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Numerical Study of Natural Convection of Al_2O_3-Water Nanofluid with Variable Properties in a Cavity

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ABSTRACT

Heat transfer enhancement of Al_2O_3-water nanofluid with variable properties in a square cavity is investigated by solving the boundary layer equation and the Boussinesq-approximation form of the boundary layer equation. The governing equations are solved using the finite volume method and the SIMPLER algorithm. Temperature difference between the hot and cold walls of the cavity is considered to be 50°C, and the results are presented for Rayleigh numbers from 10^3 to10^5 and volume fraction of the nanoparticles from 0.0 to 0.09. The results show that the average Nusselt number and the maximum absolute value of the stream function for the case with variable density are greater than the corresponding value for the constant density case. Moreover, for the variable density case, the maximum heat transfer enhancement for the nanofluid occurs at $Ra=10^3$. However for $\varphi=0.09$, the average Nusselt number of the nanofluid for $Ra=10^4$ and 10^5 are lower than that of the base fluid. For $\varphi=0.01$, the maximum relative enhancement of the Nusselt number for $Ra=10^3$, $Ra=10^4$, and 10^5 are %26, %24 and %23, respectively.

KEYWORDS

Natural Convection, Nanofluid, Variable Properties, Cavity, Boussinesq Approximation.

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1- INTRODUCTION

Ultrahigh cooling performance is one of the most vital needs in many industrial technologies. However, inherently low thermal conductivity is a primary limitation against developing energy-efficient heat transfer fluids. Nanofluids are engineered by suspending nanoparticles with average sizes below 100 nm in traditional heat transfer fluids such as water, oil, and ethylene glycol. Abu-Nada et al. studied the natural convection of Al_2O_3–water nanofluid with variable properties in an enclosure. They observed that, for high and low Rayleigh numbers, the average Nusselt number increased and decreased with increasing the volume fraction of the nanoparticles, respectively [1].

In previous studies, the free convection of nanofluids is simulated using theBoussinesq approximation. In this study, however, changes in water density are considered using curve fitting of the experimental data.

In this numerical study, the difference between the results obtained by using the Boussinesq and without the approximation in the natural convection of Al_2O_3-water nanofluid in the square cavity is compared. The thermal conductivity, the viscosity and the density are considered to vary with temperature according to Chon et al.'s model, Abu-Nada et al.'s model, and curve fitting of experimental data, respectively.

2- GOVERNING EQUATIONS

The governing continuity, momentum and energy equations are given by [2]:

$$\frac{\partial \rho_{nf} u}{\partial x}+\frac{\partial \rho_{nf} v}{\partial y}=0 \tag{1}$$

$$\begin{aligned}\rho_{nf}\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]&=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial y}\left[\mu_{nf}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]\\&+\frac{\partial}{\partial x}\left[2\mu_{nf}\frac{\partial u}{\partial x}+\frac{2}{3}\mu_{nf}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]\end{aligned} \tag{2}$$

The momentum equation without using the Boussinesq approximation, and the energy equation are:

$$\begin{aligned}\rho_{nf}\left[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]&=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left[\mu_{nf}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]\\&+\frac{\partial}{\partial y}\left[2\mu_{nf}\frac{\partial v}{\partial y}+\frac{2}{3}\mu_{nf}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]-\rho_{nf}g\end{aligned} \tag{3}$$

$$(\rho c_p)_{nf}\left[u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right]=\frac{\partial}{\partial x}\left(k_{nf}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{nf}\frac{\partial T}{\partial y}\right) \tag{4}$$

The Boussinesq-approximation form of the momentum equation is given by:

$$\begin{aligned}\left[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]&=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+g\beta_{nf}\left(T-T_r\right)\\&+\frac{1}{\rho_{nf}}\left[\frac{\partial}{\partial x}\left(\mu_{nf}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{nf}\frac{\partial v}{\partial y}\right)\right]\end{aligned} \tag{5}$$

The density, the specific heat, the viscosity, and the thermal conductivity of nanofluid are [1, 3, 4]:

