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Numerical study of mixed convection flows in a lid-driven enclosure filled with nanofluid using variable properties

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ABSTRACT

This paper focuses on the study of mixed convection heat transfer characteristics in a lid-driven enclosure filled with nanofluids using variable thermal conductivity and variable viscosity. The fluid in the enclosure is a water-based nanofluid containing Al_2O_3 nanoparticles. The top and bottom horizontal walls are insulated, while the vertical walls are kept at different constant temperatures with the top surface moving at a constant speed. The study has been carried out for the Richardson numbers of 0.01–100, the solid volume fraction of 0–0.06 and the Grashof number of 10^4. Various results for the streamlines and isotherms as well as the local and average Nusselt numbers are presented. The variable viscosity and thermal conductivity of both the Brinkman and the Maxwell–Garnett model were compared. Significant differences are found between the magnitudes of heat transfer enhancement in the enclosure for two employed models.

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1. Introduction

Mixed convection of heat transfer has been a subject of interest in recent years due to its applications, especially those related to lubrication technologies, electronic cooling, food processing and nuclear reactors [1–2]. But, low thermal properties of working fluids are a main limitation. Suspending different types of small solid particles is an innovative way to improve the heat transfer. A dilute suspension of solid nanoparticles called a nanofluid, a term firstly used by Choi [3].

Mixed convection heat transfer is affected by nanofluid properties, such as viscosity and thermal conductivity. Up to now, most studies have used the Brinkman model for viscosity and Maxwell–Garnett (MG) model for thermal conductivity. These models have some defects. The Brinkman model does not consider the effect of nanofluid temperature or nanoparticles size and the Maxwell–Garnett model does not emphasize important mechanisms for heat transfer in nanofluids such as Brownian motion.

The effect of nanoparticle concentration and nanoparticle size on nanofluids viscosity under a wide range of temperatures was experimentally studied by Nguyen et al. [4] and Angue Minsta et al. [5]. They found that viscosity drops sharply with increasing temperature, especially for high concentrations of nanoparticles. In addition, Chon et al. [6] experimentally studied the combined effect of temperature, nanoparticle size and nanoparticle volume fraction on the thermal conductivity of nanofluids.

Abu-Nada [7,8] studied the effect of variable properties of Al_2O_3–water and CuO–water nanofluids on natural convection in an annular region. He found that for Ra $\geqslant 10^4$ the heat transfer was elevated by increasing the concentration of nanoparticles. Additionally, Abu-Nada et al. [9] investigated the role of nanofluid variable properties in differentially heated enclosures and found that the effect of nanofluid variable properties play a major role in the prediction of heat transfer enhancement.

Sensibility of mixed convection heat transfer to variable viscosity and thermal conductivity of nanofluids in a lid-driven enclosure is the aim of this work. When nanofluid viscosity is a function of temperature and nanoparticles concentration, experimental results of Nguyen et al. [4] are adopted. For the thermal conductivity, the model derived by Chon et al. [6] is used. Under a wide range of volume fractions of nanoparticles and different Richardson numbers, the enhancement of heat transfer will be evaluated.

2. Physical model and governing equations

Fig. 1 shows a lid-driven square enclosure filled with a nanofluid. The top and bottom horizontal walls are insulated, while the vertical walls are kept at different constant temperatures with the top surface moving at a constant speed. The fluid in the enclosure is a water-based nanofluid containing Al_2O_3 nanoparticles.

The nanofluid in the enclosure is Newtonian, incompressible and laminar. In addition, it is assumed that both the fluid phase and nanoparticles are in the thermal equilibrium state and they

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Nomenclature

g	gravitational acceleration
Gr	Grashof number
H	enclosure height
Nu	Nusselt number
k	thermal conductivity
p	pressure
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
T	temperature
u, v	components of velocity
U, V	dimensionless of velocity component
U_p	velocity of the moving lid
x, y	Cartesian coordinates
X, Y	dimensionless of Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
φ	solid volume fraction
μ	dynamic viscosity
v	kinematics viscosity
ρ	density
θ	dimensionless temperature

