International Journal of Heat and Mass Transfer 114 (2017) 1086–1097

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of uniform inclined magnetic field on mixed convection in a lid-driven cavity having a horizontal porous layer saturated with a ferrofluid

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ARTICLE INFO

Article history:
Received 2 May 2017
Received in revised form 26 June 2017
Accepted 1 July 2017

Keywords:
Uniform inclined magnetic field
Mixed convection
Horizonal porous layer
Lid-driven cavity
Ferrofluid
Numerical results

ABSTRACT

MHD mixed convection in a lid-driven cavity with partially filled with a porous medium saturated with a ferrofluid has been analyzed numerically. The domain of interest consists of a bottom porous layer and a nanofluid layer over the porous one with a heated motionless bottom wall and cooled upper moved wall. The governing partial differential equations formulated on the basis of a single-phase model for nanofluid, Brinkman-extended Darcy model for porous layer and Boussinesq approximation for buoyancy force have been solved by finite difference method of the second-order accuracy. Analysis has been carried out for a wide range of Hartmann number, magnetic field inclination angle, Darcy number, porous layer height, and nanoparticles volume fraction. It has been revealed that average Nusselt number is a non-monotonic function of Darcy number and porous layer height, while a growth of Hartmann number illustrates the heat transfer rate reduction.

1. Introduction

The porous media filled systems can be seen in different engineering applications such as heat exchangers, building design, solar collectors, insulation materials or soil sourced heat pump systems [1–3]. In these systems, combined convection, namely, natural and forced convection are occurred in the same time. Both porous media and magnetic field are good control parameters for heat and fluid flow in engineering applications.

Selimefendigil et al. [4] performed a work on combined convection in superposed nanofluid and porous layers in an enclosure in the presence of inner rotating cylinder. They observed that the heat transfer enhances almost linearly with nanoparticle volume fraction for different cylinder sizes and adding solid nanoparticles to the base fluid is favorable for the locations for high values of local Nusselt number. Roy et al. [5] analyzed the fluid and heat flow in entrapped porous triangular cavities for different thermal boundary conditions such as hot horizontal walls and cold inclined walls or cold horizontal walls and hot inclined walls by using finite element technique. They observed that the average heat transfer rates are almost constant with Reynolds and Darcy numbers. Mojumder et al. [6] made a computational analysis on mixed convection heat transfer in a porous media filled L-shaped cavity. Ismael and Chamkha [7] numerically studied laminar natural convection inside a square cavity including a solid wall, a porous layer, and a nanofluid layer. Chamkha and Al-Naser [8] analyzed double-diffusive convective flow of a binary gas mixture in an inclined rectangular enclosure filled with a uniform porous medium. In this study, the thermal and the compositional buoyancy forces are assumed to be opposite. Chamkha [9] extended the previous paper [8] to the case of heat generation or absorption effects under the cooperating influence of temperature and concentration gradients. Chamkha [10] performed investigation of free convection boundary-layer flow over an isothermal inclined plate embedded in a thermally stratified porous medium in the presence of a non-uniform transverse magnetic field. He found that the skin-friction coefficient and local Nusselt number is an increasing function of the Hartmann number. Roy et al. [11] used the finite element simulation of the combined convection in porous square cavities for Darcy–Brink man–Forchheimer model and they obsersed that the strengths of fluid and heat circulation cells are less at $Re = 100$ compared to $Re = 10$ for all the cases due to weak buoyancy force at the high Reynolds number. Aleshkova and Sheremet [12] numerically studied natural convection heat transfer in a Darcy–Brinkman porous cavity bounded by heat-conducting solid walls with a local heater. It was found that for constant Darcy number an increase in the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.07.001
0017-9310/

Nomenclature

Roman letters

$\overline{B}$	uniform magnetic field
B_0	magnitude of uniform magnetic field
c_p	specific heat at constant pressure
Da	Darcy number
$\overline{F}$	electromagnetic force
$\mathbf{g}$	gravitational acceleration vector
Ha	Hartmann number
Gr	Grashof number
h	height of the porous layer
$H_1(\phi), H_2(\phi), H_3(\phi), H_4(\phi), H_5(\phi,\varepsilon), H_6(\phi,\varepsilon)$	special functions
$\overline{J}$	electric current
K	permeability of porous layer
L	length and height of the cavity
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
$\overline{p}$	dimensional pressure
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
T	dimensional temperature
t	dimensional time
T_c	upper wall temperature
T_h	bottom wall temperature
u, v	dimensionless velocity components
$\overline{u}, \overline{v}$	dimensional velocity components
$\overline{V}$	velocity vector
V_0	moving lid velocity
x, y	dimensionless Cartesian coordinates
$\overline{x}, \overline{y}$	dimensional Cartesian coordinates

