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HEAT TRANSFER ENHANCEMENT IN NATURAL CONVECTION USING WATER BASED Fe_3O_4 NANOFLUID INSIDE A SQUARE CAVITY

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ABSTRACT

Natural convection heat transfer has many applications, especially in the field of solar thermal applications, electronic cooling etc., Heat transfer enhancement techniques in natural convection deals essentially with addition of fins of various configuration. Since the introduction of nanofluids by Choi et al [1], nanofluids continue to be considered as one of the sought after options of heat transfer enhancement. This is due to the excellent improvement in heat transfer characteristics due to the addition of nanosized solid particles into base fluids such as water, ethylene glycol etc., In the present study, an effort is made to study the heat transfer enhancement inside a square cavity when the water is seeded with magnetic Fe_3O_4 nanoparticles using numerical experiments. The volume fractions considered in the analysis range from 0.1% to 0.6%. It is observed that the enhancement is less than 10% for 0.1% and 0.3% volume fractions considered in the analysis for the range of Rayleigh numbers considered.

INTRODUCTION

Natural convection is dominant mode of heat transfer in many applications, viz., cooling of commercial high voltage electrical power transformers, cooling of reactor cores in nuclear power plants in the event of failure of coolant supply, cooling of electronic devices etc., Heat transfer enhancement techniques which are of passive type have proved to be effective in the natural convection situations. Since the introduction of nanofluids by Choi et al [1], nanofluids containing nanoparticles (1–100 nm) which are uniformly and stably distributed in a base fluid continue to be considered as one of the sought after options of heat transfer enhancement because of their adjustable thermophysical properties, by varying particle concentrations depending on the application.

This is due to the excellent improvement in heat transfer characteristics compared to the conventional solid–liquid suspensions for heat transfer intensifications due to the availability of high heat transfer surface between the particles and the fluid and high dispersion stability with predominant Brownian motion of particles. Many mechanisms were proposed to explain the enhancement of heat transfer with nanofluids. Some of the studies considered the effect of Brownian motion and the effect of clustering of nano particles in the improvement of thermal conductivity of nanofluid. Layering of fluid around the nano particles and ballistic phonon transport were also proposed mechanisms for the enhancement of thermal conductivity of nanofluid.

NOMENCLATURE

k	[W/mK]	Thermal conductivity
T	[K]	Temperature
A	[m^2]	Area perpendicular to the heat transfer
C	[J/kg-K]	Specific Heat
Q	[W]	Heat transfer rate
h	[W/m^2K]	Heat transfer coefficient
S	[unit]	Source term
u	[m/s]	Velocity
Special characters		
ρ	[kg/m^3]	Density
μ	[Pa-s]	Viscosity
$\varnothing$	[-]	Volume concentration
Γ	[m^2/s]	Diffusion term
Subscripts		
w		Water
nf		Nanofluid
Fe_3O_4		Fe_3O_4 nano powder
H		Hot wall
C		Cold wall
j		Coordinate direction

Khanafer et al. [2] is the first person to investigate the problem of buoyancy-driven heat transfer enhancement of nanofluids in a two-dimensional enclosure. The results illustrated that the nanofluid heat transfer rate increases with an increase in the nano particle volume fraction. Hwang et al. [3] investigated the buoyancy-driven heat transfer of water-based Al_2O_3 nanofluids in a rectangular cavity. They showed that the ratio of heat transfer coefficient of nanofluids to that of base fluid is decreased as the size of nanoparticles increases, or the average temperature of nanofluids is decreased.

Jou and Tzeng [4] used nanofluids to enhance natural convection heat transfer in a rectangular enclosure. They conducted a numerical study using Khanafer's model. They indicated that volume fraction of nanofluids cause an increase in the average heat transfer coefficient. For example Philip et al. [5] considered kerosene based Fe_3O_4 nanofluid and observed thermal conductivity enhancement of 300% ($K_{nf}/k_{basefluid}$=4.0) at a particle loading of 6.3% volume fraction with a particle size of 6.7 nm under the influence of an applied magnetic field. It is observed from the extensive literature survey that significant amount of work reported in the literature has essentially focused on the use of nanoparticles, viz., Al_2O_3, TiO_2 etc., In the present study, an effort is made to study the heat transfer enhancement inside a square cavity when the water is seeded with magnetic Fe_3O_4 nanoparticles.

