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EFFECT OF ASPECT RATIO ON NATURAL CONVECTION HEAT TRANSFER INSIDE ENCLOSURE WITH NANOFLUIDS USING TWO-PHASE EULERIAN-EULERIAN MODEL

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1. ABSTRACT

In the present work, Numerical investigation is performed to analyse the influence of the aspect ratio of a rectangular enclosure on flow and heat transfer with Cu-H_2O as a nanofluid using the Eulerian-Eulerian model. The enclosure considered is differentially heated, with top and bottom walls insulated. The aspect ratios (AR=H/W) of the enclosure considered in this study are 0.5, 1.0 and 2.0. All the governing equations are discretised with the help of finite difference methods. The flow and heat transfer study is conducted at three different aspect ratios for various Grashof numbers (Gr $=10^3$ to 10^6) and nanoparticle volume fractions (Φ_s=1% to 3%). The enhancement in heat transfer performance is observed as the aspect ratio increased from 0.5 to 2.0 at a specific Grashof number. The heat transfer augmentation is also observed by increasing the Grashof number and volume fraction at a particular aspect ratio.

2. INTRODUCTION

For enhancement of heat transfer, an advanced heat transfer fluid named nanofluid [1] is introduced by suspending nanoparticles in conventional fluids like water, ethylene glycol, oils, etc. Nanofluids exhibit greater thermal conductivity than base fluids, which may lead to greater heat transfer. In natural convection flow applications like cooling of electronic devices, solar collectors, automobile radiators, etc., where heat transfer requires a cooling medium, nanofluids can be a suitable replacement for conventional fluids. In their experimental work, Ho et al. [2] showed an enhancement in heat transfer with Al_2O_3-H_2O nanofluid inside an enclosure under natural convection. The majority of numerical studies utilised a single-phase model to analyse nanofluid flows. In this model, the nanofluid is treated as a homogeneous mixture, and its thermophysical properties are evaluated as a function of both constituents. Khanafer et al. [3] noted an enhancement in heat transfer with nanofluids in a square cavity using the single-phase model. Abhijitith and Venkatasubbaiah [4] used a two-phase Eulerian-Eulerian approach to study forced convection in a nanofluid-filled minichannel, finding that it provides results closer to experimental values than the single-phase model. This study investigates the effect of the aspect ratio of an enclosure filled with Cu-H_2O nanofluid on flow and heat transfer behaviour using a two-phase Eulerian-Eulerian model, aiming for more accurate and realistic results than the single-phase model.

3. FORMULATION AND NUMERICAL METHODOLOGY

The natural convection inside a rectangular enclosure with Cu/H_2O nanofluid is investigated for three different height (H) to width (W) ratios (AR = H/W) such as 0.5, 1.0 and 2.0. The enclosure is differentially heated, with left and right walls maintained hot and cold respectively, and the top and bottom walls considered adiabatic. The Fortran-based Eulerian-Eulerian solver is developed to investigate the nanofluid flow in our study. The two-phase Eulerian-Eulerian model considers the governing equations for individual phase independently and coupling of two phases is done using interfacial interaction forces like drag and additional mass forces. The governing equations for each phase are shown below:

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3.1 Continuity equations

$$\frac{\partial}{\partial t}(\Phi_l\rho_l) + \nabla.(\Phi_l\rho_l v_l) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\Phi_s\rho_s) + \nabla.(\Phi_s\rho_s v_s) = 0 \tag{2}$$

3.2 Momentum equations

$$\frac{\partial}{\partial t}(\Phi_l\rho_l v_l) + \nabla.(\Phi_l\rho_l v_l v_l) = -\Phi_l\nabla \mathrm{p} + \nabla.\left[\Phi_l \mu_l\left(\nabla v_l + \nabla v_l^T\right)\right] + \Phi_l\rho_l\beta_l(T_l - T_c)g - F_d + F_v \tag{3}$$

$$\frac{\partial}{\partial t}(\Phi_s\rho_s v_s) + \nabla.(\Phi_s\rho_s v_s v_s) = -\Phi_s\nabla \mathrm{p} + \nabla.[\Phi_s \mu_s(\nabla v_s + \nabla v_s^T)] + \Phi_s\rho_s\beta_s(T_s - T_c)g - F_d + F_v - F_{col} \tag{4}$$

3.3 Energy equations

$$\frac{\partial}{\partial t}\left(\Phi_l\rho_l C_{p,l}T_l\right) + \nabla.\left(\Phi_l\rho_l C_{p,l} v_l T_l\right) = \nabla.\left[\Phi_l k_{eff,l}\nabla T_l\right] - h_v(T_l - T_s) \tag{5}$$

$$\frac{\partial}{\partial t}\left(\Phi_s\rho_s C_{p,s}T_s\right) + \nabla.\left(\Phi_s\rho_s C_{p,s} v_s T_s\right) = \nabla.\left[\Phi_s k_{eff,s}\nabla T_s\right] + h_v(T_l - T_s) \tag{6}$$

In equations, Φ, ρ, v denote volume fraction, density and velocity vector respectively with l and s in the subscript indicates liquid, solid phase respectively. The terms $\mathrm{F_d}$, $\mathrm{F_v}$, and $\mathrm{F_{col}}$ signify drag, additional mass, and particle-particle interaction forces, while $\mathrm{C_p}$, T, $\mathrm{h_v}$, and $\mathrm{k_{eff}}$ in the energy equations stand for specific heat, temperature, heat exchange coefficient, and effective thermal conductivity. The detailed information related to governing equations and the expressions for interfacial interactions are discussed in the work of Leelasagar and Venkatasubbaiah [5].

