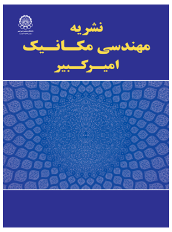

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Numerical analysis of flow and natural convection heat transfer in a circular enclosure heated from bottom utilizing porous layer

F. Mobadersani[1,*], F. Tavakkol[2]

[1] Faculty of Mechanical Engineering, Urmia University of Technology, Urmia, Iran
[2] Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

ABSTRACT: In the present paper, laminar flow and heat transfer of Fe_3O_4 /water nanofluid in a circular enclosure have been numerically carried out using the Buongiorno's model. A porous layer is attached to the hot wall of the enclosure and an applied uniform external magnetic field generates magnetohydrodynamic effect in the cavity. The simulations are performed utilizing a two-phase model and nano particle concentration distribution is presented. All of the equations are solved in dimensionless form. The control parameters in this study are Darcy number $(1e-6 \le Da \le 1e-1)$, angle of the applied magnetic field $(0 \le \gamma \le 90)$, Hartmann number $(0 \le Ha \le 200)$, effective conductive heat transfer coefficient of the porous layer $(10 \le k_{eff} \le 100)$, Rayleigh number $(1e3 \le Ra \le 5e5)$, geometrical parameters like porous layer thickness $(0.01 \le t_{layer} \le 0.09)$, and central angle of the cavity . The gained results which are derived in form of plots, contours, and also streamlines show the dependency of Nusselt number to control parameters. According to the results, any changes in Darcy number cause Nusselt number variations, and also there is a specified Darcy number that heat transfer reduces by an increase of Darcy number. Moreover, by an increment of Hartmann number, leading to higher Lorentz force, the average Nusselt number will reduce because the momentum of fluid flow and consequently convective heat transfer decrease inside the enclosure.

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1- Introduction

Natural convection heat transfer has attracted the attention of many researchers due to its extensive applications in engineering such as electrical cooling, air conditioning, insulation of reactors, solar collectors, fire protection systems, heat exchangers, etc. [1, 2]. Numerous numerical and experimental studies have been performed on various applications of heat transfer in the cavity. In the experimental investigation field, the studies of Davis [3] and Giva et al. [4] are momentous. Shi and Khodadai [5] numerically studied heat transfer in a cavity, in which a fin was placed on the hot wall. Park et al. [6] examined natural heat transfer in an inclined cavity with circular hot obstacles inside it numerically. Choi et al. [7] investigated the effect of placing a circular cylinder in a rhombus cavity on the natural heat transfer. They concluded that by changing the cylinder location from bottom to top of the cavity, the Nusselt number reduces significantly. Khanafer et al. [8] studied laminar natural heat transfer in a cavity with a porous fin attached to the hot wall. Kakarantzas et al. [9] studied nanofluid natural convection in a cavity under magnetic field effect and concluded that any increase in Hartmann number leads to a decrease of Nusselt number. Also, Rudraiah et al. [10] reached the same conclusion about the significance of conduction in a cavity in high Hartmann numbers.

As mentioned, cavities with different geometries have various applications in air conditioning systems, renewable energy, heat exchangers, etc., and due to the poor thermal performance of ordinary fluids, the researchers look for any active or passive methods to improve thermal performance. Indeed, it will be important to study any geometry or other possibility that may result in better thermal performance in the cavities. Based on the authors' best knowledge, there is no work about the nanofluid flow and heat transfer in a quarter of a circular cavity considering two-phase method, so far. Additionally, magnetohydrodynamics effects are considered in the present paper by applying a uniform magnetic field, and also, a porous thin layer has been inserted above the hot wall of the cavity.

