INVESTIGATION OF PARTICLE DEPOSITION OF NANOFLUIDS IN A SQUARE CAVITY

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Abstract—

This paper reports a numerical study on particle deposition of nanofluids in a square cavity filled with CuO–Water nanofluids. Both upper and lower surfaces are being insulated, whilst a uniform constant temperature field applied in horizontal walls. The governing equations of fluid flow are discretized using a finite volume method with a collocated grid arrangement.

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1. INTRODUCTION

Enhancement of thermal conductivity of liquids is an extremely important topic from the energy efficiency point of view. The latest technique on this challenging subject is the using of addition of some particle into the base fluid. In this context, as Pioneer of these methods, Masuda [1] reported the liquid dispersions of submicron solid particles or nanoparticles, then, the term of "nanofluid" was first proposed by Choi [2]. Nanofluid becomes more attractive in recent years due to easy production methods and inexpensive price. Also, thermal conductivity of nanofluids relative to the base fluids is very high. Thus, nanofluids can be applied in many energetically systems such as cooling of nuclear systems, radiators, natural convection in enclosures. There are some review papers that show applications and detail solutions on nanofluids [3-5].

Number of studies on Brownian, Dufour and thermophoresis effects on natural convection in nanofluid filled enclosures is extremely limited. Among these, Buongiorno [6] investigated different slip mechanisms between nanoparticles and base fluid. He indicated that there are many slip mechanisms such as inertia, Brownian diffusion, thermophoresis, diffusiophoresis, magnus effect, fluid drainage, and gravity. He concluded that only Brownian diffusion and thermophoresis are important slip mechanisms in the absence of turbulent effects.

2. PHYSICAL MODEL

The physical model under consideration is natural convection in a square enclosure of side length L schematically shown in Fig. 1. The left vertical wall is maintained at a constant temperature t_h higher than the constant temperature t_c of the of the right vertical wall. Other walls of the enclosures are all thermally insulated. The fluid in the enclosure is a water based nanofluid containing CuO nanoparticles. The nanofluid is assumed incompressible and Newtonian and only Brownian diffusion and thermophoresis are important slip mechanisms between the two media. Water and CuO nanoparticles are in thermal equilibrium and the flow is also conceived as laminar and two-dimensional.

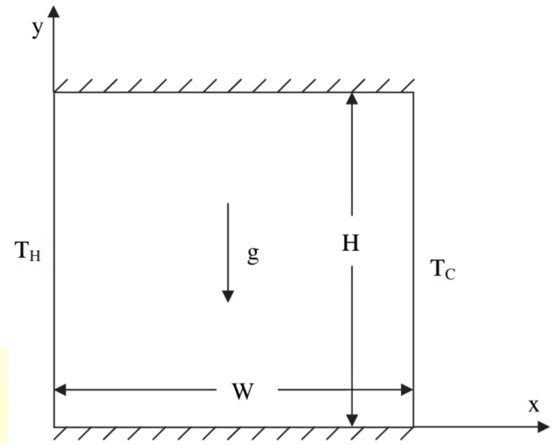

Fig. 1. A schematic diagram for the problem with boundary conditions.

3. GOVERNING EQUATIONS

Governing equations describing the conservation of total mass, momentum, thermal energy, and nanoparticles for the laminar, two-dimensional and steady state natural convection are written as:

$$\nabla . V^{*} = 0 \tag{1}$$

$$V^{*} . \nabla V^{*} = -\frac{1}{\rho_{nf}} \nabla p + \nabla \tau + g \tag{2}$$

$$V^{*} . \nabla T^{*} = -\frac{1}{c_{nf}\rho_{nf}} \nabla (k . \nabla T^{*}) + \frac{c_{p}\rho_{p}}{c_{nf}\rho_{nf}} \left(D_{B}^{*} \nabla \phi^{*} \nabla T^{*} + D_{T}^{*} \frac{\nabla T^{*} \nabla T^{*}}{T_{C}^{*}} \right) \tag{3}$$

$$V^{*} . \nabla \phi^{*} = \nabla . \left(D_{B}^{*} \nabla \phi^{*} + D_{T}^{*} \frac{\nabla T^{*}}{T_{C}^{*}} \right) \tag{4}$$