The Simplified Marker and Cell (SMAC) method is employed for solving the governing equations on a non-staggered grid, incorporating sixth-order compact schemes for nonlinear terms. The developed solver results are compared by experimental and numerical outcomes found in the existing literature.

4. RESULTS

This study investigates the effect of aspect ratio on flow and heat transfer for various values of Grashof number and volume fraction. The streamlines are represented in Fig. 1 for different aspect ratios demonstrating that the circulation intensifies with an increase in aspect ratio. As the aspect ratio increases, the distance between the hot and cold walls decreases, which leads to the transfer of heat from the hot wall to the cold wall very fast. Hence, the heat transfer is enhanced by increasing the aspect ratio, as mentioned in Table 1 for all Grashof numbers. It is also observed from the average Nusselt number values mentioned in Table 1 that at a fixed Grashof number, increasing the volume fraction boosts the flow velocity within the enclosure, leading to enhanced heat transfer rates for all the aspect ratios due to higher energy transport. Further by increasing the Grashof number the temperature difference between the left and right walls increases, which intensifies the convection currents due to an increase in buoyancy force leading to greater heat transfer.

The average Nusselt number correlation for the hot wall is proposed with Cu-H_2O nanofluid for the parameter ranges of $10^3 \le Gr \le 10^6, 0.5 \le AR \le 2.0, 1\% \le \Phi_s \le 3\%$. The correlation with a coefficient of determination $R^2 = 0.98$ is given below:

$$Nu_{avg} = 0.2417\, AR^{1.014}(1 + \Phi_s)^{5.219} Gr^{0.3577} \tag{7}$$

5. CONCLUSIONS

- The enclosure's aspect ratio has a significant impact on heat transfer. By increasing the enclosure's aspect ratio, heat transfer improves for all Grashof numbers.
- For a fixed Grashof number, the increase in volume fraction leads to increase in heat transfer.

- Among the three variables considered, the Grashof number (Gr) has the most significant effect on heat transfer, followed by the aspect ratio (AR) and the volume fraction (Φ_s).

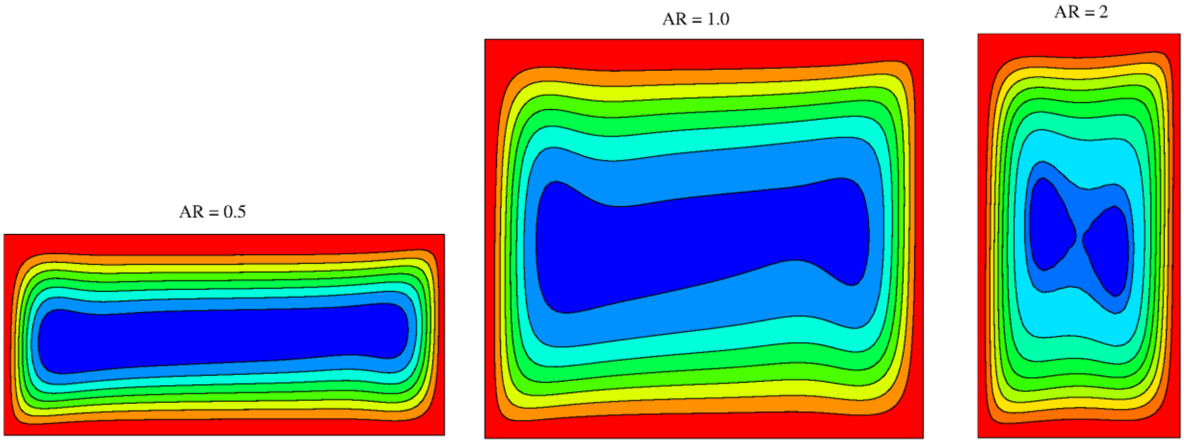

Fig 1. Stream function contours at Gr = 10^6 and volume fraction Φ_s = 2% for various aspect ratios.

Table 1: Average Nusselt number values at the left hot wall for different combinations of parameters

Gr	AR = 0.5				AR = 1.0				AR = 2.0			
	Pure Water	**(Φ_s) 1%**	**(Φ_s) 2%**	**(Φ_s) 3%**	**Pure Water**	**(Φ_s) 1%**	**(Φ_s) 2%**	**(Φ_s) 3%**	**Pure Water**	**(Φ_s) 1%**	**(Φ_s) 2%**	**(Φ_s) 3%**
10^3	0.588	0.621	0.672	0.720	2.027	2.296	2.420	2.504	4.351	4.396	4.646	4.826
10^4	1.672	1.807	1.923	2.129	4.291	5.018	5.213	5.521	8.314	9.181	9.968	9.302
10^5	5.370	5.567	6.102	6.883	8.657	10.143	10.587	11.183	15.923	17.012	17.820	18.016
10^6	10.921	12.986	13.238	14.144	17.991	22.248	23.756	24.847	35.418	37.818	38.316	39.562

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