International Journal of Heat and Fluid Flow 32 (2011) 932–942

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Numerical study on magneto-convection of cold water in an open cavity with variable fluid properties

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ARTICLE INFO

Article history:
Received 26 March 2011
Received in revised form 8 July 2011
Accepted 12 July 2011
Available online 6 August 2011

Keywords:
Convection
Open cavity
Density maximum
Magnetic field
Surface tension

ABSTRACT

The aim of the present study is to understand the problem of buoyancy and thermocapillary induced convection of cold water near its density maximum in an open cavity with temperature dependent properties in the presence of uniform external magnetic field. The governing equations are solved by the finite volume method. The results are discussed for various values of reference temperature parameter, density inversion parameter, Rayleigh, Hartmann and Marangoni numbers. It is observed that the temperature of maximum density leaves strong effects on fluid flow and heat transfer due to the formation of bi-cellular structure. Convection heat transfer is enhanced by thermocapillary force when buoyancy force is weakened.

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1. Introduction

Convective heat transfer of cold water near its density maximum region occurs commonly in our environment and in many engineering and technical process. Convective flow and heat transfer of water around its density maximum is complicated (Joshi and Gebhart, 1984; Lin and Nansteel, 1987). An experimental and theoretical investigation of transient natural convective heat transfer to water near its maximum density in a rectangular cavity is reported by Braga and Viskanta (1992). They demonstrated that the density inversion of water has a great influence on the natural convection in the cavity. Wei and Koster (1994) numerically investigated transient natural convection in a water layer subjected to density inversion. They found that the temperature difference, which determines the position of the maximum density plane in the water layer, can alter flow field and heat transfer substantially. The significant effect of aspect ratio on transient natural convection is also investigated. The heat transfer is maximized in a square enclosure and is less at other aspect ratios. The effect of the aspect ratio on natural convection of water subject to density inversion has been investigated by Tong (1999). He found that the transport across a vertical wall diminishes for small aspect ratio due to the decrease of the effective buoyancy force as well as heat transfer decreases for a large aspect ratio due to the enhanced shear stress effect.

Ishikawa et al. (2000) numerically investigated the natural convection with density inversion in a two-dimensional square cavity with variable fluid properties. They chose the cavity size from 1 cm to 10 cm for different hot wall temperature. Ho and Tu (2001) investigated numerically and experimentally the natural convection of water near its maximum density in a differentially heated rectangular enclosure. They found that the periodic traveling wave motion of the maximum density contour of water in the temperature visualization experiment. Three dimensional natural convection of water with variable physical properties is investigated by Moraga and Vega (2004). Hossain and Rees (2005) studied unsteady laminar natural convection flow of water subject to density inversion in a rectangular cavity with internal heat generation. They found that the flow and temperature fields depend very strongly on the internal heat generation parameter and mean temperature of solid walls. Sivasankaran and Ho (2008a) studied the effect of temperature dependent fluid properties on natural convection of water around density maximum region in the rectangular enclosure. They found that the average Nusselt number for considering variable viscosity are higher than the value of average Nusselt number for considering both variable viscosity and thermal conductivity. They also investigated the similar problem in the presence of magnetic field (Sivasankaran and Ho, 2008b). Varol et al. (2010) investigated numerically the natural convection heat transfer of cold water near 4 °C in a thick bottom walled

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doi:10.1016/j.ijheatfluidflow.2011.07.004

Nomenclature

$\boldsymbol{B}$	uniform magnetic field
B_0	magnetic induction (T)
c_p	specific heat (J/kg K)
$\boldsymbol{F}$	electromagnetic force
$\boldsymbol{g}$	acceleration due to gravity (m/s^2)
Ha	Hartmann number
$\boldsymbol{J}$	electric current
k	thermal conductivity (W/m K)
k^*	dimensionless thermal conductivity
L	height of the cavity (m)
Ma	Marangoni number
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
p	pressure (Pa)
Ra	Rayleigh number
T	dimensionless temperature
T_m	dimensionless density inversion parameter
t	time (s)
u, v	velocity components (m/s)
U, V	dimensionless velocity components
x, y	cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity (m^2/s)
β	volumetric coefficient of thermal expansion (K^{-1})
ε	reference temperature parameter
θ	temperature (K)
θ_m	temperature at density maximum (K)
θ_r	temperature at reference state (K)
Φ	electric potential
μ	viscosity (N s/m^2)
μ^*	dimensionless viscosity
ρ	density (kg/m^3)
σ	surface tension
σ_e	electrical conductivity (S/m)
τ	dimensionless time
ψ	stream function (m^2/s)
Ψ	dimensionless stream function
ω	vorticity (1/s)
Ω	dimensionless vorticity