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_p \tag{6}$$

$$(\rho c_p)_{nf}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_p \tag{7}$$

$$\begin{aligned}\mu_{Al_2O_3}&=\exp(3.003-0.04203T-0.5445\varphi\\&+0.0002553T^2+0.0524\varphi^2-1.622\varphi^{-1})\end{aligned} \tag{8}$$

$$\begin{aligned}k_{nf}&=(1+64.7\varphi^{0.7640}\left(d_f/d_p\right)^{0.3690}\\&\times\left(k_p/k_f\right)^{0.7476}\mathrm{Pr}_T{}^{0.9955}\mathrm{Re}^{1.2321})k_f\end{aligned} \tag{9}$$

The viscosity, the expansion coefficient and the density of the base fluid (water) are

$$\begin{aligned}\mu_f&=(1.272(\ln T)^5-8.736(\ln T)^4+33.7(\ln T)^3\\&+246.6(\ln T)^2+518.9(\ln T)+1153.9)\times10^{-6}\end{aligned} \tag{10}$$

$$\beta_f=8.9\times10^{-6}(\ln T)^{2.872} \tag{11}$$

The density of water while not using the Boussinesq approximation, obeys the following relation:

$$\rho_f=1094.1\exp(-0.001045T)-94.137\exp(-0.01252T) \tag{12}$$

When using the Boussinesq approximation, the water density is obtained from the following relation:

$$\rho_f=\rho_{f_0}(1-\beta_{f_0}(T-T_r)) \tag{13}$$

Dimensionless variables including the Raleigh number, the Prandtl number, the Nusselt number and the average Nusselt number are:

$$\begin{aligned}Ra&=\frac{g\beta_{f_0}(T_H-T_C)H^3}{\alpha_{f_0}\nu_{f_0}}\\\mathrm{Pr}&=\frac{\nu_{f_0}}{\alpha_{f_0}}\\Nu&=\frac{hH}{k_f}=-\frac{k_{nf}}{k_f}\frac{\partial\theta}{\partial X}\bigg|_{X=0}\\Nu_{avg}{}^{*}&=\frac{Nu_{avg}(\varphi)}{Nu_{avg}(\varphi=0)}\end{aligned} \tag{14}$$

3- SIMULATION RESULTS

The mean Nusselt number obtained using variable density is compared with that obtained for constant density for Ra=10^5 in figure 1. It is observed that the mean Nusselt number for variable density is less than that of the constant density.

To show the effect of nanoparticles on the heat transfer coefficient, the Nusselt number versus Rayleigh number for the nanofluid and the base fluid is compared in figure 2. As observed, the averageNusselt number of nanofluids increases about 25%.

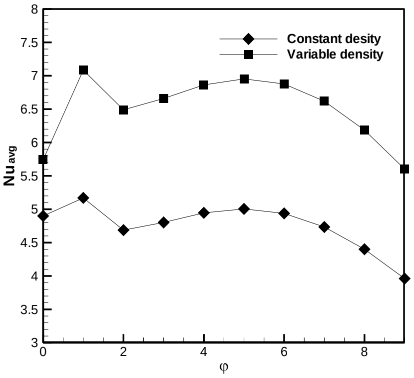

Figure. 1: Variations of average Nusselt number with φ for Ra=10^5

4- CONCLUSIONS

By considering the reference temperature at the cold wall compared to mean temperature, the density difference between the Boussinesq approximation and the non-Boussinesq case will increase.

The predicted average Nusselt number and stream function for constant density are higher in the case with variable density.

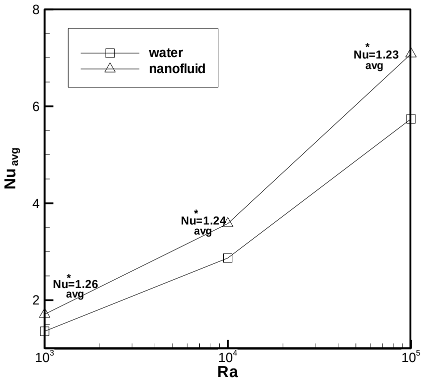

Figure. 2: Variations of Nusselt number versus Ra: comparison between the nanofluid and the base fluid

5- REFERENCES

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