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Numerical study on convective heat transfer for water-based alumina nanofluids

M.A. Kheram*

Department of mechanics, Islamic Azad University-Marvdasht branch, Marvdasht, Iran

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ABSTRACT

The present work is an experimental study of steady state convective heat transfer of de-ionized water with a (0.04% by volume) volume fraction of Al_2O_3 nanoparticles dispersed to form a nanofluid that flows through an aluminium tube.Laminar fully developed flow heat transfer coefficient of Al_2O_3 nanoparticles are dispersed in water in circular tube is discussed in this paper. In order to validate the heat transfer coefficient of nanofluid in circular tube commercially available CFD software FLUENT 6.3.26 is used. The thermo-physical properties of the Al_2O_3nanofluid are estimated by using the equations available in literature. Thermo-physical properties of the nanofluid are considered for heat transfer coefficient by assuming nanofluid is a single-phase fluid. Constant Wall Heat Flux (CWHF) boundary condition is incorporated for heat transfer analysis. The flow and temperature fields are assumed fully developed (x/D>10). The analysis is conducted in the volume concentration from 0.4%.A maximum of 2.25 times heat transfer enhancement is obtained by using nanofluid as working medium.

Keywords: *Nanoparticles, Nanofluid, Heat transfer enhancement, Thermal conductivity enhancement, Convective heat transfer*

INTRODUCTION

In recent years, technology development has intensified with the understanding of the physics behind microscale and nanoscale domains. The unprecedented growth in electronics, optical devices, power stations, transportation, etc. has led to a number of applications requiring high heat flux dissipation. A liquid coolant is widely used to prevent the overheating or heat transfer rate improvement of equipments such as electronic devices, heat exchangers and transportation vehicles. However, conventional heat transfer fluid such as water or ethylene glycol generally has poor thermal properties.

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*Corresponding author:
Mohammad Ali Kheram
Islamic Azad University - Marvdasht branch
Tel +98 9361292823
Fax +98 728 3311172
Email
Mohammadalikheram@gmail.com

Thus many efforts for dispersing small particles with high thermal conductivity in the liquid coolant have been conducted to enhance the thermal properties of the conventional heat transfer fluids. Fluids with suspended submicron-sized -100 nm - particles or fibers were named as nanofluids [1].Since then, researchers have attempted to understand and predict the behaviour of nanofluids. Compared with base fluids, a number of recent experiments have indicated dramatic improvements in the effective static thermal conductivity and the effective static thermal conductivity depends on the concentration of nanoparticles, one of the particular interests in convective heat transfer of nanofluids is that the increment of convective heat transfer coefficient is generally higher than that of effective thermal conductivity. Moreover the exact mechanism of convective heat transfer enhancement of nanofluids has not been explained in detail, although it becomes well known that the enhancement of thermal conductivity of nanofluids is due to Brownian motion of nanoparticles suspended in fluid.

Nanoparticles have great potential to improve more effectively the thermal transport properties of HTFs than micrometer and millimeter sized particles. This is mainly due to the tininess of nanoparticles or other nanostructures, which not only improves the stability and the applicability of liquid suspensions, but also increases the specific surface area (SSA) and the diffusion mobility of Brownian motion of nanoparticles.

A large variety of combinations of nanostructures and heat transfer fluids can be used to synthesize stable nanofluids with improved thermal transport properties. Nanostructures made from metals, oxides, carbides and carbon nanotubes can be dispersed into HTFs, such as water, ethylene glycol, hydrocarbons and fluorocarbons with or without the presence of stabilizing agents. Conventional heat transfer fluids such as water and ethylene glycol and oil have inherently low thermal conductivity relative to metals and even metal oxides. Therefore fluids with dispersed solid particles are expected to have better heat transfer properties compared to that of traditional heat transfer fluids.

THEORY

Heat Transfer in Nanofluids

- **Thermal Conduction in Nanofluids**

Dispersions of oxide nanoparticles in water are the first batch of nanofluids which have been investigated. In 1993, Masuda et al. [2] dispersed Al_2O_3 nanoparticles of13 nm in diameter into water with a volume fraction up to 4.3%, and obtained an enhancement in thermal conductivity of 30%. Zeinali et al. [3] also reported an enhancement of 30% in thermal conductivity in water suspensions of Al_2O_3 nanoparticles with an average diameter is 33 nm, at a volume fraction of 5%. Wang et al. [4] studied the effects of synthesis process on the thermal conductivity of water based nanofluids containing Al_2O_3 nanoparticles.

