



Mixed convection of Al_2O_3 -water nanofluid in a lid-driven cavity having two porous layers



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ARTICLE INFO

Article history:

Received 27 August 2017

Received in revised form 18 October 2017

Accepted 6 November 2017

Keywords:

Mixed convection

Lid-driven cavity

Porous layers

Nanofluid

Numerical results

ABSTRACT

In this study, mixed convection of Al_2O_3 -water nanofluid in a lid-driven cavity under the effect of two porous layers is numerically studied. Porous layers of different thermal properties, permeability and porosity are located on the bottom wall. This bottom wall of the cavity is kept at hot temperature T_h , while upper moved wall is kept at constant cold temperature T_c and other walls of the cavity are supposed to be adiabatic. Governing equations with corresponding boundary conditions formulated in dimensionless stream function and vorticity using Brinkman-extended Darcy model for porous layers have been solved numerically using finite difference method. Numerical analysis has been carried out for a wide range of the Richardson number ($Ri = 0.01$ – 10.0), the Darcy number for the porous layer I ($Da_1 = 10^{-7}$ – 10^{-3}), porous layers thickness ($\delta = 0.1$ – 0.3) and nanoparticles volume fraction ($\phi = 0$ – 0.04). It has been found that in the natural convection regime an addition of nanoparticles leads to the heat transfer enhancement, while for mixed convection and forced convection regimes an increase in nanoparticles volume fraction leads to the heat transfer reduction.

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1. Introduction

Conduction and convection can be occurring in many engineering systems such as building roof or indoor air heating or ventilation, cooling of electronic systems, avionics and heat exchangers [1,2].

Varol et al. [3] studied the entropy generation due to convection and conduction in closed spaces bounded by vertical solid wall at different wall thicknesses. They used finite difference method and found that thickness of the walls is the main parameters on heat transfer. Oztop et al. [4] worked on natural convection in a vertically divided closed space to different areas as air and water. Jue [5] studied the torsionally-oscillatory lid with thermal stable stratification in an enclosure filled with a porous medium by using finite element method. The author found that the influence of oscillatory frequency is so serious in heat flux variation at some particular frequency for different Darcy numbers. Khanafer and Chamkha [6] solved mixed convection problem in a lid-driven enclosure filled with a fluid-saturated porous closed space with

thermal stable stratification. Oztop [7] solved the similar problem with Khanafer and Chamkha [6] in the presence partial heater on the wall of the cavity.

Sometimes, walls can be solid or porous thick blocks. In this context, Baytas et al. [8] studied the conduction and convection heat transfer problem in a square porous cavity. In their case, the closed space consists of two horizontal solid walls on top and bottom and the middle part is filled with air and porous media. They observed that flow strength inside the cavity is completely related with ratio of conductivity between solid and fluid. Steady conjugate natural convection and conduction heat transfer in a 2D porous closed space with finite wall thickness is studied numerically by Saeid [9]. In his case, horizontal heating is considered, where the vertical boundaries are isothermal at different temperatures with adiabatic horizontal boundaries. He observed that in the most of the cases that either increasing the Rayleigh number and the thermal conductivity ratio or decreasing the thickness of the bounded wall can increase the average Nusslet number for the porous enclosure (Nup). In special cases at low Rayleigh number and high conductive walls, the values of Nup are increasing with a growth of the wall thickness. Sheremet and Trifonova [10] examined transient natural convection in a vertical cylinder bounded by solid walls of finite thickness under the effect of a horizontal

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Nomenclature

Roman letters

c_p	specific heat at constant pressure [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$]
Da	Darcy number [–]
$\mathbf{g}$	gravitational acceleration vector [$\text{m}\cdot\text{s}^{-2}$]
h_1	thickness of porous layer I [m]
h_2	thickness of porous layer II [m]
$H_1, H_2, H_3, H_4, H_5, H_6$	special functions [–]
K_1	permeability of the porous layer I [m^2]
K_2	permeability of the porous layer II [m^2]
L	length and height of the cavity [m]
Nu	local Nusselt number [–]
$\overline{Nu}$	average Nusselt number [–]
$\bar{p}$	dimensional pressure [Pa]
Pr	Prandtl number [–]
Re	Reynolds number [–]
Ri	Richardson number [–]
T	dimensional temperature [K]
t	dimensional time [s]
T_c	upper wall temperature [K]
T_h	bottom wall temperature [K]
u, v	dimensionless velocity components [–]
$\bar{u}, \bar{v}$	dimensional velocity components [$\text{m}\cdot\text{s}^{-1}$]
U_0	moving lid velocity [$\text{m}\cdot\text{s}^{-1}$]
x, y	dimensionless Cartesian coordinates [–]
$\bar{x}, \bar{y}$	dimensional Cartesian coordinates [m]