Where the stress tensor in Eq. 2 is given as [8]:

$$\tau = \mu_{nf} \ \nabla V^{*} + \ \nabla V^{*\ t} \tag{5}$$

Here, ρ_{nf} is the effective density of the nanofluid, μ_{nf} is the effective dynamic viscosity of the nanofluid, ϕ^{*} is nanoparticle volume fraction and g is the acceleration due to gravity. The coefficients that appear in Eqs. (3) and (4) are the Brownian diffusion coefficient D_B and the thermophoretic diffusion coefficient D_T as reported are given by:

$$D_B^* = \frac{k_B T^*}{3\pi \mu_f d_p} \tag{6}$$

$$D_T^* = \left(\frac{\mu_f}{\rho_f}\right)\left(0.26\frac{k_f}{2k_f + k_p}\right)\phi^* \tag{7}$$

Where μ_f is the viscosity of the fluid, d_p is the nanoparticle diameter and k_f and k_p are the thermal conductivity of the fluid and particle materials, respectively. The effective density (ρ_{nf}) and heat capacitance $(\rho C_p)_{nf}$ of the nanofluid are defined as:

$$\rho_{nf} = (1-\phi^*)\rho_f + \phi^* \rho_p \tag{8}$$

$$(\rho c_p)_{nf} = (1-\phi^*)(\rho c_p)_f + \phi^*(\rho c_p)_p \tag{9}$$

Thermal diffusivity of the nanofluids is

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_p)_{nf}} \tag{10}$$

4. NUMERICAL PROCEDURE

The dimensionless governing equations were discretized by the dimensional finite volume method. The grid layout was arranged by utilizing collocated grid procedure, while the Hybrid and Quick scheme were adopted for the convection–diffusion terms for calculation in the fluid domain. The coupling between velocity and pressure is solved using the SIMPLEC algorithm and the Rhie and Chow interpolation is used to avoid the checker–board solutions for the pressure.

For these simulations, the convergence was considered to be reached when the relative error on the value of a property per unit mass denoted by Φ between twosuccessive iterations, n and n+1 was smaller than a chosentolerance:

$$\frac{\sum \left|\Phi_{i,j}^{n+1} - \Phi_{i,j}^{n}\right|}{\sum \left|\Phi_{i,j}^{n+1}\right|} \le 10^{-6} \tag{33}$$

To test and assess grid independence of the solution scheme, the average Nusselt number for seven different grid sizes is performed as shown in Table. 2 in case Ra= 10^5 and ϕ=5%. Based on the results illustrated in the table and considering the accuracy of the results required and computational time involved, an 51×51 uniform grid is used for all of the subsequent numerical calculations.

TABLE I. GRID INDEPENDENCE STUDY

Grid size	**Nu_{avg}**
20×20	3.28702
30×30	3.26587
40×40	3.25015
50×50	3.24556
60×60	3.24398
70×70	3.24283

5. CODE VALIDATION

The present FORTRAN code is validated by comparing the present code results against the numerical simulation of Khanafer et al. and Oztab et al. for enclosures filled with a water–Cu nanofluid (Ra = 10^5, ϕ =5%, Pr = 6.2) a shown in Fig. 2. The agreement is found to be good and little differences could be duo to different models that used for nanofluids modeling.

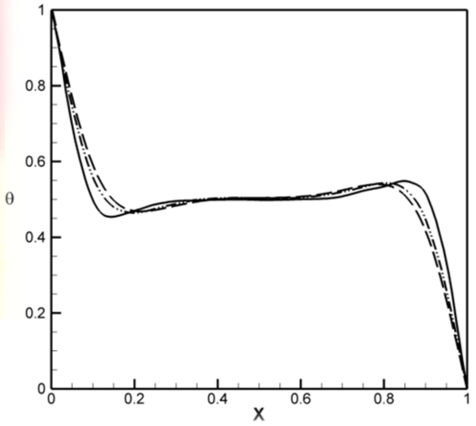

Fig. 2. Validation of the present code against other studies for a square enclosure filled with a Cu-water nanofluid (Ra = 10^5, ϕ =5%, Pr = 6.2)

6. RESULTS

The overall objective of this current study is to investigate the nanoparticles distribution and heat transfer behavior of natural convection inside a cavity filled with CuO–water nanofluid in both presence and absence of Brownian and thermophoresis effects. The ranges of the magnitude of the Rayleigh numbers and volume fractions of nanoparticles used in this study are $Ra=10^4–10^5$ and $0 \leq \phi \leq 7\%$, respectively. It is worth mentioning that the difference between the hot and the cold walls is fixed to 1°C and it is assumed that the Prandtl number (Pr) equals 6.2.

Fig. 3 and Fig. 4 portray the nanoparticle distribution for Ra= 10^5 (left side) and Ra=10^6 (right side) for different nanoparticle volume fraction. The general view of the figures shows that thermophoresis and Brownian effects make the nanoparticles distribution to become non-uniform throughout the domain. Nanoparticle distribution is more non-uniform for lower particle concentration and high Rayleigh number.

