International Communications in Heat and Mass Transfer 37 (2010) 1504–1512

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical simulation of mixed convection flows in a square lid-driven cavity partially heated from below using nanofluid☆

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ARTICLE INFO

Available online 14 October 2010

Keywords:
Nanofluid
Mixed convection
Lid-driven
Finite difference method

ABSTRACT

The present numerical study deals with mixed convection in a square lid-driven cavity partially heated from below and filled with water-base nanofluid containing various volume fractions of Cu, Ag, Al_2O_3 and TiO_2. Finite difference method was employed to solve the dimensionless governing equations of the problem. The effects of governing parameters, namely, Reynolds number, solid volume fraction, different values of the heat source length and different locations of the heat source on the streamlines and isotherms contours as well as Nusselt number and average Nusselt number along the heat source were considered. The present results are validated by favorable comparisons with previously published results. The results of the problem are presented in graphical and tabular forms and discussed.

1. Introduction

Nanofluids are created by dispersing nanometer-sized particles (<100 nm) in a base fluid such as water, ethylene glycol or propylene glycol. Use of high thermal conductivity metallic nanoparticles (e.g., copper, aluminum, silver and silicon) increases the thermal conductivity of such mixtures, thus enhancing their overall energy transport capability [1]. Nanofluids have attracted attention as a new generation of heat transfer fluids in building heating, in heat exchangers, in plants and in automotive cooling applications, because of their excellent thermal performance. Various benefits of the application of nanofluids include: improved heat transfer, heat transfer system size reduction, minimal clogging, micro channel cooling and miniaturization of systems [2]. Therefore, research is underway to apply nanofluids in environments where higher heat flux is encountered and the conventional fluid is not capable of achieving the desired heat transfer. Xuan et al. [3] have examined the transport properties of nanofluid and have expressed that thermal dispersion, which takes place due to the random movement of particles, takes a major role in increasing the heat transfer rate between the fluid and the wall. This requires a thermal dispersion coefficient, which is still unknown. Brownian motion of the particles, ballistic phonon transport through the particles and nanoparticles clustering can also be the possible reason for this enhancement [4]. Das et al. [5] has observed that the thermal conductivity for nanofluid increases with increasing temperature. They have also observed the stability of Al_2O_3–water and Cu–water nanofluid. Experiments on heat transfer due to natural convection with nanofluid have been studied by Putra et al. [6] and Wen and Ding [7]. They have observed that heat transfer decreases with increase in concentration of nanoparticles. The viscosity of this nanofluid increases rapidly with the inclusion of nanoparticles as shear rate decreases. More applications and good understanding of the subject is given in the recent articles [8–17].

On the other hand, fluid flow and heat transfer in a cavity filled by pure fluid which is driven by buoyancy and shear have been studied extensively in literature [18–20]. The most usage of the mixed convection flow with lid-driven effect is to include the cooling of the electronic devices, lubrication technologies, drying technologies, etc.

Motivated by the investigations mentioned above, the purpose of the present work is to consider mixed convection flows of Cu–water, Ag–water, Al_2O_3–water and TiO_2–water nanofluid in a square cavity with a moving lid that moves uniformly in the horizontal plane and partially heated from below.

2. Mathematical formulation

Consider a steady two-dimensional flow inside a square cavity filled with nanofluid. In the present problem, the following assumptions have been made

I. In the cavity, the left, right and top walls are kept to be cooled
II. A heat source is located on a part of the bottom wall and the other parts are thermally insulated.
III. The top wall moves from left to right with uniform velocity U_0.

☆ Communicated by W.J. Minkowycz.

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doi:10.1016/j.icheatmasstransfer.2010.09.004

Nomenclature

B	length of the heat source (b/H)
C_p	specific heat, $Jkg^{-1}K^{-1}$
D	distance of heat source from the left wall(d/H)
Gr	Grashof number($g\beta_f H^3 \Delta T/v_f^2$)
g	gravitational acceleration,ms^{-2}
H	length of the cavity, m
k	thermal conductivity, $Wm^{-1}K^{-1}$
Nu_s	Nusselt number along the heat source
Nu_m	average Nusselt number along the heat source
p	pressure, pa
P	dimensionless pressure($p/p_{nf}U_0^2$)
Pr	Prandtl number (v_f/α_f)
$q"$	heat generation per area, W/m^2
Ra	Rayleigh number ($g\beta_f H^3 \Delta T/v_f \alpha_f$)
Re	Reynolds number ($\rho_f U_0 H/\mu_f$)
T	temperature, K
u,v	velocity components in x,y directions,ms^{-1}
U,V	dimensionless velocity components ($u/U_0, v/U_0$)
x,y	Cartesian coordinates, m
X,Y	dimensionless coordinates ($x/H, y/H$)