2- Mathematical Modeling

In this paper, the incompressible, steady, and two-dimensional flow assumptions are considered to investigate natural convection inside a floor-heated circular cavity with a porous layer mounted on its hot wall. The geometry of the problem is presented in Fig. 1 along with the boundary conditions. The radius of the circular cavity is R and the boundary conditions in this case, whose geometry is a quarter of a circle, are the hot temperature T_h at the bottom of the

*Corresponding author's email: fmobadersani@gmail.com

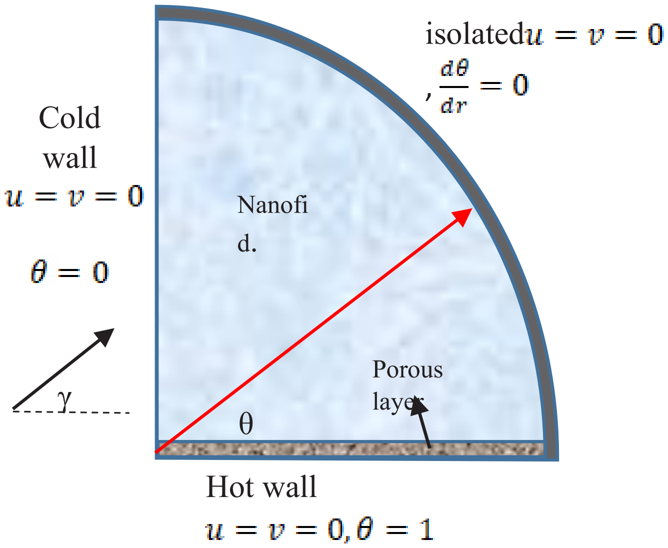

Fig. 1. Geometry and boundary conditions

cavity and the cold temperature T_c at the left wall, as well as the arc of the cavity is adiabatic. It should be noted that the values of hot and cold temperatures are assumed to be such that the fluid does not change phase. Also, any changes in physical properties of the base fluid with respect to temperature can be ignored (except for the fluid density). The chamber contains nanofluid Fe_3O_4-water and also has a porous layer according to the shape with a dimensionless thickness T_{layer} located on the floor of the cavity attached to the hot wall. It is assumed that the surface of the nanoparticles is covered with surfactant, which prevents them from settling on the solid wall of the porous area or sticking to each other [11]. It should be noted that the presence and absence of this layer, as well as its dimensionless thickness, are among the control parameters of the problem and variable. In the porous region, the Local Thermal Equilibrium (LTE) is assumed and the developed Darcy (Forchheimer-Brinkman) relationship is used. The uniform magnetic flux *B* is induced by the angle γ to the fluid field, which leads to the application of the Lorentz force (magnetohydrodynamic force) on the fluid elements. The diameter of the nanoparticles of Fe_3O_4 is 10 nanometers and the base fluids Prandtl number is 6.97. It is assumed that the density changes are only a function of temperature and follow the Boussinesq approximation. On the other hand, the distribution of nanoparticles inside the cavity has been calculated using the Buongiorno model.

The governing equations including continuity, momentum, energand nanoparticle distribution equations for both the clear and porous regions are solved numerically.

The governing equations for the porous layer are as follows:

-continuity equation:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

-Momentum equation in *X*-direction:

$$\begin{aligned}\frac{\rho_{nf}}{\rho_f}\frac{1}{\varepsilon^2}(U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y}) = -\frac{\partial P}{\partial X} + \frac{\Pr}{\varepsilon}(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2})\frac{\mu_{nf}}{\mu_f} - \frac{\Pr}{Da}U\left(\frac{\mu_{nf}}{\mu_f}\right) \\ -\frac{F}{\sqrt{Da}}|V|U - Ha^2 \Pr\left(\frac{\sigma_{nf}}{\sigma_f}\right)(B_y{}^2 U - B_x B_y V)\end{aligned} \tag{2}$$

