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RESEARCH ARTICLE OPEN ACCESS

Simulation of the mixed convection in 3d cylindrical cavity filled with Copper-OxideWater nanofluid

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ABSTRACT
The problem of mixed convection heat transfer and flow of Copper oxide and water nanofluid were studied for different Reynolds numbers and concentrations. The geometry of the simulation is a cylindrical lid-driven cavity with hottop wall and cold bottom wall. The rest of the walls were kept as isolated walls. The top wall is rotating around the axis of the cylinder with a constant angular velocity. The equations were converted to non-dimensional form and the effect of nano particles were implementedby considering the effective Reynolds and Prandtl numbers. The case was simulated for Re= 100, 400 and 1000 and nanoparticle mass concentration of 0 to 5%. The results were presented in the form of the isothermal contours and average Nusselt number curves of the top walls for different Re numbers and concentrations. The results show that the particles do not have any effect on the flow field which decreases the risk of corrosion. Also, the most effective parameter is the Reynolds number which increases the Nusselt number dramatically. Increasing concentration of the particles increase the Nusselt number but there is an optimum value for it and for larger values, it starts decreasing.
***Keywords*–**Convection, Nanofluid, Cavity, Cylindrical Coordinate

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I. INTRODUCTION

In many industrial cases, we need to remove heat from surfaces and for this matter liquids are the best medium to transfer heat. But in many cases, the thermal properties of the liquids are not enough to have efficient heat transfer. To increase thermal properties of liquids, the most effective way is to add small particles of order of tens of nanometer in the liquids. For the first time, Choi and Eastman showed that adding nanoparticles to the base fluid can increase the thermal conductivity of the base fluid[1]. Many researches have shown the thermal conductivity could be increased by adding low concentration of nanoparticles[2]–[5]. Nanoparticles are small particles of metals and metal-oxides which their size is between 1 to 150 nanometers. One feature of this small size is to sustain in the liquids and making homogeneous liquids although, if they stop moving, they will settle down.

Hatami studied free convection in a wavy-wall cavity including a heated cylinder[6]. They showed that the Nusselt number increases by increasing the internal diameter of the cylinder while the diameter is less than one. As the diameter increases more than one, the heat transfer performance decreases due to occupying the space inside the cavity by the cylinder. Alsbary et al. Numerically studied mixed convection in differentially heated cavity with a cylinder inside the cavity[7]. They found that the shape of cavity wave and cylinder size can be a critical parameter to control heat transfer performance inside the cavity.

Natural convection in a partially heated side walls cavity was studied by Tiwari et al. [8]. They used a finite volume method for simulation of a cavity with insulated top and bottom walls. The cavity contained nanofluid of copper and water. They studied the effect of Richardson number and nanoparticles concentration on the heat transfer from the side walls. They found out for the low Richardson number the effect of concentration is higher. Ho et al. Studied the effect of different thermal conductivity and viscosity model on the simulation of the water and alumina nanofluid in a square cavity[9]. They discovered that different models can hugely affect the predicted Nusselt numbers.

Mixed convection of heat transfer was studied in a rectangular lid-driven cavity using finite volume method by Muthtamilselvan et al. [10]. The side walls of cavity were insulted while the top and bottom walls had constant temperature and the cavity was filled with copper and water nanofluid. They observed that the particle concentration and the aspect ratio of the cavity influences the heat transfer performance inside the cavity. Talebi et al simulated mixed convection in a cavity with partially heated side walls while the top and bottom walls keep insulated[11]. They used a finite volume code for simulation, and they used copper nanoparticles and water as nanofluid. They found that for all Reynolds and Richardson numbers adding nanoparticles can enhance heat transfer of inside the cavities. Niazmand et. Al studied the effect of adding Alumina nanoparticles in the lid driven cylindrical cavity[12]. They used a finite volume method to simulate the mixed convection inside the cavity. They found that the height ratio of the cylindrical cavity increases the heat transfer inside the cavity up to 46%.

Nada et al investigated mixed convection in an inclined square cavity filled water and Al2O3[13]. They used finite volume method to solve stream function vorticity equation rather than Navier Stokes. They found that adding nanoparticles can hugely increase the performance of heat transfer and they observed this increase for all Reynolds and Richardson numbers. Influence of variable properties of two nano fluids (water- CuO and Water- Al2O3) in a rectangular enclosure were studied by Abu-nada et al [14]. They observed at high Richardson viscosity has higher influence on Nusselt number compare to thermal conductivity.