Subscripts

c	cold wall
h	hot wall
r	reference state

cavity filled with a porous medium. The obtained results show that multiple circulation cells are formed in the cavity and the local Nusselt numbers at the bottom wall and solid–fluid interface are highly affected by formed cells.

The importance of Marangoni effects on the buoyancy driven convective flows has been investigated by several researchers due to wide applications such as crystal growth, ice making, glass manufacturing, welding, metallurgy, chemical processing. Behnia et al. (1995) studied the problem of combined buoyancy and thermocapillary convection in an enclosure. They found that there is a strong thermal boundary layer located near to the upper-right corner due to the effect of thermocapillary convection in the vicinity of the free surface. Combined buoyancy and thermocapillary convection in open cavities was investigated by Chippada et al. (1995). They found that Marangoni convection causes very high velocities near the free surface. Thermocapillary convection in an open cavity in the presence of a magnetic field is studied by Rudraiah et al. (1995). They found that the average Nusselt number increases with Marangoni number. Thermocapillary- and buoyancy-driven convection in open cavity with differentially heated end walls was investigated by Lu and Zhuang (1998). They found that the thermocapillary force could have a quite significant effect on the stability of a primarily buoyancy-driven flow. Thermosolutal convection flow under surface tension and buoyancy effects was studied by Jue (1999). He found that the surface tension induced flow changes the flow evolution and influences the heat and mass transfer rates near the area of free surface locally. Combined thermocapillary-buoyancy convection had been investigated numerically in an extended cavity with differently heated walls by Shevtsova et al. (2003). They found that the steady (bicellular or multi-cellular) flow gives rise to the oscillatory flow with increasing Marangoni number.

Hossain et al. (2005) numerically investigated the buoyancy and thermocapillary driven convection flow of electrically conducting fluid in an enclosure. They studied the effect of direction of the external magnetic field and internal heat generation also. They found that increasing the value of heat generation parameter causes for development of more cells in the cavity. Grosan et al. (2009) made a numerical investigation on the magneto-convection in a rectangular cavity filled with a fluid-saturated porous medium and with internal heat generation. They found that the convection modes within the cavity depend upon both the strength and the inclination of the magnetic field. The effect of double-diffusive natural convection of water in a partially heated enclosure with Soret and Dufour coefficients around the density maximum is studied numerically by Nithyadevi and Yang (2009). They found that the rate of heat and mass transfer increases when the values of thermal Rayleigh number increase in all heating locations. The effect of magnetic fields in different direction on the instability of thermocapillary convection in a rectangular cavity with differentially heated side walls filled with two viscous fluids is investigated by Zhou and Huang (2010). The time-periodic conjugate convection in an inclined enclosure with conductive bounding walls is investigated by Zhang et al. (2011) a high accuracy multi-domain temporal–spatial pseudospectral method. They found that the total heat transfer rate is dependent on the amplitude and period of the pulsating sidewall temperature. Sankar et al. (2011) studied the effect of magnetic field on the combined buoyancy and surface tension driven convection in a cylindrical annular enclosure. They found that the surface tension effect is predominant in shallow cavities compared to the square and tall annulus.

It is observed from the most of the studies available in the literature that convection in open cavities with temperature dependence of the physical properties of the fluid is not studied so far. Recently, Sivasankaran and Ho (2010) investigated buoyancy and thermocapillary induced natural convection of cold water near its density maximum temperature in an open cavity. The present study examines the influence of temperature dependent properties of the water near its density maximum on magneto-convection in an open cavity.

2. Mathematical formulation

Consider a two-dimensional square cavity of height L filled with water as shown in Fig. 1a. The vertical isothermal sidewalls of the cavity are maintained at different temperatures θ_h and θ_c, where

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