-Momentum equation in *Y*-direction:

$$\begin{aligned}\frac{\rho_{nf}}{\rho_f}\frac{1}{\varepsilon^2}(U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y}) = -\frac{\partial P}{\partial Y} + \frac{\Pr}{\varepsilon}(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2})\frac{\mu_{nf}}{\mu_f} - \frac{\Pr}{Da}V\left(\frac{\mu_{nf}}{\mu_f}\right) \\ -\frac{F}{\sqrt{Da}}|V|V - Ha^2 \Pr\left(\frac{\sigma_{nf}}{\sigma_f}\right)(B_x{}^2 V - B_x B_y U) \\ +Ra\Pr\left(\frac{\beta_{nf}}{\beta_f}\right)\left(\frac{\rho_{nf}}{\rho_f}\right)\theta\end{aligned} \tag{3}$$

-Energy equation:

$$\begin{aligned}B(U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y}) = \frac{k_{eff}}{k_{nf}}(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}) + N_b(\frac{\partial \phi}{\partial X}\frac{\partial \theta}{\partial X} + \frac{\partial \phi}{\partial Y}\frac{\partial \theta}{\partial Y}) \\ +N_t\left[(\frac{\partial \theta}{\partial X})^2 + (\frac{\partial \theta}{\partial Y})^2\right]\end{aligned} \tag{4}$$

-Nanoparticle distribution

$$\begin{aligned}(U\frac{\partial \phi}{\partial X} + V\frac{\partial \phi}{\partial Y}) = \frac{\varepsilon}{Le}(\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2}) \\ +\frac{N_t \varepsilon}{LeN_b}(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2})\end{aligned} \tag{5}$$

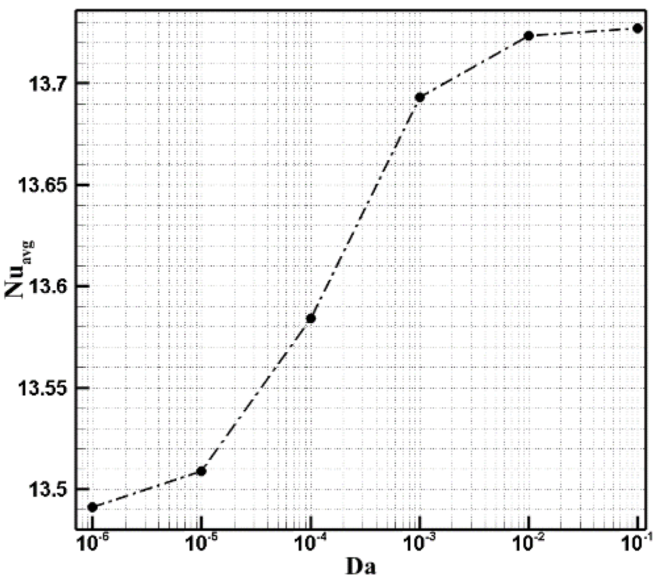

Fig. 2. Variations in the average Nusselt number by Darcy number considering

Ra=1E5, Ha=30, γ=45, k_eff=10

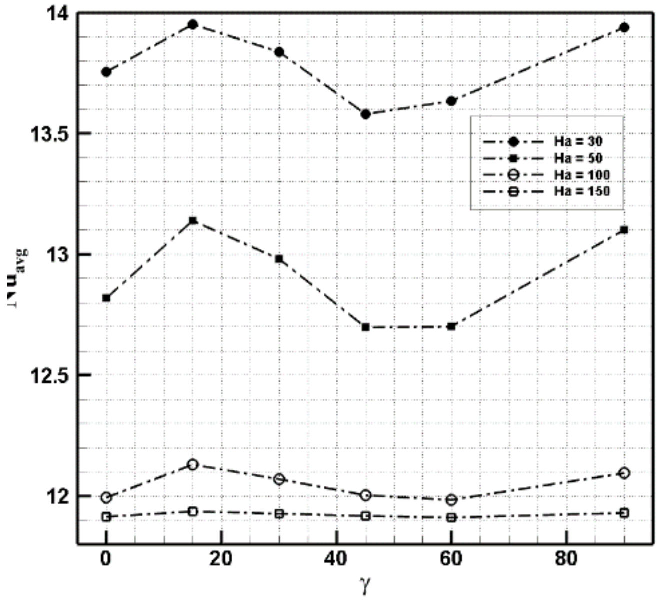

Fig. 3. Variations in the Nusselt number according to the magnetic field applying angle and