Greek symbols

α	thermal diffusivity, $m^2s^{-1}(k/\rho C_p)$
β	thermal expansion coefficient, k^{-1}
ΔT	Ref. temperature difference ($q''H/k_f$)
ϕ	solid volume fraction
θ	dimensionless temperature($T-T_c/\Delta T$)
μ	dynamic viscosity. $kgm^{-1}s^{-1}$
υ	kinematic viscosity,$m^2s^{-1}(\mu/\rho)$
ρ	density,kgm^{-3}

Subscripts

c	cold wall
f	pure fluid
m	average
nf	nanofluid
0	reference state
p	nanoparticle
s	surface of the heat source

IV. The base fluid (water) and the solid spherical nanoparticles (Cu, Ag, Al_2O_3 and TiO_2) are in thermal equilibrium.
V. The thermo-physical properties of the nanofluid are assumed constant except for a variation of the density which is determined based on Boussinesq approximation.
VI. Table 1 presents the thermo-physical properties for the base fluid and the nanoparticles.

Table 1
Thermo-physical properties of water and nanoparticles [10].

	Pure water	Copper (Cu)	Silver (Ag)	Alumina Al_2O_3	Titanium Oxide (TiO_2)
$\rho(kgm^{-3})$	997.1	8933	10500	3970	4250
$C_p(Jkg^{-1}K^{-1})$	4179	385	235	765	686.2
$k(Wm^{-1}K^{-1})$	0.613	401	429	40	8.9538
$\beta(K^{-1})$	21×10^{-5}	1.67×10^{-5}	1.89×10^{-5}	0.85×10^{-5}	0.9×10^{-5}

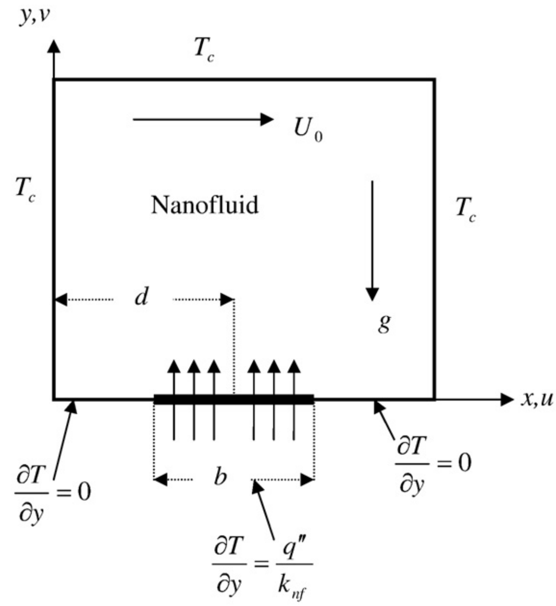

Fig. 1. Physical model of the problem.

The geometric and the Cartesian coordinate system are schematically shown in Fig. 1. Under the above assumptions, the governing equations are (see [9,10])

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{nf}}\left[-\frac{\partial p}{\partial x} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)\right] \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}\left[-\frac{\partial p}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + (\rho\beta)_{nf}g(T-T_c)\right] \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where, ρ_{nf} is the effective density of the nanofluid and it is given by

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{5}$$

Table 2
Grid independency results (Cu–water, $B=0.4, Ra=10^3, \mathrm{Re}=10, \phi=0.1, D=0.5$).

Grid	ψ_{min}	θ_{max}	Nu_m
31×31	−0.1317955	0.1108473	13.61545
41×41	−0.1311382	0.1099841	13.95723
61×61	−0.1304138	0.1096524	14.25467
81×81	−0.1293423	0.1151547	13.78368
101×101	−0.1271867	0.1296093	12.2746

Table 3
Comparisons of $-\psi_{min}$ for classical fluids.

Calculation method	$Gr=0, \mathrm{Re}=100$	$Gr=10^4 \mathrm{Re}=100$
Finite difference [19]	0.1013	–
Multigrid [20]	0.103423	–
Spline [18]	0.1054	0.0934
Finite difference (Present study)	0.1042828	0.0913895