Greek symbols

β	thermal expansion coefficient [K^{-1}]
δ_1	dimensionless thickness of the porous layer I [–]

δ_2	dimensionless thickness of the porous layer II [–]
ε_1	porosity of the porous layer I [–]
ε_2	porosity of the porous layer II [–]
η_1	heat capacitance ratio for the porous layer I [–]
η_2	heat capacitance ratio for the porous layer II [–]
θ	dimensionless temperature [–]
λ	thermal conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]
μ	dynamic viscosity [$\text{Pa}\cdot\text{s}$]
ρ	density [$\text{kg}\cdot\text{m}^{-3}$]
ρc_p	heat capacitance [$\text{J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$]
$\rho\beta$	buoyancy coefficient [$\text{kg}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$]
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	porous medium saturated with nanofluid
nf	nanofluid
p	(nano) particle
s	solid matrix of porous layer

porous layer. It was shown that at small values of the thermal conductivity ratio the linear Darcy model is valid for the conjugate natural convection problems, while an increase in thermal conductivity ratio leads to more essential quantitative differences between the results obtained on the basis of the Darcy model and the Brinkman-extended Darcy model for the transport processes through the porous layer.

Porous baffles can find a specific application on ocean engineering as given by Cho et al. [11], heat exchangers (Wang et al. [12]) and solar air heaters (Bayrak et al. [13]). Biswas and Manna [14] studied the convective heat transfer in a lid-driven porous cavity in case of aspiration. They observed that the aspiration can magnificently enhance heat transfer without any additional expenses for pumping power of it. Alshuraiaan and Khanafer [15] studied the effect of the position of the heated thin porous fin on the laminar natural convection in a closed space. They found that the presence of a horizontal porous fin increases the average Nusselt number when compared with the differentially heated cavity for various Rayleigh numbers and thermal conductivity ratios. Sheikholeslami and Shamlooei [16] used the CVFEM method to simulate the convective flow of nanofluid in a lid-driven cavity filled with porous media. They observed that heat transfer improves with increasing of Darcy and Reynolds numbers while it decreases with enhance of Hartmann number. Gutt and Grosan [17] analyzed the motion of an incompressible viscous fluid through a porous medium located in a two-dimensional square closed space, i.e., the lid-driven flow problem described by a generalized Darcy–Brinkman model. Gibanov et al. [18,19] studied the mixed convection in a lid-driven cavity filled with a water-based nanofluid in the presence of a bottom heat-conducting solid backward step [18] or porous layer [19]. They observed that sizes and thermal conductivity of a backward step can essentially modify the flow and heat transfer patterns

with the process intensity. Chamkha [20] investigated numerically mixed convection in a square cavity under the effects of internal heat generation/absorption, uniform magnetic field and moved left vertical wall. It was found that the internal heat generation decreases the average Nusselt number for aiding flow and increases it for opposing flow. Mansour et al. [21] examined numerically laminar mixed convection cooling of a square cavity filled with a water-based nanofluid. The effects of nanoparticles material and control parameters have been analyzed. Chamkha and Abu-Nada [22] studied the steady laminar mixed convection flow in single and double-lid square cavities filled with an alumina-water nanofluid. It was shown 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. Sheikholeslami and Chamkha [23] analyzed mixed convection in a double-sided lid-driven cavity with a wavy wall under the effect of a variable magnetic field using the control volume-based finite element method. They found 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. Other studies on mixed convection in lid-driven cavities can be found in [24–33].

The objective of the present paper is a numerical analysis of convective heat transfer of a nanofluid in a cavity with two porous layers located in the bottom part of the cavity under the effects of moving upper wall and vertical temperature gradient. Based on authors' knowledge and above literature survey there is no work on composite porous layer located inside the lid-driven cavity. Thus, obtained results will help to readers and make contribution to understand the heat transfer, fluid flow and thermodynamics

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