Ra=1E5, Da=5E-5, =10

Due to the continuum hypothesis of temperature, momentum, and nanoparticle distribution at the porous and clear regions interfaces and also the no-slip condition at the solid walls, the boundary conditions are as follows:

-At the interface of the clear and porous region:

$$U_{Nanofluid} = U_{porous} \ , \ V_{Nanofluid} = V_{porous} \ , \ \left.\frac{\partial U}{\partial n}\right|_{fluid} = \frac{1}{\varepsilon}\left.\frac{\partial U}{\partial n}\right|_{porous} \ , \ \left.\frac{\partial V}{\partial n}\right|_{fluid} = \frac{1}{\varepsilon}\left.\frac{\partial V}{\partial n}\right|_{porous} \quad \theta_{Nanofluid} = \theta_{porous} \ , \quad \phi_{fluid} = \phi_{porous} \ , \quad \left.\frac{\partial \phi}{\partial n}\right|_{fluid} = \left.\frac{\partial \phi}{\partial n}\right|_{porous} \tag{6}$$

-At the walls:

$$U(0,Y) = V(0,Y) = 0, \quad \theta(0,Y) = 1, \quad \theta(\sqrt{X^2+Y^2}=1) = 0, \quad N_b \left.\frac{\partial \phi}{\partial X}\right|_{\sqrt{X^2+Y^2}=1} + N_t \left.\frac{\partial \phi}{\partial X}\right|_{\sqrt{X^2+Y^2}=1} = 0 \ , \ U(\sqrt{X^2+Y^2}=1) = V(\sqrt{X^2+Y^2}=1) = \quad U(X,0) = V(X,0) = 0 \ , \ \frac{\partial \phi(X,0)}{\partial Y} = \frac{\partial \phi(X,1)}{\partial Y} \tag{7}$$

3- Result and Discussion

In the present paper, the flow and heat transfer of nanofluid within a circular enclosure with a porous layer over the hot wall are analyzed using two-phase method. In addition, a uniform magnetic field on the fluid field has been applied, which caused magnetohydrodynamic effects. The numerical results are verified by comparing against different previously published numerical and experimental data. By examining the various simulations, we can obtain the effective parameters in this problem, which include: the angle of the enclosure (in small Hartmann numbers), the Hartmann number, the angle of application of the magnetic field, the dimensionless thickness of the porous layer and the Darcy number (in numbers).

Fig. 2 reports the average Nusselt number variations versus Darcy number. In low Darcy numbers, the pressure drop increases due to the low permeability of the porous region. Thus, the fluid elements' momentum decreases which results in a reduction of the Nusselt Number.

To investigate the Lorentz force effects on the fluid flow and heat transfer in the enclosure, average Nusselt number changes versus Hartmann number and the magnetic field applying angle are illustrated in Fig. 3. Whenever **γ** is zero the Lorentz force is applied in *Y* direction which leads to weakening the *Y* direction elongated vortices. According to this figure, the maximum Nusselt number happens in the case of **γ**=90, in which the buoyancy force is not affected by Lorentz force.

4- Conclusions

In the present paper, the nanofluid heat transfer in a quarter of a circular cavity has been performed. Also, a uniform magnetic field has been applied to the fluid field to study the Lorentz force.

The results indicate that severe nanoparticle distribution gradients are formed in lower sector angles. According to the results, any changes in Darcy number cause Nusselt number variations, and also there is a specified Darcy number that heat transfer reduces by an increase of Darcy number. Moreover, by an increment of the Hartmann number, leading to a higher Lorentz force, the average Nusselt number will reduce.

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