Review of the pertinent literature on the heat transfer characteristics of nanofluids shows that, over the years, considerable efforts have been given to investigate this problem experimentally, however, very few studies were reported on the numerical investigations of natural convection heat transfer. Therefore, the objective of this work is to numerically simulate natural convective heat transfer of Fe_3O_4-water nanofluid with different volume concentrations. The numerical simulations were carried out using the computational fluid dynamic (CFD) approach

NUMERICAL MODEL

Earlier numerical investigations on convective heat transfer using nanofluids considered nanofluids as a homogeneous fluid and adopted a single phase approach to predict heat transfer enhancement. More recently, the two phase approach has been used by some researchers, viz., Bianco et al [6] and reported that single phase approach is good enough for numerical modelling of heat transfer with nanofluids. In the present study, the nanofluid is modelled as single phase fluid.It is also assumed that the nanoparticles and the base fluid are in thermal equilibrium with each other and thus the relative velocity is negligible or equal to zero.

PROPERTIES OF THE NANOFLUID

The thermophysical properties of Fe_3O_4 nanofluids (nf) such as viscosity (μ), density (ρ) and specific heat (C) are estimated using the following empirical correlations developed by Pak and Cho [7] and for effective thermal conductivity (K) Wasp model is used. The particle size of the Fe_3O_4 nanoparticles is considered as 36nm.

$$\mu_{nf} = \mu_w (1 + 39.11\phi + 533.9\phi^2) \quad \text{Eq (1)}$$

$$k_{nf} = k_w \left\{ \frac{k_{Fe_3O_4} + 2k_w - 2\phi\left(k_w - k_{Fe_3O_4}\right)}{k_{Fe_3O_4} + 2k_w + 2\phi\left(k_w - k_{Fe_3O_4}\right)} \right\} \quad \text{Eq (2)}$$

$$\rho_{nf} = \rho_{Fe3O4}\emptyset + (1 - \emptyset)\rho_w \quad \text{Eq (3)}$$

$$C_{nf} = C_{Fe3O4}\emptyset + (1 - \emptyset)C_w \quad \text{Eq (4)}$$

Simulations have been carried in a square cavity as used in the experimental setup of Putra et al [8]. The geometry is square enclosure containing base fluid and nanofluid with hot and cold walls on left and right, respectively, while top and bottom walls insulated. To obtain the solution of this problem, the continuity, momentum and energy equations are solved and the density term in the momentum equations is modelled using the Boussinesq's approximation. Figure 1 shows the descretized domain of the square cavity.

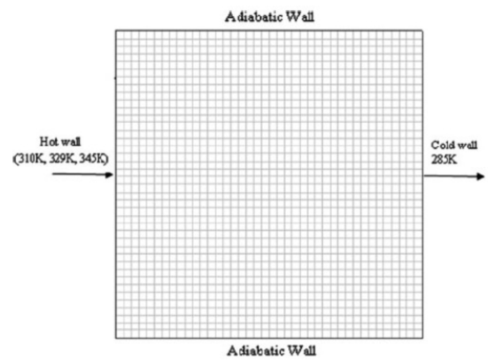

Figure 1 Mesh model of the square cavity

SOLUTION METHODOLOGY

To solve the present problem, continuity, momentum and energy equations, given below form the governing equations.

$$\frac{\partial(\rho u_j)}{\partial x_j} = 0 \quad \text{Eq (5)}$$

$$\frac{\partial(\rho u_j \emptyset)}{\partial x_j} = \frac{\partial\left(\Gamma\frac{\partial\emptyset}{\partial x_j}\right)}{\partial x_j} + S \quad \text{Eq (6)}$$

where Ø represents x and y directional velocities for momentum equations and temperature for energy equation. The subscript, j represents the coordinate direction.

The governing equations of fluid flow are numerically solved using segregated solver under steady state conditions. Laminar model is used to simulate the natural convection flow. SIMPLE scheme is used for pressure–velocity coupling and PRESTO scheme is used for pressure. Second order discretization scheme is employed for all simulations. The simulations were carried out using ANSYS-CFX 14. The simulations were performed with 0.1%. 0.3% and 0.6% volume fractions of Fe_3O_4 nano particles in water. The total surface heat flux (q') is computed from hot wall in each case using surface integrals. Heat transfer coefficient is then calculated using the value of total surface heat flux as follows.

$$h = \frac{Q}{A(T_H - T_C)}$$

The results are plotted to compare the natural convection heat transfer inside a square cavity with and without nanofluid.

