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ORIGINAL ARTICLE

Buoyancy driven heat transfer in nanofluids due to wall mounted heat source

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Abstract This work is focussed on the numerical modeling of mixed convection heat transfer effects in a lid-driven cavity filled with a copper–water nanofluid. A heated wall mounted block with constant heat flux is attached along the vertical wall. The left vertical wall is maintained at higher temperature compared to the right vertical wall and the other (top and bottom) walls are insulated. A finite volume based numerical approach with QUICK scheme is used for the solution of nonlinear governing equations. A computational visualization technique is used to represent the two dimensional results of streamlines, isotherms, average Nusselt number and bulk-average temperature for a wide range of physical parameters, namely Reynolds number, Rayleigh number and solid volume fraction. The effective fluid flow and heat transfer variation are analyzed by placing the heated mounted block first along the left vertical wall (Case-I) and then along the right vertical wall (Case-II) to test the maximum heat transfer effects. The changes in main characteristics of the flow due to variation of Reynolds number and Rayleigh number are elaborated. The effect of various flow parameters on the thermal conductivity behavior for both cases is discussed based on average Nusselt number and bulk-average temperature and found that Case-I shows higher heat transfer rate compared to Case-II, for higher Re, Ra and ϕ.

1. Introduction

In recent years, nanofluids have attracted enormous interests from researchers due to their large scale applications in industry, power plants and reactors for cooling processes. Normally fluids such as water, propylene glycol or ethylene glycol are used for cooling process but these compounds possess very low thermal conductivity. The term nanofluid refers to the fluid in which nanoscale particles are suspended in the base fluid to utilize their suspension stability effectively [1]. Metallic nanoparticles with high thermal conductivity lead to remarkable increase in effective thermal conductivity of these types of fluids. However, the increase in the thermal conductivity depends on shape and size of the solid nanoscale particles. The scalar transport properties can also be enhanced considerably by adding these particles to liquid flow. The dependence of thermophysical properties in nanoparticles-fluid mixture is estimated by Xie et al. [2]. They found that nanoparticle fluid mixtures containing nano-sized particles have high thermal conductivity compared to the same liquid without nanoparticles. Keblinski et al. [3] worked on the possible mechanisms

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Nomenclature

C_p	specific heat capacity (J/K)
Gr	Grashof number $\left(\frac{g\beta_T(T_0-T_\infty)L^3}{v^2}\right)$
g	gravitational acceleration (m/s^2)
k	thermal conductivity (W/m K)
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
T	temperature (K)
θ	dimensionless temperature
x', y'	Cartesian coordinates (m)
x, y	dimensionless Cartesian coordinates
u, v	components of velocity in x' and y' directions (m/s)
U, V	dimensionless of velocity components in x and y directions
H	height of cavity (m)
W	width of cavity (m)

Greek letters

Ψ	stream function (m^2/s)
ψ	dimensionless stream function (Ψ/α_f)
Ω	vorticity (s^{-1})
ω	dimensionless vorticity ($\Omega H^2/\alpha_f$)
α	thermal diffusivity ($k/(\rho C_p)$) (m^2/s)
β	coefficient of volume expansion (K^{-1})
ϕ	solid volume fraction
μ	dynamic viscosity (Pa s)
v	kinematics viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

f	fluid
m	average
nf	nanofluid
o	reference state
p	solid
w	wall
c	cold

of enhancing thermal conductivity and suggested that the size effect, the surface absorption and clustering of nanoparticles could be the major reasons for heat transfer enhancement. The model developed by Maxwell [4] has shown that effective thermal conductivity of suspensions containing spherical particles can be increased by increasing the solid volume fraction of the nanoparticles. The proposed model also depicted the dependence of thermal conductivity of nanofluid on the solid volume fraction ratio which is applicable to only micro sized particles with low dense mixtures. Consequently, Maxwell's model is improved by the number of authors, e.g. Kumar et al. [5], Patel et al. [6], Yu and Choi [7] and Prasher et al. [8] by varying the particle size, solid volume fraction ratio and temperature to find the higher thermal conductivity.

In the natural convection process, it is found that dynamic viscosity plays a vital role for heat transfer enhancement of the nanofluid. Xu et al. [9] proposed a model for calculation of the thermal conductivity of nanofluids, due to Brownian motion of nanoparticles in the base fluid depending upon average size of nanoparticles, temperature, fractal dimensions and concentration of nanofluids. Sheremet and Pop [10] studied a steady natural convection in a square porous enclosure filled with nanofluid by using Buongiorno's model. Two vertical side walls are used as heat source for the convection heat transfer and Darcy's law for the flow in the porous medium and the Boussinesq approximation for the buoyancy effects. It is observed that high thermophoresis parameter, low Brownian motion parameter, low Lewis and Rayleigh numbers and high thermal conductivity ratio reflect essential non-homogeneous distribution of the nanoparticles inside the porous cavity.

Eastman et al. [11] experimentally observed that thermal conductivity can be increased up to 60% by using a nanofluid consisting of water and 5% CuO nanoparticles. Khanafer et al. [12] conducted a numerical study of natural convection utilizing copper–water nanofluid in a two-dimensional enclosure. They found that for any Grashof number, heat transfer in the enclosure is increased by changing the volume fraction of copper nanoparticles in water. Lee et al. [1] experimentally observed that thermal conductivity of nanofluids increases with the increase in solid volume fraction by considering both Al_2O_3–water and CuO–water mixture. Ho et al. [13] numerically investigated the effects of uncertainties due to adopting various formulae for the effective thermal conductivity and dynamic viscosity of the Al_2O_3–water nanofluid in a vertical square enclosure. It is also found that by adding nanoparticles in pure water improves its cooling performance at low Rayleigh numbers. Mixed convection flow in lid-driven cavity with a horizontal sliding wall is a subject of interest for many years since this phenomenon often affects the thermal performance of the system. Khanafer et al. [12] investigated the problem of buoyancy-driven heat transfer enhancement of nanofluids in a two-dimensional enclosure by a natural convection process where the vertical walls are maintained at high and low temperature and other walls are insulated, non-conducting and impermeable to mass transfer. Heat transfer performance is discussed based on the buoyancy effects, solid particle dispersion and various flow controlling parameters. Hwang et al. [14] 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 [15] by predicting the effective thermal conductivity of nanofluids. Tiwari and Das [16] investigated numerically heat transfer augmentation in a lid-driven cavity filled with a nanofluid and found that the presence of nanoparticles in base fluid is capable of increasing the heat transfer capacity. Sheremet et al. [17] also used the model suggested by Tiwari and Das and discussed the natural convection heat transfer in a porous enclosure utilizing nanofluid in conditions of thermal stratification. They have tried to find the effects of Rayleigh number, thermal stratification parameter, porosity of the porous medium, solid volume fraction parameter of nanoparticles, and the solid volume fraction