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NATURAL CONVECTION HEAT TRANSFER IN NANOFLUIDS - A NUMERICAL STUDY

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ABSTRACT

Natural convection heat transfer in nanofluids has been investigated numerically using computational fluid dynamics (CFD) approach. Analytical models that describe molecular viscosity, density, specific heat, thermal conductivity and coefficient of thermal expansion have been considered in terms of volume fraction and size of nanoparticles, size of base fluid molecule and temperature. The uniform suspensions of different concentrations of Al_2O_3 in base fluid (water) are considered as nanofluids. Thermal conductivity of the nanofluids has been obtained by solving the governing equations in conjunction with Kinetic model and interfacial layer model using FLUNET 6.3. Numerical simulations have been carried out in a closed pipe for L/D=1.0. The numerical values of k have also been compared with the experimental values available in the literature. Both the models gave similar predictions with experimentally compared values of k.

Key words: Nanofluids, Al_2O_3-water, CFD, thermal conductivity

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INTRODUCTION

Conventional fluids, such as water, engine oil and ethylene glycol are normally used as heat transfer fluids. Although various techniques are applied to enhance the heat transfer, the low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. Nanofluids are dispersions of nanometer sized particles (metallic or non-metallic) in base fluid such as water, ethylene glycol, synthetic oil etc. The enhancement of thermal conductivity of conventional fluids by the suspension of solid particles, such as millimeter- or micrometer-sized particles, has been well known for more than 100 years [1]. The presence of nano particles enhances the transport and thermal properties of the base fluid significantly. For example, Xuan and Li [2] presented a study on the thermal conductivity of a nanofluid consisting of copper nanoparticles and base liquid. The measured data showed that the suspended nanoparticles obviously increased the thermal

conductivity of the base liquid. Thermal conductivity of the nanofluid increased with increasing volume fraction of nanoparticles. The ratio of thermal conductivity of Cu–water to that of the base liquid increased from 1.24 to 1.78 when the volume fraction of the nanoparticles varied from 2.5 to 7.5%.

From the literature review it is observed that the thermal conductivity of nanofluids increased as a function of thermal conductivity of both the base fluid and the nanoparticle material, the volume fraction, the surface area, and the shape of the nanoparticles suspended in the liquid. There are no theoretical formulas currently available in open literature for predicting the thermal conductivity of nanofluids.

The objective of the study is to numerically simulate convective heat transfer of nanofluids and validate them with the previous experimental results. The numerical simulations were carried out using the computational fluid dynamic (CFD) approach. CFD is a technique or a tool which enables us to study the fluid flow, heat transfer and associated phenomena based on computer simulations. In this study, CFD software FLUENT 6.3 is employed to study natural convection heat transfer of nanofluids. CFD simulations have been carried out in a geometry of L/D = 1.0 as used in the experimental setup of [3]. The geometry is an enclosed cylinder containing nanofluid enclosed by hot wall and cold wall on right and left and curved wall is adiabatic surface. The numerical results are presented in terms of non-dimensional parameters such as Nusselt number and Rayleigh number. Theoretical model such as kinetic model and interfacial model describing the thermal conductivity of the nanofluids and other physical properties (such as density, viscosity and specific heat) of the nanofluids have been employed using user defined function in the FLUENT 6.3.

The aim of the experiment was to find the effect of higher thermal conductivity of the nanofluid on the natural convection heat transfer inside the enclosed cylinder. The hot wall temperature was controlled using input DC power supply. The temperature of hot wall was varied from 305K tom 345K while the temperature of cold wall was maintained constant at 295K, respectively. Simulations have been carried out for Al_2O_3-water nanofluid by varying the volume fraction of the nanoparticles (ϕ = 0%, 1% and 4%) and three different temperatures (310K, 329K and 345K), respectively.

THEORETICAL MODELS

The fluid properties of the nanofluids vary when nanoparticles are suspended in them. There are two ways to describe material properties of the nanofluid. First is to assume the nanofluid as a mixture of two fluids and secondly to treat them as single phase. Former is used due to its accuracy. In this work, two theoretical models: Kinetic model and interfacial model are used to calculate the thermal conductivity of the nanofluid.