Subscript

avg	average
c	cold wall
eff	effective
f	fluid
h	hot wall
nf	nanofluid
p	particle

flow with the same velocity. The nanoparticles are assumed to have uniform shape and size. The density variation in the body force term of the momentum equation is satisfied by Boussinesq's approximation. The thermal conductivity and the viscosity of the nanofluid are taken into consideration as variable properties; both of them change with volume fraction and temperature of nanoparticles. Under the above assumptions, the system of governing equations is [10]:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

x-momentum equation:

$$\rho_{\mathrm{nf},0}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{\mathrm{nf}}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{nf}}\frac{\partial u}{\partial y}\right)+\frac{\partial \mu_{\mathrm{nf}}}{\partial y}\frac{\partial v}{\partial x}+\frac{\partial \mu_{\mathrm{nf}}}{\partial x}\frac{\partial u}{\partial x} \tag{2}$$

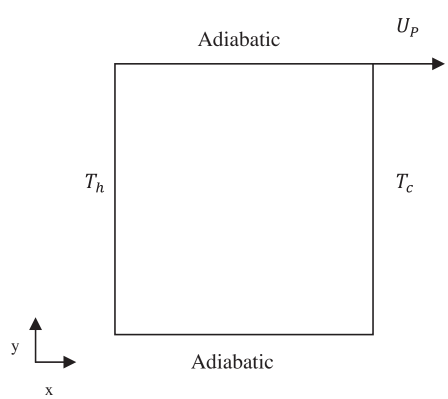

Fig. 1. Geometry and coordinate system.

y-momentum equation:

$$\rho_{\mathrm{nf},0}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu_{\mathrm{nf}}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\mathrm{nf}}\frac{\partial v}{\partial y}\right)+\frac{\partial \mu_{\mathrm{nf}}}{\partial y}\frac{\partial v}{\partial y}+\frac{\partial \mu_{\mathrm{nf}}}{\partial x}\frac{\partial u}{\partial y}+[\phi\rho_{p,0}\beta_s+(1-\phi)\rho_{f,0}\beta_f]g(T-T_c) \tag{3}$$

Energy equation:

$$(\rho c_p)_{\mathrm{nf}}\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial x}\left(k_{\mathrm{nf}}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{\mathrm{nf}}\frac{\partial T}{\partial y}\right) \tag{4}$$

The effective density of the nanofluid at reference temperature is

$$\rho_{\mathrm{nf},0}=(1-\phi)\rho_{f,0}+\phi\rho_{p,0} \tag{5}$$

and the specific heat capacity of nanofluid is

$$(\rho\beta)_{\mathrm{nf}}=(1-\varphi)(\rho\beta)_f+\varphi(\rho\beta)_p \tag{6}$$

$$(\rho c_p)_{\mathrm{nf}}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_p \tag{7}$$

as given by Xuan and Li [11]. The effective thermal conductivity of the nanofluid calculated by the Chon et al. model [6] is

$$\frac{k_{\mathrm{nf}}}{k_f}=1+64.7\varphi^{0.4076}\left(\frac{d_f}{d_p}\right)^{0.3690}\left(\frac{k_p}{k_f}\right)^{0.7476}\mathrm{Pr}_T^{0.9955}\mathrm{Re}^{1.2321} \tag{8}$$

Here Pr_T and Re are defined by

$$\mathrm{Pr}_T=\frac{\mu_f}{\rho_f\alpha_f} \tag{9}$$

$$\mathrm{Re}=\frac{\rho_f k_b T}{3\pi\mu_f l_f} \tag{10}$$

$k_b = 1.3807 \times 10^{-23}$ J/K is the Boltzmann constant and l_f= 0.17 nm is the mean path of fluid particles [6]. Accuracy of this model was confirmed by the experiments of Angue Minsta et al. [5]. The results of Eq. (8), will be compared to the Maxwell–Garnett (MG) model given by [12]

Table 1
Grid independence study.

Grid size	21 × 21	61 × 61	81 × 81	101 × 101	121 × 121	141 × 141	161 × 161
$\mathrm{Nu_{avg}}$	6.743	7.534	8.788	9.011	9.264	9.228	9.228

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