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Mixed convection flow of a nanofluid in a lid-driven cavity with a wavy wall☆

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ABSTRACT

This work is focused on the numerical modeling of steady laminar mixed convection flow in a lid-driven cavity with a wavy wall filled with a water–CuO nanofluid. The left and right walls of the enclosure are kept insulated while the bottom and top walls are maintained at constant temperatures with the top surface being the heated lid wall and moving at a constant speed. The governing equations for this investigation are given in terms of the stream function–vorticity formulation and are non-dimensionalized and then solved numerically subject to appropriate boundary conditions by a second-order accurate finite-volume method. Various comparisons with previously published work are performed and the results are found to be in good agreement. A parametric study of the governing parameters such as the Richardson number, bottom wall geometry ratio (B/H) and the nanoparticles volume fraction is conducted and a representative set of graphical results is presented and discussed to illustrate the effects of these parameters on the flow and heat transfer characteristics. It is found that the presence of nanoparticles causes significant heat transfer augmentation for all values of Richardson numbers and bottom wall geometry ratios.

1. Introduction

The topic of mixed convection flow in a lid-driven cavity with a horizontal sliding wall has been a subject of interest for many years due to their ever increasing applications in lubrication technologies, electronic cooling, food processing and nuclear reactors [1–6]. A nanofluid is a base fluid with suspended metallic nanoparticles [7]. Because traditional fluids used for heat transfer applications such as water, mineral oils and ethylene glycol have a rather low thermal conductivity, nanofluids with relatively higher thermal conductivities have attracted enormous interest from researchers due to their potential in the enhancement of heat transfer with little or no penalty in pressure drop. In their experimental work, Eastman et al. [8] showed that an increase in thermal conductivity of approximately 60% can be obtained for a nanofluid consisting of water and 5 vol.% CuO nanoparticles. This is attributed to the increase in surface area due to the suspension of nanoparticles. Das et al. [9] reported a 2–4-fold increase in thermal conductivity enhancement for water-based nanofluids containing Al_2O_3 or CuO nanoparticles over a small temperature range, 21–51 °C. Keblinski et al. [10] reported on the possible mechanisms of enhancing thermal conductivity, and suggested that the size effect, the clustering of nanoparticles and the surface adsorption could be the major reason of enhancement, while the Brownian motion of nanoparticles contributes much less than other factors since Brownian motion of nanoparticles is too slow to transport significant amount of heat through a nanofluid and this conclusion was also supported by their results of molecular dynamics simulation. Wang et al. [11] used a fractal model for predicting the effective thermal conductivity of liquid with suspension of nanoparticles and found that it predicts well the trend for variation of the effective thermal conductivity with dilute suspension of nanoparticles.

The convective heat transfer characteristic of nanofluids depends on the thermo-physical properties of the base fluid and the ultra-fine particles, the flow pattern and flow structure, the volume fraction of the suspended particles, the dimensions and the shape of these particles. The utility of a particular nanofluid for a heat transfer application can be established by suitably modeling the convective transport in the nanofluid. Several studies of convective heat transfer in nanofluids have been reported in recent years. Khanafer et al. [12] investigated the problem of buoyancy-driven heat transfer enhancement of nanofluids in a two-dimensional enclosure. Hwang et al. [13] have carried out a theoretical investigation of the thermal characteristics of natural convection of an alumina-based nanofluid in a rectangular cavity heated from below using Jang and Choi's model [14] for predicting the effective thermal conductivity of nanofluids (and various models for predicting the effective viscosity). Santra et al. [15] studied heat transfer characteristics of copper–water nanofluid in a differentially heated square cavity with different viscosity models. Ho et al. [16] reported a numerical simulation of natural convection of nanofluid in a square enclosure considering the effects due to uncertainties of viscosity and thermal conductivity. Oztop and Abu-Nada [17] studied heat transfer and fluid flow due to buoyancy forces in a partially heated enclosure using nanofluids with various types of nanoparticles. They found that

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Nomenclature

B	peak height of the wavy surface (m)
C_p	specific heat at constant pressure ($\mathrm{kJ\ kg^{-1}\ K^{-1}}$)
d	diameter (m)
g	gravitational acceleration ($\mathrm{m\ s^{-2}}$)
Gr	Grashof number, $Gr = \frac{g\beta(T_H - T_L)H^3}{\nu_f^2}$
H	height of the enclosure (m)
h	local heat transfer coefficient ($\mathrm{W\ m^{-2}\ K^{-1}}$)
k	thermal conductivity ($\mathrm{W\ m^{-1}\ K^{-1}}$)
Nu	Nusselt number, Nu = hH/k
Pr	Prandtl number, $\mathrm{Pr} = \nu_f/\alpha_f$
q_w	heat flux, ($\mathrm{W\ m^{-2}}$)
Re	Reynolds number, $\mathrm{Re} = \frac{U_p H}{\nu_f}$
Re	Reynolds number, $Ri = \frac{Gr}{\mathrm{Re}^2}$
T	dimensional temperature (C)
u, v	dimensional x and y components of velocity ($\mathrm{m\ s^{-1}}$)
U, V	dimensionless velocities, $V = vH/\alpha_f, U = uH/\alpha_f$
U_p	lid speed (m/s)
W	width of the enclosure (m)
x, y	dimensionless coordinates, $x = x'/H, y = y'/H$
x′, y′	dimensional coordinates (m)

