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Numerical Study of Mixed Convection Heat Transfer in a Cavity Filled with Non-Newtonian Nanofluids Utilizing Two-phase Mixture Model

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ABSTRACT: In the present research, the problem of mixed convection flow of a non-Newtonian nanofluid in a lid-driven cavity is simulated using a two-phase mixture model. Nanofluid of water-copper in this problem shows a shear-thinning behavior. To study the effects of non-Newtonian fluid with power-law model on the amount of heat transfer, various power-law indices are considered. After applying the governing equations and related models in the computational code, its validation is done by simulating the problem with Newtonian and non-Newtonian fluid behavior and comparing the results with those of other researchers. Afterwards, simulation of the problem is accomplished for the Richardson numbers of 0.001-1 and power-law indices of 0.2-1 while the volume fraction of nanoparticles alters from 0 to 0.09. The obtained results show that the increase in Richardson number decreases the amount of heat transfer. For all Richardson number decrease in the power law index leads to a decrease in the average Nusselt number. Variation of volume fraction from 0 to 0.09 at the power law index of 0.2 leads to an approximate increase of 15.75% and 17.32% in the average Nusselt number for Ri=0.001 and 1, respectively.

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1- Introduction

Nanofluids are a new class of fluids composed of suspended solid nano-particles in a base fluid. The higher heat conductivity of metallic particles in comparison to the base fluid leads to a higher thermal conductivity of nanofluid in comparison to the base fluid [1].

Nowadays, by growing different industries, the use of non-Newtonian fluids, where the relation between shear stress and the rate of shear is nonlinear, is increasing [2]. Adding solid nanoparticles into the non-Newtonian base fluids results in non-Newtonian nanofluids where their thermal properties are usually better than the base fluid.

For numerical simulation of nanofluids, single and two-phase models may be used. In the present research, however, the two-phase mixture model is utilized. In this model, the slippage between the phases is taken into the account by considering an algebraic formula [3].

In this article, mixed convection of non-Newtonian nanofluids in a lid-driven cavity is investigated using a two-phase mixture model. The effects of the Richardson number, power-law index and solid volume fraction on the heat transfer enhancement of nanofluids are examined.

2- Methodology

The well-known two-phase mixture model is used for mathematical modeling of the problem. In this model, in addition to the continuity, momentum and energy equations, a partial differential equation for volume fraction and an algebraic equation for slippage between the phases are derived to be able to compute the velocity and volume fraction of each phase. The PIMPLE algorithm [4] of open source code, OpenFOAM 2.4.0 is used for velocity-pressure coupling. The solver "dirftFluxFoam" is employed and developed to solve the governing equations of the non-Newtonian mixture model for nanofluids. Additionally, the Boussinesq approximation is used for computation of buoyancy force.

2- 1- Governing equations

The following set of equations is solved for the mathematical modeling of the problem according to the two-phase mixture model [5]:

-continuity

$$\nabla.(\rho_{eff}\vec{V}_m)=0 \tag{1}$$

-momentum

$$\begin{aligned}\nabla.(\rho_{eff}\vec{V}_m\vec{V}_m)&=-\nabla P+\nabla.[\tau]\\&+\rho_{eff}\,\beta_{eff}\,g\,(T-T_0)+\nabla.(\sum_{k=1}^{2}\phi_k\,\rho_k\vec{V}_{dr,k}\vec{V}_{dr,k})\end{aligned} \tag{2}$$

-energy

$$\nabla.\sum_{k=1}^{2}(\phi_k\,\rho_k\vec{V}_k C_{p,k}T)=\nabla.(K_{eff}\nabla T) \tag{3}$$

-volume fraction

$$\nabla.(\phi_p\rho_p\vec{V}_m)=-\nabla.(\phi_p\rho_p\vec{V}_{dr,p}) \tag{4}$$

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The effective density, volumetric specific heat and thermal expansion coefficient of nanofluid are calculated using the following relations [3]:

$$\rho_{eff} = \rho_p \phi + (1-\phi)\rho_f \tag{5}$$

$$(\rho C_p)_{eff} = (\rho C_p)_p \phi + (\rho C_p)_f (1-\phi) \tag{6}$$

$$(\rho\beta)_{eff} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_p \tag{7}$$

Furthermore, the conductivity of nanofluid can be computed using Hamilton–Crosser as follows [6]:

$$\frac{K_{eff}}{K_f} = \frac{K_p + 2K_f - 2\phi(K_f - K_p)}{K_p + 2K_f + \phi(K_f - K_p)} \tag{8}$$

3- Description of the problem

The problem under investigation consists of a lid-driven cavity is shown in Fig. 1. This cavity is filled by water and copper nanoparticles while the nanofluid shows a shear thinning behavior. In this study, three Richardson numbers (i.e. 0.001, 0.01 and 1), different values of power-law indices (ranges from 0.02 to 1) and volume fractions (ranges from 0.0 to 0.09) are selected to examine their effects on the thermal characteristics and hydrodynamic behaviors of the problem.

