International Journal of Heat and Mass Transfer 108 (2017) 1057–1067

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Natural convection heat transfer combined with melting process in a cubical cavity under the effects of uniform inclined magnetic field and 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

ARTICLE INFO

Article history:
Received 24 September 2016
Received in revised form 25 December 2016
Accepted 29 December 2016

Keywords:
Melting
Natural convection
Uniform magnetic field
Cubical cavity
Heat source
Vector potential functions
Numerical results

ABSTRACT

Natural convective heat transfer combined with melting in a cubical cavity filled with a pure gallium under the effects of inclined uniform magnetic field and local heater has been studied numerically. The domain of interest is an enclosure bounded by two isothermal opposite vertical surfaces of low constant temperature and adiabatic other walls. A heat source of constant temperature is located on the bottom wall. An inclined uniform magnetic field affects the melting process inside the cavity. 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 Hartmann number, magnetic field inclination angle and dimensionless time on streamlines, isotherms, profiles of temperature and velocity as well as mean Nusselt number at the heat source surface have been analyzed. The obtained results revealed that a growth of magnetic field intensity reflects the convective flow suppression and heat transfer rate reduction. High values of Hartmann number homogenize the liquid flow and heat transfer inside the melting zone.

1. Introduction

Magnetic fields are utilized in industry for control different processes including food processing, crystal growth, chemical reactions and also magnetoconvective flows are developed in different applications in geophysics and astrophysics [1–8]. Nowadays, analysis of magnetohydrodynamic processes is carried out using experimental techniques [9–14] and theoretical methods [13–21]. Thus, Bednarz et al. [10] have experimentally studied natural convection of a paramagnetic fluid in a cubical cavity under the effects of horizontal magnetic field and Rayleigh–Benard configuration. It has been found that the gravitational effects associated with the temperature difference become less important when the magnetic field strength increases. Minohara et al. [11] have investigated the melting transition of Ga and In using a high resolution nW-DSC working in a magnetic bore. The authors have revealed that the melting temperatures of Ga and In with the magnetic field of 5 T were 8.3 ± 1.7 and 10.2 ± 1.5 m K, respectively higher than those without the magnetic field, illustrating that the solid phase to be relatively more stable under the magnetic field. Experimental analysis of hydrodynamics and heat transfer for a mercury in a vertical round tube under the effects of transverse magnetic field with non-uniform heat flux has been carried out by Melnikov et al. [12]. The authors have shown that the development of secondary flows in the presence of magnetic field induces low-frequency fluctuations of abnormally high peak-to-peak values, which pose hazard to heat exchanger structures. Wrobel et al. [13] have examined experimentally and numerically a thermo-magnetic convective flow of paramagnetic fluid in an annular cavity with a cylindrical copper rod core and a cylindrical outer wall. Numerically the considered problem has been analyzed using Fluent software. It has been found that a strong magnetic field can control the magnetic convection of paramagnetic fluid. Variations of direction and strength of the magnetic field can lead to the enhancement or suppression of convective heat transfer inside the region. Dadzis et al. [14] have studied experimentally and numerically directional solidification and melting processes utilizing pure gallium. Numerical simulation of unsteady 3D melt flow and heat transfer has been conducted on the basis of finite volume package OpenFOAM. It has been revealed that a weak

* 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).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.108
0017-9310/

Nomenclature

Roman letters

$\bar{B}$	magnetic field intensity
c	specific heat
$\bar{F} = (\bar{j} \times \bar{B})$	Lorentz force
g	gravitational acceleration
h	enthalpy
Ha	Hartmann number
$\bar{j} = \sigma(\bar{V} \times \bar{B})$	current density
k	thermal conductivity
L	length of the cavity
L_m	latent heat
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	dimensional pressure
Pr	Prandtl number
Ra	Rayleigh number
Ste	Stephan number
T	dimensional temperature
t	dimensional time
T_c	low constant temperature
T_h	heat source temperature
T_m	melting temperature
u, v, w	dimensional velocity components
U, V, W	dimensionless velocity components
$\bar{V}$	velocity vector
x, y, z	dimensional Cartesian coordinates
X, Y, Z	dimensionless Cartesian coordinates