Besides, Al_2O_3, CuO is another extensively investigated oxide due to its higher thermal conductivity and easy availability. Eastman et al. [3] studied the thermal conductivity enhancement of water dispersions of 36nm CuO nanoparticles and found the enhancement increase is linearly proportional to the particle concentration. The thermal conductivity enhancement was measured as approximately 60% at a CuO nanoparticle concentration of 5 vol.%, significantly higher than the 30% enhancement measured in Al_2O_3 -in-water nanofluids at the same concentration. This is due to the fact that CuO has a higher intrinsic thermal conductivity than that of Al_2O_3. Lee et al. [5] also obtained similar results with their nanofluids of CuO particles in both water and ethylene glycol. They found greater enhancements in CuO nanofluids than those in Al_2O_3 nanofluids. Also it varies with base fluid characterization. Rostami reported that it was caused by the difference number. Eastman et al. [6] observed that there is an increase of 40% thermal conductivity of copper nanoparticles dispersed in ethylene glycol at 0.3% volume concentration.

Das et al. [7] have reported a 10-25% increase of thermal conductivity of alumina nanoparticles suspended in water with a volume concentration of 1-4%. The theoretical models such as Maxwell and Hamilton-Crosser [1963] are also available to predict the thermal conductivity of solid – liquid mixtures.

- **Thermal Convection in Nanofluids**

It should be noted that the enhancement in thermal conductivity alone is not sufficient to prove that nanofluids have improved thermal transport properties and the performance of nanofluids in convective environments is a stronger evidence to evaluate the nanofluids. Experimental research on the convective heat transfer performance of nanofluids can be traced back to 1998, It is remarkable that there are still only relatively few publications of such. Yang et al. investigated convective heat transfer coefficient of nanofluids for a constant temperature under laminar flow in a horizontal tube heat exchanger. Their experimental results showed that the nanofluids with 2.5 wt% nanoparticles loading had a typical increase in convective heat transfer coefficient of 22% over the base fluid, while its thermal conductivity was about 50% higher than that of the base fluid. This is a different result from that presented by previous papers. Heris et al [8] have observed the heat transfer enhancement of CuO/water and Aluminium oxide Al_2O_3 - water nanofluid in circular tube under laminar flow condition. All the investigators have studied the heat transfer enhancement of different types of nanofluids in circular tube.

The main purpose of this research is to extend the scope of the measured convective heat transfer behaviour of Al_2O_3 -based nanofluids. The focus will be on the convective heat transfer capability of nanofluids in a millimeter-scale tube in the laminar flow regime. With the help of FLUENT software, it is possible to study the heat transfer rate of nanofluids by assuming nanofluid is a single-phase fluid. This paper investigates the heat transfer of nanofluid in circular tube for different volume concentrations.

Mathematical Modelling

- **Assumptions**

Study on fully developed laminar flow is more important for understanding the physical phenomena than any other regime because the boundary layer does not grow any longer, and velocity and dimensionless temperature profiles do not change with axial distance under fully developed laminar flow. Therefore, in this paper, our main objective is to investigate flow and convective heat transfer characteristics of water-based Al_2O_3nanofluids flowing through a circular tube with the constant heat flux in fully developed laminar regime. The nanoparticles in the base fluid may be easily fluidized and consequently the effective mixture behaves like a single-phase fluid Xuan and Li [9]. The compression work and the viscous dissipation are assumed negligible in the energy equation. Under these assumptions, the classical theory of single phase fluid can be applied to nanofluids.

It is also assumed that the fluid phase and nanoparticles are in equilibrium with zero relative velocity. Furthermore, the assumption for single phase for a nanofluid is validated. In order to compare the results with the experiments, similar configurations like the geometry of the tube and the concentration of the copper oxide nanoparticles were considered. The length of the tube is long enough for the fully developed condition to success. The effective thermophysical properties are assumed to be dependent on the temperature and concentration of the nanoparticles.

Conservation of mass:

$$\text{Div}\ (\rho V) = 0 \qquad (1)$$

Conservation of momentum:

$$\text{Div}\ (\rho VV) = -\text{grad}\ P + \mu\nabla^2 V \qquad (2)$$

Conservation of energy:

$$\text{Div}\ (\rho V C p T) = \text{div}\ (k \text{grad} T) \qquad (3)$$

- **Thermo-Physical Properties of Nanofluid**

The following equations are used for calculating the thermophysical properties of Al_2O_3nanofluid. The subscripts 'p', 'bf' and 'nf' refer to the particles, the base-fluid and the nanofluid respectively, while 'r' refers to the 'nanofluid/base fluid' ratio of the physical quantity under consideration:

Density: The effective density of the nanofluid containing suspended particles can be evaluated through the following equation:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \qquad (4)$$

Specific heat: Yang and Zhang [10] proposed the equation for calculating the specific heat of nanofluids based on the heat capacity concept:

$$(\rho c_p)_{nf} = (1-\varphi)\left(\rho c_p\right)_{bf} + \varphi(\rho c_p)_p \qquad (5)$$

*Dynamic viscosity:*As very dilute suspensions were used in this work. The Einstein equation was used to estimate the viscosity of nanofluids. Wen and Ding [11] also used the same equation for calculating the viscosity:

$$\mu = \mu_0(1 + 2.5\varphi) \qquad (6)$$

Note that all nanofluid thermal properties are determined at the average temperature of the nanofluid, which is justified here over the limited temperature range of our experiments (20–45°C).