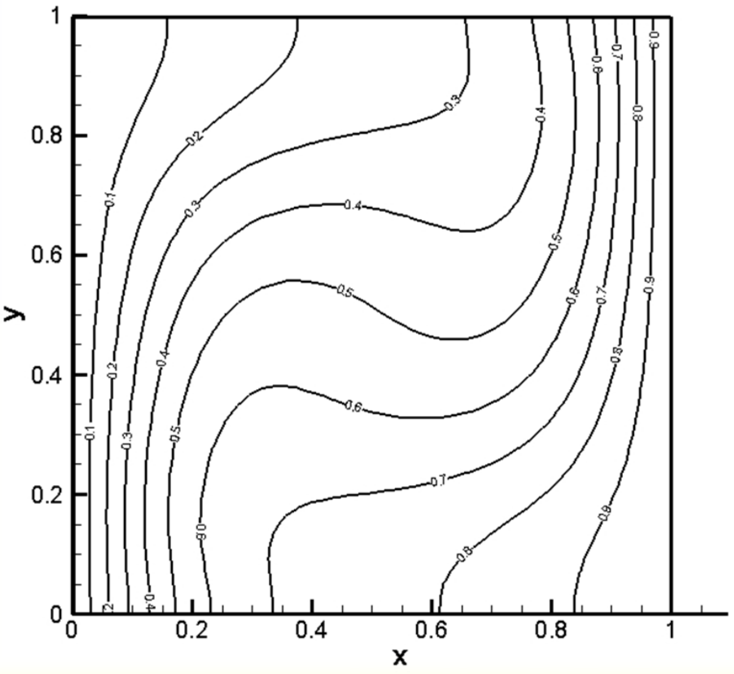

Fig. 3. Variation of nanoparticle distribution along the hot wallat Ra = 10^5

However, it is more uniform for low Rayleigh number. For any case, nanoparticle concentration is higher at the top middle side and values are decreased with increasing of volume fraction. This decreasing is more clear at higher Rayleigh numbers. On the contrary, nanoparticle volume fraction values are very small near the left and right bottom corners. This indicates that in the analysis of thermal transport in nanofluid, one must be concerned about the near wall region which may have a lower or higher particle concentration, leading to higher or lower heat transfer rates.

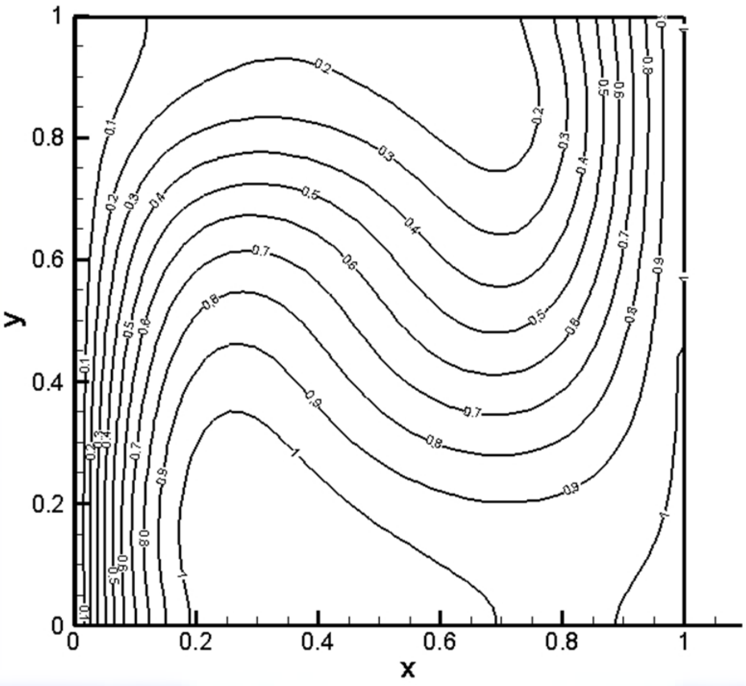

Fig. 4. Variation of nanoparticle distribution along the hot wallat Ra = 10^6

7. CONCLUSION

Buoyancy induced flow and heat transfer in a square enclosure filled with a water–Cu nanofluid has been numerically investigated. Main efforts of this investigation were focused on influence of Brownian and thermophoresis effects on the fluid flow and heat transfer characteristics. In the analysis of thermal transport in nanofluid, one must be concerned about the near wall region which may have a lower or higher particle concentration, leading to higher or lower heat transfer rates.

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