Kinetic model of thermal conductivity: There are two types of kinetic model proposed in the literature [4]. One assumes that the particles are stationary (stationary particle model0 and other assumes that the particles are in motion (moving particle model) inside the base fluid. In the present study, stationary particle model is employed in the numerical simulations. In the stationary particle model, heat flows through liquid molecules and through the nanoparticles. The heat transfer rate is given by the equation [5].

$$q = -k_m A_m \left(\frac{dT}{dx}\right)\left[1+\frac{k_p \phi r_m}{k_m (1-\phi) r_p}\right] = -k_{eff} A_m \left(\frac{dT}{dx}\right) \quad (1)$$

The equation for effective thermal conductivity (stationary particle model) can be deduced using the heat transfer equation (1) given by,

$$k_{eff} = k_m \left[1+\frac{k_p \phi r_m}{k_m (1-\phi) r_p}\right] \quad (2)$$

Equation (3) is used in numerical simulations to compute the thermal conductivity of the nanofluid. The radius of the fluid (water) particle used is $3.2\times10^{-10} m$ and that of Al2O3 nanoparticle is $131.2\times10^{-9} m$ as used in the experiment of [3].

Interfacial layer model of thermal conductivity: A model for predicting thermal conductivity of nanofluid is proposed by [5] which take into account the effect of interfacial layer between solid particle and liquid and particle size. The model also takes into account some

additional effects of volume fraction, interfacial layer thickness and thermal conductivity of interfacial layer given by equation (3).

$$k_{eff} = \frac{(k_p - k_{lr})\phi_1 k_{lr}[2\beta_1^3 - \beta^3 + 1] + (k_p + 2k_{lr})\beta_1^3[\phi_1\beta^3(k_{lr} - k_f) + k_f]}{\beta_1^3(k_p + 2k_{lr}) - (k_p - k_{lr})\phi_1[\beta_1^3 + \beta^3 - 1]} \quad (3)$$

where

$\beta = 1+\gamma,\ \beta_1 = 1+\gamma/2,\ \phi_{lr} = \phi_p(\beta^3 - 1),\ \phi_f = (1-\phi_p)\beta$

and $\gamma = t/a$

The prediction for the model were done for h=1.0*nm*, k_{lr} =3*kf* and k_{lr}=2k_f.

Density

The density of the nanofluid is expressed in terms of density of fluid, density of nanoparticles, and volume fraction of nanoparticles as given in equation (4);

$$\rho = (1-\phi)\rho_f + \phi\rho_p \quad (4)$$

Equation (3) shows that the density of nanofluid increases with increase in volume fraction of nanoparticles.

Specific heat

The specific heat of nanofluid is given by,

$$C_p = \frac{(1-\phi)\rho_f C_{pf} + \phi\rho_p C_{pp}}{\rho} \quad (5)$$

Equation (5) predicts small decrease in specific heat of the nanofluid with increase in nanoparticle volume fraction.

Viscosity

The viscosity of the nanofluid increases with increase in the nanoparticle concentration. For low volume fraction of nanoparticles, Einstein's model can be used to predict the viscosity of the nanofluid [4, 6]

$$\mu = (1+2.5\phi)\mu_f \quad (6)$$

and $\mu_f = \mu_o\left[e^{-1.704-5.306\left(\frac{T_{ref}}{T}\right)+7.003\left(\frac{T_{ref}}{T}\right)^2}\right]$ (7)

Equation (6) shows the dependence of viscosity of base fluid on temperature. Einsteins's equation (5) is valid only for small volume fraction of nanoparticles $(\phi < 0.05)$. It is application for the numerical simulations performed in this paper as the maximum volume fraction of nanoparticles is 0.04.

Thermal expansion coefficient

The thermal expansion coefficient is considered to be independent of volume fraction of the nanoparticles. It is dependent only on temperature of the base fluid. In this work, the values of thermal expansion coefficient are calculated based on the average temperature between hot wall and cold wall. The values used in this study are tabulated below.