Greek symbols

α	fluid thermal diffusivity ($\mathrm{m^2\ s^{-1}}$)
β	thermal expansion coefficient ($\mathrm{K^{-1}}$)
ε	numerical tolerance
φ	nanoparticle volume fraction
ν	kinematic viscosity ($\mathrm{m^2\ s^{-1}}$)
η	transformed coordinate
θ	dimensionless temperature, $\theta = (T - T_C)/(T_H - T_C)$
ψ	dimensional stream function ($\mathrm{m^2\ s^{-1}}$)
Ψ	dimensionless stream function, $\Psi = \psi/\alpha_f$
ω	dimensional vorticity ($\mathrm{s^{-1}}$)
Ω	dimensionless vorticity, $\Omega = \omega H^2/\alpha_f$
ξ	transformed coordinate
ρ	density ($\mathrm{kg\ m^{-3}}$)
μ	dynamic viscosity ($\mathrm{N\ s\ m^{-2}}$)

Subscripts

avg	average
C	cold
f	fluid
H	hot
nf	nanofluid
p	particle
w	wall

the use of nanofluids caused heat transfer enhancement and that this enhancement is more pronounced at a low aspect ratio than at a high one. Abu-Nada studied the effects of variable viscosity and thermal conductivity of CuO–water and Al_2O_3–water nanofluid on heat transfer enhancement in natural convection [18,19]. Aminossadati and Ghasemi [20] studied natural convection cooling of a localized heat source at the bottom of a nanofluid-filled enclosure.

With regard to the studies that focused on mixed convection, Abu-Nada et al. [21] explored heat transfer enhancement in combined convection around a horizontal cylinder. Tiwari and Das [22] investigated numerically heat transfer augmentation in mixed convection in a lid-driven cavity filled with a nanofluid and found that the presence of nanoparticles in a base fluid is capable of increasing the heat transfer capacity of the base fluid. Muthtamilselvan et al. [23] reported on the heat transfer enhancement of copper–water nanofluids in a lid-driven enclosure with different aspect ratios. Chamkha and Abu-Nada [24] conducted a study of laminar mixed convective flow and heat transfer of a nanofluid made up of water and Al_2O_3 in single and double-lid driven cavities. At moderate and large Richardson numbers, they reported an enhancement of heat transfer with nanoparticles volume fraction. Nasrin et al. [25] focused on the mixed convective heat transfer in a double lid driven cavity filled with water–CuO nanofluid in the presence of internal heat generation. The obtained results depict that the Richardson number plays a significant role on the heat transfer characterization. Otherwise, the enhancement depends on the used model of nanofluid viscosity.

The objective of this work is to study steady laminar mixed convection in a lid-driven cavity with a wavy bottom wall filled with a nanofluid (water with CuO nanoparticles). A second-order accurate finite volume scheme is devised for the purpose of solution of the governing equations.

2. Governing equations and problem formulation

Fig. 1(a) shows a schematic diagram of the wavy walled cavity. The height and the width of the cavity are defined by *H*. The lid is heated and maintained at a constant temperature (T_H) whereas the bottom wavy wall of the cavity is kept at cold temperature (T_C). The left and the right walls of the cavity are insulated. The nanofluid is assumed incompressible and the flow is assumed to be laminar. It is assumed that the base fluid (i.e. water) and the nanoparticles are in thermal equilibrium and no slip occurs between them. The thermo-physical properties of the nanofluid are given in Table 1. The thermo-physical properties of the nanofluid are assumed to be constant except for the density variation, which is approximated by the Boussinesq model. The governing equations for the laminar, two-dimensional, steady state natural convection in terms of the stream function–vorticity formulation are written as:

$$\frac{\partial}{\partial x'}\left(\omega\frac{\partial\psi}{\partial y'}\right) - \frac{\partial}{\partial y'}\left(\omega\frac{\partial\psi}{\partial x'}\right) = \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial\omega}{\partial x'^2} + \frac{\partial\omega}{\partial y'^2}\right) + \left(\varphi\beta_p + (1-\varphi)\beta_f\right)g\left(\frac{\partial T}{\partial x'}\right) \tag{1}$$

$$\frac{\partial}{\partial x'}\left(T\frac{\partial\psi}{\partial y'}\right) - \frac{\partial}{\partial y'}\left(T\frac{\partial\psi}{\partial x'}\right) = \alpha_{nf}\left(\frac{\partial^2 T}{\partial x'^2} + \frac{\partial^2 T}{\partial y'^2}\right) \tag{2}$$

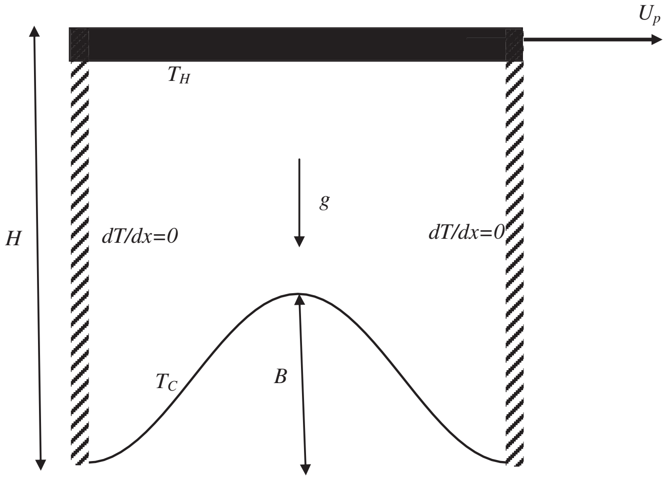

Fig. 1. Schematic of the wavy lid driven cavity.