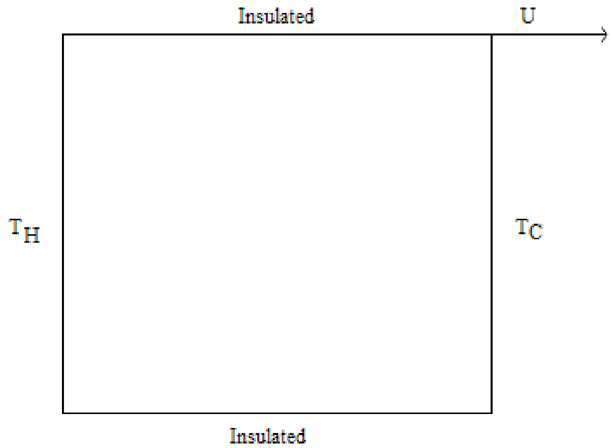

Fig. 1. Geometry of the present study

4- Results and Discussion

As shown in Fig. 2, by increasing the volume fraction of solid particles, the temperature at the middle of the cavity decreases. The reason is that the increase of volume fraction leads to a higher temperature gradient near the solid wall and then a decrease in the value of temperature at the middle of the cavity occurs. The aforementioned numerical experiment is performed at Ri = 0.001 and n=0.2.

One of the advantages of two-phase mixture model over single phase model is its ability to predict the distribution of solid volume fraction in the cavity. Hence, the variation of volume fraction at X=0.2 using different values of Richardson number is plotted in Fig. 3. As this figure shows, by decreasing the Richardson number, the value of a solid particle on the wall of the cavity increases. Solid particles

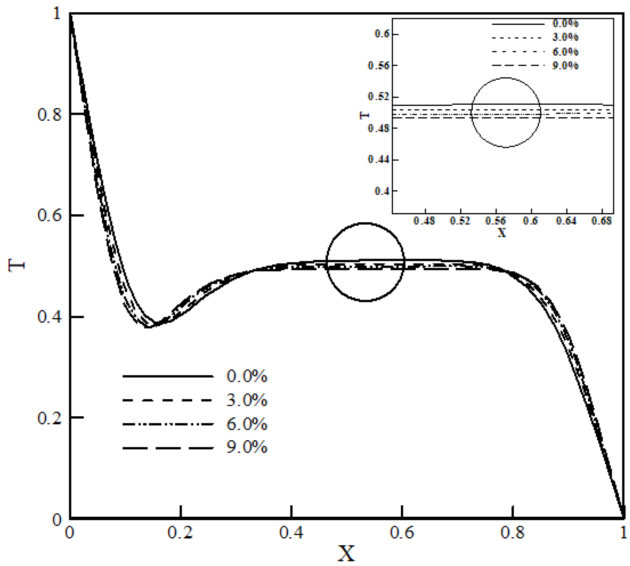

Fig. 2. Distribution of temperature in the middle of the cavity (Y=0.5) for different volume-fractions at n=0.2 and Ri=0.001

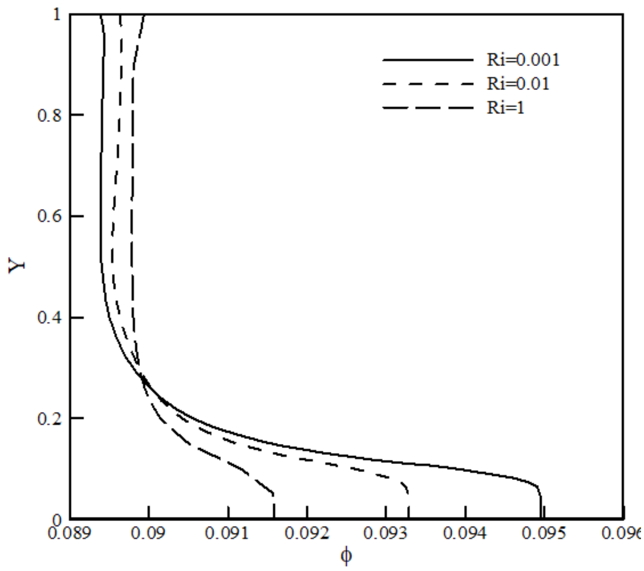

Fig. 3. Distribution of nanoparticles at (X=0.2) for different Richardson numbers and n=0.2

accumulate in the vicinity of the wall by decreasing the Richardson number. Due to a decrease in the Richardson number, the value of Reynolds number increases and hence the streamlines come closer together in the neighborhood of the wall and this makes more accumulation of solid particles in the vicinity of the wall.

5- Conclusion

Mixed convection heat transfer in a lid-driven cavity filled with a non-Newtonian nanofluid was examined using a two-phase mixture model. The effects of the Richardson number, power law index and volume fraction on the thermal characteristics and hydrodynamics of the problem were examined. It was found that, by increasing the solid volume fraction a higher temperature gradient at the pipe wall and lower temperature gradient at the middle of the pipe took place. Furthermore, by decreasing Richardson number, accumulation of solid particles in the vicinity of the cavity wall can be seen.

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