Mansour et al. studied the effect of Reynolds number, different location of the heater and concentration of different nanoparticles[15]. Their findings showed that the larger heater increases the Nusselt number similar to increasing the concentration of nanoparticles. Shahi et al. numerically investigated mixed convection in a partially heated cavity[16]. The cavity had an inlet and outlet and filled with nanofluid. They studied the effect of Richardson number and different concentration of the nanoparticles and they found at low Richardson number, adding nanoparticles has more influence on the heat transfer rather than Richardson number increasing. Also, many current researches havefocused on the effect of the magnetic field on the nanoparticles during manufacturing processes[17]–[19].

In the current work, heat transfer inside a cylindrical cavity filled is investigated. The volume concentration of the nanoparticles varies from 0 to 5 percent and the Reynolds varies from 10 to 400 while the Richardson number is between 10^3 to 10^5. Most of the previous cases just focused on the square (2D) or cubical (3D) cavities but in industries many have cylindrical cases and therefore, for this work a one-fourth 3D cylindrical cavity has simulated with finite volume CFD method. Eventually the results are shown in the form of isotherms, streamlines and average Nusselt numbers.

II. MODELING

Figure 1 shows the computational domain of this study. The domain includes a cylindrical cavity with inner diameter of the 0.5 and the outer diameter of the 1. The height of the cylinder is 1 for all cases while the slice angle is 90 degree. The boundary condition for this study is as mentioned below:

1- Top wall:
$$u_r = 0, u_\phi = r\omega, u_z = 0, \theta = 1$$
2- Bottom wall:
$$u_r = 0, u_\phi = 0, u_z = 0, \theta = 0$$
3- Other walls:
$$u_r = 0, u_\phi = 0, u_z = 0, \frac{\partial \theta}{\partial n} = 0$$

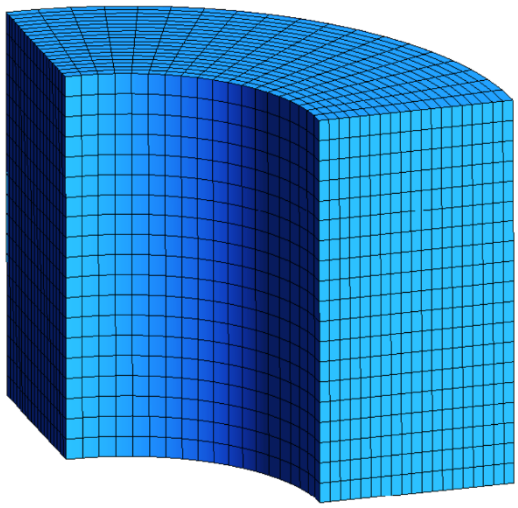

Figure 1: Structured grid used as computational domain

the Navier-Stokes and the energy equations were solved with a coupled method. To make it easier to control the parametric study, the equations were non-dimensionlized based on the reference parameters. Equations 1-4 show the nondimensional form of the NS and energy equations. For solving these equations, a Fortran code was developed based on the SIMPLE methods. This method is a coupling method for pressure and continuity equation[20].

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

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re}\left[\frac{\nu_{nf}}{\nu_f}\right]\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + Ri\cos\vartheta \tag{2}$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re}\left[\frac{\nu_{nf}}{\nu_f}\right]\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + Ri\sin\vartheta \tag{3}$$

$$\frac{\partial \theta}{\partial \tau} + U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{RePr}\left[\frac{\alpha_{nf}}{\alpha_f}\right]\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{4}$$

Where $\tau = \frac{t}{L/U}, X = \frac{x}{L}, Y = \frac{y}{L}, U = \frac{u}{u_{ref}}, V = \frac{v}{u_{ref}}, P = \frac{p}{\rho U^2}, \theta = \frac{T-T_c}{T_H-T_c}, Re = \frac{u_{ref}\,R_{ave}}{v_f}, Pr = \frac{v_f}{\alpha_f}$ and the key parameters are defined as $Gr = \frac{g\beta\,(T_H-T_c)H^3}{{v_f}^2}$, $Gr = Ra.Pr^{-1}$, $Ri = Gr.Re^{-2}$.

To increase the performance of cooling usually nanoparticles are added to the base liquid. These particles normally are metals and metal oxides due to higher thermal conductivity compare to the base liquid. There are many theoretical equations which let us to calculate the properties without doing experimental measurement which is really expensive. For properties like density, heat capacity and thermal expansion coefficient, a simple averaging is enough, and those models can predict the properties perfectly. Equation 5-7 shows the equation which was used in this study for density, specific heat, and thermal expansion coefficient.

