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# Numerical simulation of mixed convection of the nanofluid in heat exchangers using a Buongiorno model

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ABSTRACT

A numerical study of mixed convection heat transfer of nanofluid ($Al_2O_3$–water) in a lid driven cavity flow is carried out by using a Buongiorno model. Several pairs of heater and cooler (HACs) with isothermal walls of $T_h$ and $T_c$ ($T_h > T_c$) are located inside the cavity. Two-dimensional Navier–Stokes, energy and volume fraction equations are solved using the finite volume method. The effects of Brownian and thermophoresis diffusion, which cause non-homogeneity, are considered. The effects of volume fraction ($0 \le \varphi \le 0.05$) and nanoparticles' diameter (25 nm $\le d_p \le$ 145 nm) with the location, orientation and number of HACs on flow structure and heat transfer rate are examined in different Richardson numbers ($0.01 \le Ri \le 100$).

The simulation results indicate that there is an optimal volume fraction of the nano-particles at each Richardson number for which the maximum heat transfer rate can be obtained. Moreover, it is found that for a constant surface area of the HAC at the entire range of Richardson number, the rate of heat transfer is increased by changing the orientation of the HAC from horizontal to vertical. Results also indicate that at low *Ri*, the distribution of the solid particles remains almost uniform.



## 1. Introduction

The mixed convection heat transfer is a common phenomenon in both environmental processes and engineering systems. Indoor ventilation with radiators, cooling of electrical components, cooling of reactors and heat exchangers, are just a few examples of such systems. The topic of mixed convection in rectangular cavity has received many attentions in recent years [1–3]. Khanafer et al. [1] investigated the mixed convection heat transfer in a lid-driven cavity flow with a circular body inside. They reported that, the presence of the cylinder results in an increase in heat transfer rate for both, the adiabatic and isothermal boundary conditions of the cylinder. In addition, they found that the optimal heat transfer, for various Richardson numbers, can be obtained when the cylinder is located near the bottom wall of the cavity. A similar study has been done by Islam et al. [2] in a lid-driven cavity with an isothermally heated square blockage. Their results showed that Richardson number, size and location of the heater eccentricities affect the average Nusselt number of heater. The nanofluids are the mixture of nano-sized solid particles (usually smaller than 150 nm) in a base fluid, with a higher thermal conductivity in comparison to the base fluid. In recent years, these types of fluids have been used to increase the rate of heat transfer in many practical engineering applications. Thermophysical properties of nanofluids have also been studied by many researchers [4–8]. Corcione [5], presented two empirical correlations to predict the effective thermal conductivity and dynamic viscosity of nanofluids, with a 1.86% standard deviation of error, based on more than twenty experimental data sets. In general, numerical simulation of the velocity field, the temperature distribution and the heat transfer rate of the nanofluid can be performed by using two main approaches; single-phase and two-phase methods. In the single-phase approach, it is assumed that the continuous phase and the nanoparticles are in thermal equilibrium and move with the same velocity. The various applications of nanofluids have been studied earlier by using single-phase methods such as natural convection [9–15] and mixed convection of nanofluids [16–19]. Sheikholeslami et al. [13] considered a cavity with an isoflux heater inside. They studied the effects of nanoparticles' load variation and aspect ratio changing in different Rayleigh numbers. The obtained results revealed that the heat transfer rate is increased by the rise of nanoparticles' volume fraction, Rayleigh number and aspect ratio of the heated cylinder while it is decreased with an increase in Hartmann number. Parvin et al. [11] reported a study about the natural convection heat transfer in an odd-shaped cavity using the Brinkman [4] and Maxwell–Garnetts [7] models to estimate the effective viscosity and thermal conductivity of the nanofluid. They highlighted that by

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**Nomenclature**

| | |
|---|---|
| $C_p$ | specific heat, J kg$^{-1}$ K$^{-1}$ |
| $D_B$ | Brownian coefficient, kg m$^{-1}$ s$^{-1}$ |
| $d_f$ | diameter of the base fluid molecule, m |
| $d_p$ | diameter of the nanoparticle, m |
| $D_T$ | thermophoresis coefficient, kg m$^{-1}$ s$^{-1}$ K$^{-1}$ |
| $g$ | gravitational acceleration, m s$^{-2}$ |
| $Gr$ | Grashof number ($=g\beta\Delta TH^3/\nu^2$) |
| $H$ | enclosure height, m |
| $J_p$ | particle flux vector, kg m$^{-2}$ s$^{-1}$ |
| $\vec{J}_{p,B}$ | nanoparticle mass flux due to Brownian diffusion, kg m$^{-2}$ s$^{-1}$ |
| $\vec{J}_{p,T}$ | nanoparticle mass flux to thermophoresis, kg m$^{-2}$ s$^{-1}$ |
| $k$ | thermal conductivity, W m$^{-1}$ K$^{-1}$ |
| $k_b$ | Boltzmann's constant $= 1.38066 \times 10^{-23}$ J K$^{-1}$ |
| $l$ | dimensional length of the heater, m |
| $L$ | dimensionless length of the heater or cooler t ($=l/H$) |
| $Le$ | Lewis number |
| $N_{BT}$ | ratio of Brownian and thermophoretic diffusivities |
| $\overline{Nu}_i$ | average Nusselt number of the heater or cooler ($=hH/k_f$) |
| $p$ | dimensional pressure, N m$^{-2}$ |
| $P$ | dimensionless pressure |
| $Pr_f$ | Prandtl number ($=\nu_f/\alpha_f$) |
| $Re_B$ | Brownian-motion Reynolds number |
| $Re_P$ | particle Reynolds number |
| $Re$ | Reynolds number ($=U_0H/\nu$) |
| $Ri$ | Richardson number ($=Gr/Re^2$) |
| $Sc$ | Schmidt number |
| $T$ | dimensional temperature, K |
| $p$ | dimensional pressure, N m$^{-2}$ |
| $T_{fr}$ | freezing point of the base fluid, K |
| $u,v$ | dimensional velocity components, m s$^{-1}$ |
| $u_B$ | Brownian velocity of the nanoparticle, m s$^{-1}$ |
| $U, V$ | dimensionless velocity components |
| $x,y$ | dimensional Cartesian coordinates, m |
| $X, Y$ | dimensionless Cartesian coordinates |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity, m$^2$ s |
| $\beta$ | thermal expansion coefficient, K$^{-1}$ |
| $\phi$ | normalized nanoparticle volumetric fraction |
| $\theta$ | dimensionless temperature |
| $\mu$ | dynamic viscosity, kg m$^{-1}$ s$^{-1}$ |
| $\nu$ | kinematic viscosity, m$^2$ s$^{-1}$ |
| $\rho$ | density, kg m$^{-3}$ |
| $\varphi$ | volume fraction of the nanoparticles |
| $\psi$ | stream function($=-\int_{Y_0}^{Y} U\partial Y + \psi(X, Y_0)$) |