Average Temperature (*K*)	Thermal expansion coefficient, β (*1/K*)
298.15	0.0002
307.55	0.0003
315.55	0.0004

Table 1 values of thermal expansion coefficient used in numerical simulations [7]

NUMERICAL METHOD

A uniform 2D mesh was generated using GAMBIT 2.3. The governing equations of fluid flow were numerically solved using steady state solver in FLUENT 6.3. All the material properties described in section 2 are input using User Defined Function (UDF). Iterations were performed using Gauss-Siedal method. Second order descretization scheme were employed except for volume fraction. Iterations were performed until all the residuals reached below 1×10^{-6}. All material properties, initial values of temperatures and volume fraction were provided to run the simulations in FLUENT. The output from the simulations was then used to compare the results with previous experimental results.

The total surface heat flux (Q) was computed from FLUENT from hot wall in each case using surface integrals. Heat transfer coefficient was then calculated using the value of total surface heat flux as given in equation (8). Nusselt number and Rayleigh number were then computed using equation (9) and (10) using the material properties of the nanofluids obtained from UDF's. plots of Nusselt number vs Rayleigh number were obtained for Al_2O_3-water nanofluid with 0%, 1% and 4% volume fraction for cylinder of aspect ratio of L/D = 1.0

$$h = \frac{4Q}{\pi d^2 (T_H - T_c)} \quad (8)$$

$$Nu = \frac{hL}{k_n} \quad (9)$$

$$Ra = \frac{g\beta_n \Delta T L^3}{\nu_n \alpha_n} \quad (10)$$

RESULT AND DISCUSSION

Numerical computations were carried out for convective heat transfer of nanofluids inside a cylinder bounded by hot wall, cold wall and curved adiabatic wall. Al_2O_3-water was used as the nanofluid in which the volume fraction of nanoparticles is varied from 0-4%. The computations for three different temperature differences correspond to those of experiments [3]. The results are compared in terms of Nusselt number and Rayleigh number.

For pure water $(\phi = 0)$**:** Numerical simulations were carried out for pure water. Fig 1 shows the numerical result validated against experimental values for 0% volume fraction. Nusselt number was calculated for three different Rayleigh number corresponding to three different temperatures of $310K$, $329K$ and $345K$ at hot wall and constant temp of $285K$ at cold wall.

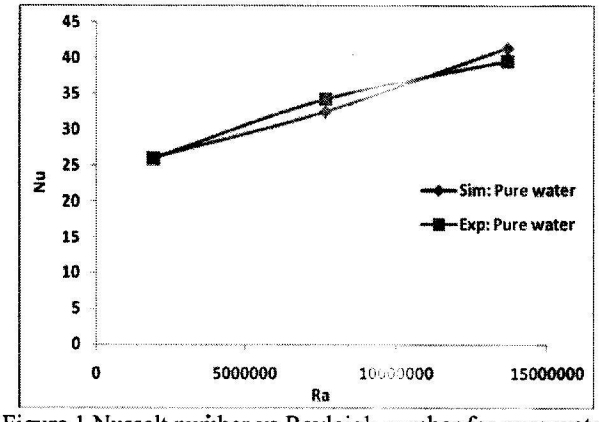

Figure 1 Nusselt number vs Rayleigh number for pure water

The computed results are in good agreement with the experimental results. As expected, both the computational and experimental results show increase in Nusselt number with increase in Rayleigh number.

For 1% volume fraction: It is seen from Fig 2 that, when the nanoparticles are added to pure water the Nusselt number decreases compared to that of pure water. The numerical results predict the similar trend as that of the experimental results. However, some discrepancy was observed between experimental and numerical results. Both the models (kinetic and interfacial model) predict the similar trend as observed from experimental results. Also, both the model gives similar results for Nusselt number. The accuracy depends upon the theoretical model employed for thermal conductivity of nanofluids.