Greek symbols

α	inclination angle of the magnetic field
β	melt thermal expansion coefficient
γ	inclination angle of the magnetic field
η	part of the smoothing function domain
Θ	dimensionless temperature
μ	dynamic viscosity
$\xi(\varphi), \zeta(\varphi)$	additional functions
ρ	density
σ	electrical conductivity
τ	dimensionless time
φ	smoothing function
Ψ_x, Ψ_y, Ψ_z	dimensionless vector potential functions
$\Omega_x, \Omega_y, \Omega_z$	dimensionless vorticity vector components

Subscripts

c	cold
h	hot
m	melt
max	maximum value
mean	mean value
min	minimum value
s	solid material

toroidal melt flow of low velocity leads to significant changes of the local melting rate and consequently a deformation of the phase interface. At the same time, the interface shape may exhibit local deflections in the corners of the cavity. Bouabdallah and Bessaih [15] have numerically investigated three-dimensional MHD fluid flow and heat transfer during solidification from a melt in a cubical cavity. The finite volume method with enthalpy formulation has been used for numerical simulation. The obtained results have shown a strong dependence between the interface shape, intensity and orientation of magnetic field. Three-dimensional natural convection of different fluids such as mercury, air and dielectric liquid in a cubical cavity induced by a thermally active plate in the presence of external magnetic field has been numerically examined by Purusothaman et al. [16] using finite volume method with uniform staggered grid. It has been shown that an increase in Hartmann number leads to suppression of convective heat transfer by the Lorentz force and the heat transfer within the cavity occurs due to heat conduction. Benos et al. [17] have analytically and numerically studied two-dimensional MHD natural convection in an internally heated horizontal shallow cavity under the effect of uniform vertical magnetic field. Analytically solution has been obtained using the matched asymptotic expansions and numerically the authors have used OpenFOAM computational software. The authors have demonstrated that the fluid is decelerated by the magnetic field leading to the dominance of the heat conduction and to reduced heat transfer rate. The analysis of distributions of magnetic force, flow field and Joule heat in the melt under the pulsed magnetic field has been carried out by Ma et al. [18] using finite element software Flotran. It has been revealed that the magnetic pressure force increases to the peak value with the growth of the pulsed magnetic field. At the same time, the magnetic pressure force appears in the inner of the melt, while magnetic pull force appears in the exterior of the melt. Feng et al. [19] using the lattice Boltzmann method have numerically investigated the effect of magnetic field on melting of solid gallium in a bottom heated rectangular cavity. The obtained results have shown that at low Hartmann number the melting characteristics are similar to those for the horizontally applied magnetic field, while for a high Hartmann number the flow retardation effect caused by the vertically applied magnetic field is more essential in the earlier stage of the melting process and less in the later stage. MHD boundary-layer free convection of an electrically conducting fluid arising from melting of a semi-infinite solid substrate has been analyzed numerically by Soni and Premnath [20] using a similarity transformation and an implicit Keller-box method. It has been found that the Prandtl and Lykoudis numbers are the most important parameters in influencing the free convective heat transfer, melting rate, the thickness of velocity and thermal boundary layers.

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 under the effect of uniform inclined magnetic field. It should be noted that the present analysis has an essential applications in industry and technology. The externally imposed magnetic field is a widespread opportunity, for example, to control the melt flow during the crystal growth process or it is used in the magnetic refrigerator, in water treatment device, in corrosion inhibition treatment, in magneto hydrodynamics (MHD) power generation and in plasma techniques [22–24]. The main objective of the electromagnetic control is to stabilize the liquid flow and to suppress the oscillatory instabilities inside the liquid (melt). The convection of electrically conducting liquids such as liquid metal in presence of a magnetic field is practically useful and interesting topic due to its direct application to various physical phenomena as well as to crystal growth processes [22–24]. The electrically conducting fluid motion is suppressed by the magnetic field is a well-known phenomenon. During manufacturing of the crystals, intensive convective flows can be essentially suppressed in melts by applying an external