*Subscripts*

| | |
|---|---|
| $c$ | cold wall |
| $f$ | fluid |
| $h$ | hot wall |
| $nf$ | nanofluid |
| $p$ | solid nanoparticles |

increasing the volume fraction of nanoparticles and Rayleigh numbers the heat transfer is enhanced. Garoosi et al. [10] and Corcione [9] investigated the numerical simulation of natural convection of nanofluid at different geometries using the proposed model in Ref. [5] to estimate the effective viscosity and thermal conductivity of nanofluid. Their obtained results have illustrated that there is an optimum volume fraction of nanoparticles, where the maximum heat transfer rate occurs. Kalteh et al. [16] investigated laminar mixed convection of nanofluid in a lid-driven square cavity with a triangular heat source. Their results showed that the nanoparticles' diameter increase leads to a decrease in the heat transfer rate for all Richardson numbers.

Pishkar et al. [18] numerically simulated the mixed convection of nanofluid in a horizontal channel. Their results indicated that at low Richardson numbers the heat transfer is increased by enlarging the volume fraction of nanoparticles. In addition, their results showed that at low values of Reynolds number, the effects of Richardson number rising on the heat transfer rate for both the nanofluid and pure fluid are negligible.

Wen et al. [15] investigated natural convective heat transfer of suspensions of titanium dioxide nanoparticles. Their results showed that in natural convection, heat transfer coefficient decreases with increasing the nanoparticle volume fraction. Unlike natural convection, experimental results show that in forced convection as well as in mixed convection, heat transfer rate has considerable enhancement which increases with the addition of the volume fraction of the nanoparticle [19].

Comprehensive experimental studies, such as [20], support the idea that the assumption of single-phase may not always be true for nanofluid simulation. It can be explained by the fact that the slip velocity between the base fluid and particles may not be zero. Therefore, some researchers were encouraged to use more complex methods, such as two phase mixture, rather than using single phase models [21–29]. One of the first attempts on this topic belongs to Buongiorno et al.[22]. He presented Brownian diffusion and thermophoresis as two important primary slip mechanisms between solid and liquid phases. He found that, with considering the effects of thermophoretic, the temperature gradient resulted in particles transport from hot to cold region. Bagheri et al. [21] performed an Eulerian–Lagrangian simulation of solid particles in a differentially heated cavity filled with air. They found the distribution and deposition of nanoparticles to be influenced by the thermophoretic and Brownian forces significantly. Moreover, their results showed that at high Rayleigh number particles trapping in the circulation decrease the deposition rate.

Corcione et al. [24] reported natural convection of nanofluids inside the differentially heated cavity (DHC) using a Buongiorno model. The results of this study confirmed that the two phase mixture method is more accurate than the single-phase method. A similar study has been done by Pakravan et al. [25] and Sheikhzadeh et al. [27] considering the heat transfer of nanofluid in the square cavity (DHC). In these studies the effects of Brownian diffusion and thermophoresis as slip mechanisms take into account. Due to the results, two-phase mixture model predictions were in good agreement with experimental results. Sheikholeslami et al. [26] studied three dimensional nanofluid flow and heat transfer in a rotating system in the presence of a magnetic field using the Buongiorno model. Their results indicated that the heat transfer rate has a direct relation with Reynolds number while it has a reverse relation with thermophoretic parameter and Brownian parameter. Moreover, they found that the concentration boundary layer thickness is decreased with an increase of thermophoretic and Brownian parameter.

This research intends to explore the rate of heat transfer of mixed convection in a lid driven cavity with several pairs of heaters and coolers (HACs) using the Buongiorno model. The effects of location, orientation and number of the HACs, volume fraction and diameter of nanoparticles are considered as design parameters. In the following sections, the investigated cases will be defined and the applied computational method will be discussed in detail. The obtained results will be plotted via streamlines, isotherms, contours of nanoparticle distribution, and average Nusselt numbers. To the best of our knowledge, this study is the first one which considered the effects of Brownian diffusion and