GRID INDEPENDENT STUDY

Prior to performing the actual simulations on nanofluid flow, grid independence study was carried out with three different (41 X 41, 61 X 61, and 81 X 81) grid sizes. These studies are performed for pure water. The hot and cold walls are maintained isothermally at temperatures of 310 and 285 K, respectively. To perform grid independent study, Nusselt number is plotted for the three different grids as shown in Figure 2 and based on this, a grid of 61 X 61 is selected for further analysis as the Nusselt number obtained for the grid size of 61X61 was approximately same as that of grid size 81X81. It is further proceeded to verify the numerical model by comparing the numerical results with the experimental results of Putra et al[8].

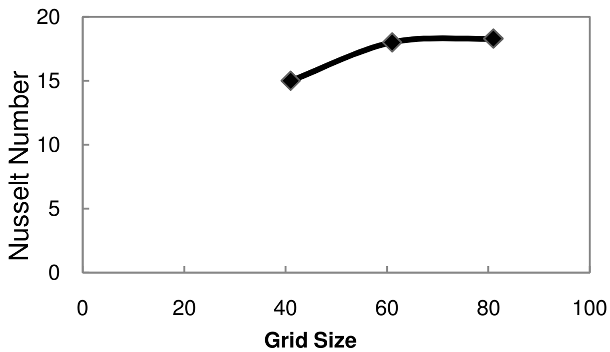

Figure 2 Grid Independent Study

The numerical model is compared with the experimental results of Putra et al [8]. Nusselt number is calculated for three different Rayleigh numbers corresponding to three different temperatures of 310, 329 and 345 K at hot wall and constant temperature of 285 K at cold wall. The computed results as shown in Figure 3 are found to be in good agreement with the experimental results. Thus the numerical model is validated.

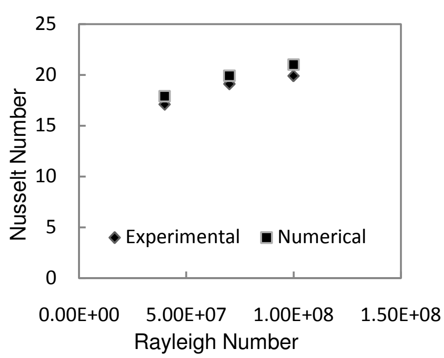

Figure 3 Comparison of Experimental results [11] and numerical results

Further simulations are performed with volume fractions of 0.1%, 0.3% and 0.6% and the results are plotted in Figure 4.

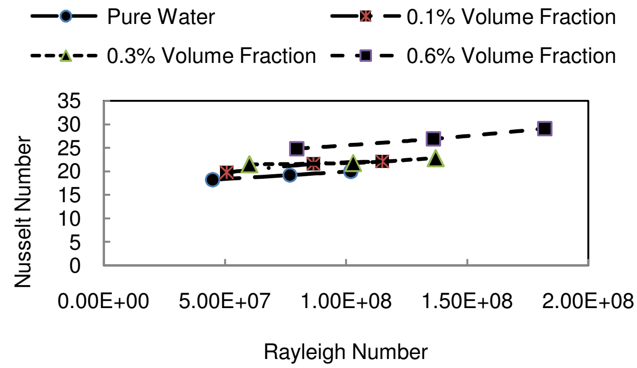

Figure 4 Graphs of Nu Vs Ø for different volume concentrations

It is observed from the Figure 4 that the variation of Nusselt number is marginal with the range of Rayleigh number considered in the analysis. An enhancement of 8.8% with 0.1% volume fraction, 9% with 0.2% volume fraction and 29% with 0.6% volume fraction was observed at the same Rayleigh Number with pure water.

CONCLUSIONS

In the present study, numerical experiments are conducted to study the heat transfer enhancement with and without Fe_3O_4 nanofluid inside a square cavity subjected to different temperatures on opposite walls. The volume fractions considered in the analysis range from 0.1% to 0.6%. The preliminary studies show that the enhancement is less than 10% for the volume fractions of 0.1% and 0.3% for the range of Rayleigh number considered in the analysis. A maximum enhancement of 29% is observed for a volume concentration of 0.6%. The results were matching the experimental results reported in the literature, however the results are to be further verified with different aspect ratios of enclosure as well as for a wide range of volume concentrations with the Fe_3O_4 nanofluid.

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