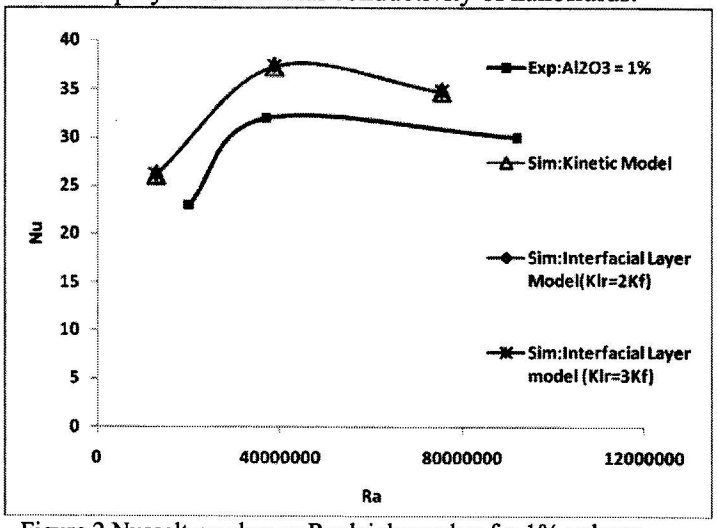

Figure 2 Nusselt number vs Rayleigh number for 1% volume fraction of Al_2O_3.

For 4% volume fraction: Fig 3 represents variation of Nusselt number vs Rayleigh number for 4% volume fraction of nanoparticle.

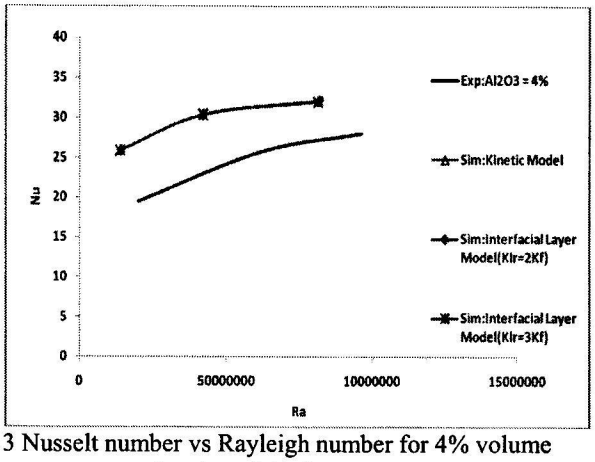

Figure 3 Nusselt number vs Rayleigh number for 4% volume fraction of Al_2O_3.

When the volume fraction of the nanoparticles is increased from 1% to 4%, the numerical solutions still exhibits the same trend as observed in the experimental results. Nusselt number decreases with increase in volume fraction of nanoparticles. It can also be observed from comparing with Fig 2. This phenomenon is paradoxical which is pointed out by [3]. Conventionally, thermal conductivity should increase with increase in volume fraction of the particles thus increasing the heat transfer. However, both the experimental and numerical results show degradation in heat transfer in natural convection. One of the reasons explained by [3] is due to slip between the nanoparticles and the fluid particles which disturb the suspension of the nanoparticles inside the liquid especially at very low velocity natural convection flow.

CONCLUSION

Natural convection heat transfer of nanofluid was studied for Al_2O_3-water in a horizontal cylinder of L/D =1.0 using CFD approach. Numerical simulations were compared with the experimental results at various values of Rayleigh number which show similar trend and are in reasonable agreement. Kinetic model and interfacial model shows similar results for Nusselt number. Nusselt number decreased with increase in volume fraction of the nanoparticles which is explained on the basis of slip between nanoparticle and fluid molecule. Thus, CFD can be effectively implemented for simulations of nanofluid.

NOMENCLATURE

A_m = surface area of the fluid particle
C_{pf} = Specific heat of fluid
C_{pp} = specific heat of particle
g = acceleration due to gravity
h = heat transfer coefficient
t = thickness
T_H = temperature of hot wall
T_C = temperature of cold wall
k_{eff} = effective thermal conductivity
k_f = thermal conductivity of the fluid
k_m = thermal conductivity of the fluid particle
k_n = thermal conductivity of nanofluid
k_p = thermal conductivity of nanoparticle
k_{lr} = thermal conductivity of interfacial layer
L = length of the cylindrical fluid container
N_u = Nusselt number
Q = input power
r_p = radius of fluid particle
R_a = Rayleigh number
T = nanofluid temperature
T_{ref} = reference temperature (293K)
μ_f = viscosity of the base fluid
μ_o = reference viscosity of water (0.001788 kgm/s)
ρ_f = density of fluid
ρ = density
ρ_p = density of nanoparticle
ϕ = volume fraction of nanoparticle
ν_n = kinematic viscosity of the nanofluid
α_n = thermal diffusivity of the nanofluid

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