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s \quad (5)$$

$$\left(\rho C_p\right)_{nf} = (1-\phi)\left(\rho C_p\right)_f + \phi\left(\rho C_p\right)_s \quad (6)$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_s \quad (7)$$

The behavior of the viscosity and thermal conductivity which are the diffusion coefficients cannot be calculated through weight averaging based on the nanoparticles concentration. Therefore, the correlation of Maxwell was used for calculation of viscosity and thermal conductivity of mixtures.

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \quad (5)$$

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\phi\left(k_f - k_s\right)}{k_s + 2k_f + \phi\left(k_f - k_s\right)} \quad (6)$$

For assuring that the discretization has no effect on the results, the grid independence tests were done for 3 different grid size. The boundary condition kept the same and the physical condition is kept at Re=100 and the Ri number is 0. The Nusselt number is calculated on the top surface and the mean value was calculated based on the area averaging. Table 1 shows the comparison for the Nusselt number of three different grids.

Table 1: grid independence test for Re=100 and three different grid sizes.

Number of grids	Average Nusselt
35k	1.798
50k	1.835
70k	1.838

Also, for validating of the case, the current geometry was simulated for the same conditions with Ref[12]. The condition for this simulation was Richardson number equal to 0.001 and the Reynolds number varies from 100 to 1000. These conditions guarantee that the flow regime stays in Laminar conditions.Table 2 shows the comparison of validation simulation with values from reference [12]. The comparison shows the error between the present simulation and the reference values are less than one percent which shows the correctness of the code developed for this purpose.

Table 2

Comparison of averaged Nusselt number at top wall

	Ri	0.001	
		Ref. [12]	present
Re	100	1.837	1.84
	400	3.94	3.96
	1000	7.15	7.17

In the current research, the thermal properties of Water and Copper oxide were substituted in the theoretical formula to calculate the effective properties for the nanofluid. Table 3 shows the thermal properties which were used in this study.

Table 3

Thermal properties of Water and Copper Oxide

	Water[2]	CuO[21]
Density(kg/m3)	998	6500
Specific heat (kJ/kg)	4.187	0.536
Viscosity(cP)	0.93	
Thermal conductivity(W/mK)	0.6	33

III. RESULTS AND DISCUSSION

In this section, the results of the numerical study are presented for a lid-driven cylindrical cavity filled with nanofluid CuO-Water for combined free and forced convection heat transfer. The results are presented in the form of streamlines, isothermal contours, and effective heat transfer coefficient (Nusselt number).

Figure 2 to Figure 4 show the streamlines in the cavity. Streamlines are vector field lines flow in a geometry. They show the direction which fluid elements travel and they are tangent to the velocity vectors. The streamlines have a circulation in the domain because the domain is closed. For the Re=100, the center of this circulation zone is at middle top of the domain. By increasing the Re to 1000, the center of this zone tends to the left due to the momentum of the flow. Also, the streamlines density of lines increases which shows that the velocity in the region between the corner and the center of the streamlines increases.

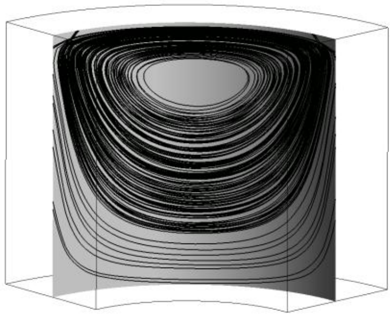

Figure 2: Streamlines of flow inside the cavity Re=100.

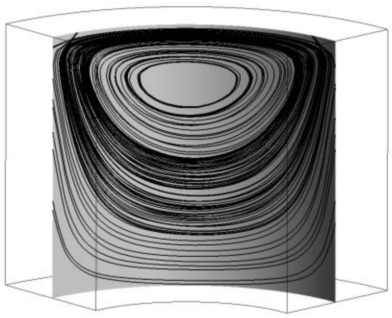

Figure 3: Streamlines of flow inside the cavity Re=400.

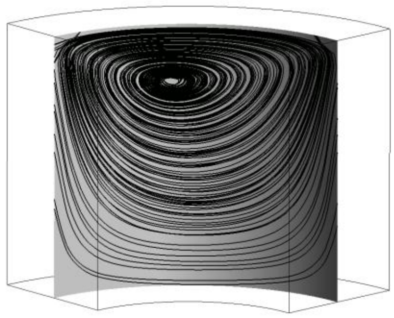

Figure 4: Streamlines of flow inside the cavity Re=1000.