Greek symbols

α	inclination angle of magnetic field
β	thermal expansion coefficient
δ	dimensionless height of porous layer
ε	porosity of porous layer
η	heat capacity ratio
θ	dimensionless temperature
λ	thermal conductivity
μ	dynamic viscosity
ρ	density
ρc_p	heat capacitance
$\rho\beta$	buoyancy coefficient
σ	electrical conductivity
τ	dimensionless time
ϕ	nanoparticles volume fraction
ψ	dimensionless stream function
ω	dimensionless vorticity

Subscripts

c	cold
f	fluid
h	hot
max	maximum value
mnf	nanofluid saturated porous medium
nf	nanofluid
p	(nano) particle
$porous$	porous medium
s	solid

Rayleigh number leads to a formation of an unstable thermal plume near the right wall. Sheremet and Trifonova [13,14] investigated natural convection in a vertical cylinder partially filled with a porous medium under the effect of heat conducting shell. It was shown that an increase in the porous layer height ratio leads to a decrease in average Nusselt number and the cooling rate of the analyzed domain. Ahmed [15] discussed the problem of mixed convection in two-sided lid-driven enclosures saturated with non-Darcy porous medium. He found that the forced convection plays a dominant role in the flow region for the low values of the Richardson number. Sheikholeslami and Chamkha [16] studied the effect of a variable spatial magnetic field on ferrofluid flow and heat transfer in a double-sided lid-driven enclosure with a sinusoidal hot wall. The results showed that an enhancement in heat transfer has a direct relationship with the Reynolds number and the Hartmann number, but it has an inverse relationship with the magnetic number. Chamkha and Al-Naser [17] numerically using finite difference method solved a problem of hydromagnetic double-diffusive convective flow of a binary gas mixture in a rectangular enclosure with the upper and lower walls being insulated. They revealed that the effect of the magnetic field reduces the overall heat transfer and fluid circulation within the enclosure. Sheikholeslami and Chamkha [18] analyzed natural convection heat transfer of Fe_3O_4–ethylene glycol nanofluid in the presence of an electric field by control volume method. Chamkha and Abu-Nada [19] examined steady laminar mixed convection flow in single and double-lid square cavities filled with an alumina/water nanofluid. They found that significant heat transfer enhancement can be obtained due to the presence of nanoparticles and that this is accentuated by increasing the nanoparticle volume fractions at moderate and large Richardson numbers using both nanofluid models for both single- and double-lid cavity configurations. Basak and Chamkha [20] using finite element method studied natural convection of nanofluids in presence of hot and cold side walls (case 1) or uniform or non-uniform heating of bottom wall with cold side walls (case 2) on the basis of heat functions or heatlines. Chattopadhyay et al. [21] made a numerical work on simulation of 2D mixed convection in a sinusoidally heated porous cavity. Both vertical walls are in motion. They found that heat transfer increases with increasing the amplitude value. Sheikholeslami [22] studied the effects of magnetic field on forced convection in a porous media filled lid-driven cubic cavity. He used lattice Boltzmann method to solve governing equations. He observed that temperature gradient increases with the increasing of Reynolds number, Darcy number and Al_2O_3 nanoparticles volume fraction. Hatami et al. [23] solved a problem for lid-driven cavity flow in a T-shaped porous medium filled cavity. They made an optimization study to improve the nanofluids mixed convection heat transfer and fluid flow. Gutt and Groşan [24] analyzed the motion of an incompressible viscous fluid through a porous medium located in a two-dimensional square cavity. Sheremet and Pop [25] numerically examined the mixed convective heat transfer and nanofluid flow in a lid-driven square cavity under the effects of Brownian diffusion and thermophoresis.

Effects of magnetic field on mixed convection in nanofluid or pure fluid filled lid-driven square cavities are studied widely. For example, Mehmood et al. [26] studied the effects of magnetic field on mixed convection in a lid-driven cavity in the presence of