged Nusselt number, are shown for the Ha = 0, 30 and 50. It is observed that, with the increase in the transverse uniform magnetic field, the dominance of the convection decreases. Therefore, the rate of melting of gallium and the heat transfer rate decreases. This indicates that there is no improvement in heat transfer, of PCMs, is possible with the use of external magnetic field. However, in future, the effect of uniform and non-uniform longitudinal magnetic field should be studied for the generalization of the results.

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