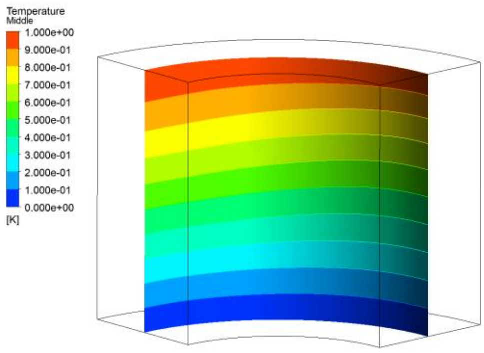

Figure 5: isothermal lines of flow inside the cavity Re=100.

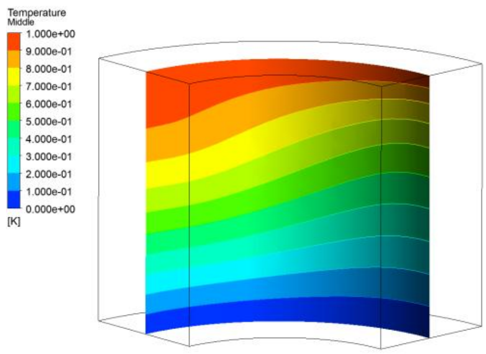

Figure 6: isothermal lines of flow inside the cavity Re=400.

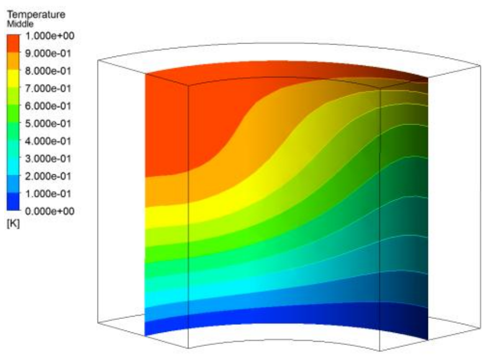

Figure 7: isothermal lines of flow inside the cavity Re=1000.s

Figure 5 to Figure 7 show the isothermal contours of the flow inside the domain. These contours show the distribution of the temperature field inside the cavity. For the Re=100, the isothermal contours are parallel which shows the conduction in the fluid is the dominant phenomena but for the Re=400 the contours bend due to velocity field. As the Re increases to 1000, the forced convection affects the heat transfer inside the domain more.Niazmand et. Al had found that the effect of the nanoparticles on the velocity field[12]is negligible in the case Alumina-Water nanofluid and for the current study,streamlines and isothermal lines of the flow field for different was compared and it was found that CuO nanoparticles have no effect on the velocity field but they just enhance the heat transfer from the walls.

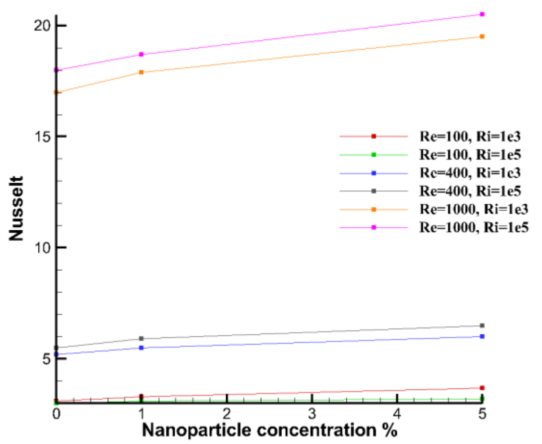

Figure 8: Effect of nanoparticle mass concentration, Re and Ri on the Nusselt number of the top wall

Figure 8 shows the effect of nanoparticle mass concentration, Reynolds, and Richardson number on the Nusselt number of the top wall. The results show that adding nanoparticles increase the Nusselt number but there is an optimum value for the concentration. This happens due to decrease of effective heat capacity. Heat capacity of solids are less than heat capacity of the liquids therefore, adding infinite number of particles do not work always. Also, Reynolds number increase the heat transfer due to increase in bulk transfer of the heat which happens due to turbulence. The Richardson number which shows the effect of gravity on the flow and thermal field does not have large effect on the Nusselt number.

IV. CONCLUSION

In the present study, the effect of adding nanoparticles to water was studied numerically using Finite volume method. The geometry includes a cylindrical lid-driven cavity which the top wall and bottom wall have constant temperature and the rest are isolated walls. The equations were solved in the form of non-dimensionlized form and the effective properties of the nanofluid were calculated based on the theoretical formula. The results depicted that adding nanoparticles to the water enhances heat transfer in the cavity but there is an optimum value for the concentration. Also, the Reynolds and Richardson number increase the heat transfer in the cavity, but the effect Reynolds number is much higher compare to the Richardson number.

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