RESULT AND DISCUSSION

Boundary Conditions and geometry

The tube has a diameter of 0.016m ID and 0.018m OD and a length of 1.5m. The fluid enters the tube with a constant inlet temperature T(in) of 300 K and uniform axial velocity V(in).

Constant Wall Heat Flux (CWHF) of 5000 W/m2 is applied on the up and down wall periphery of the tube as shown in Figure 1.

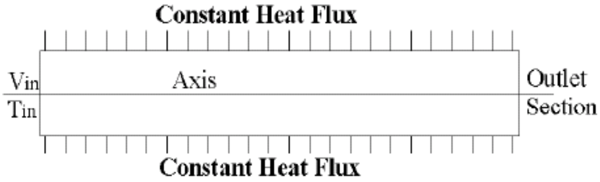

Fig.1.schematic representation of test section used

The conservation equations of mass, momentum and energy were solved iteratively using the segregated solver and a pressure correction equation was used to ensure the conservation of momentum and mass. A SIMPLE scheme was adopted for the treatment of pressure. The Reynolds number studied in this work was medium, and the laminar viscous model was employed. Contours of static temperature for nanofluid in the volume concentration 0.4% to the base fluid arerepresented in the Figure 2, 3. On the upper wall of the tube, the noslip boundary condition was imposed. The wall was subjected to a uniform heat flux.

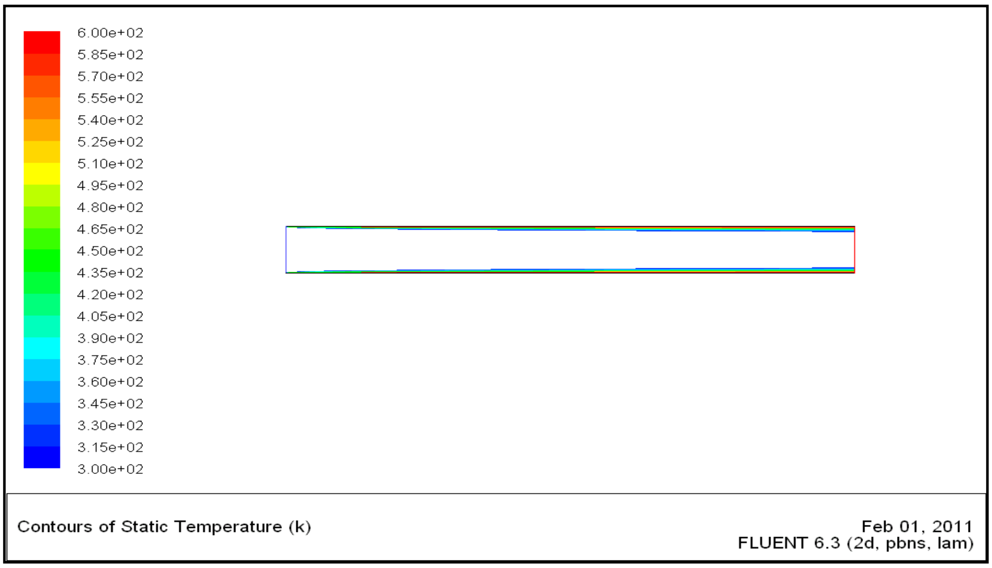

Fig.2.contours of static temperature (k) for liquid water

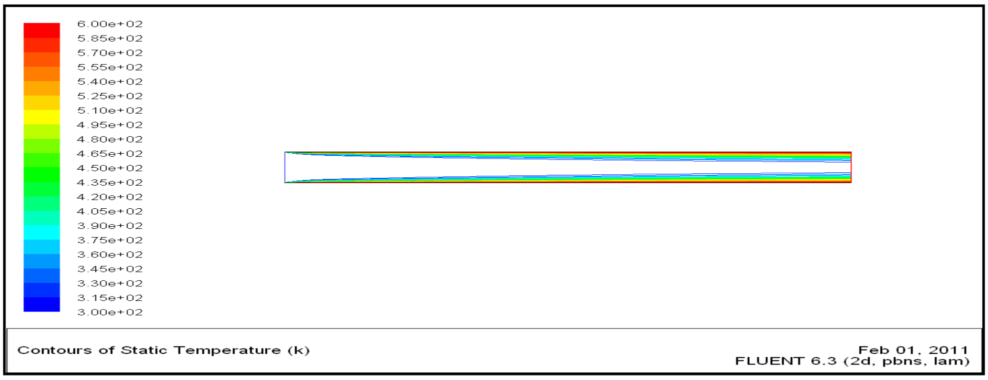

Fig.3.contours of static temperature (k) for 0.4% water based alumina nanofluids

Figure 4 show that Al_2O_3nanofluids with medium concentrations of nanoparticles have considerably higher thermal conductivities than water. The thermal conductivity ratio improvement for Al_2O_3nanofluids is approximately linear with the temperature. Furthermore, a maximum increase in thermal conductivity of 17% was observed for 0.4 vol.-% Al_2O_3. Nanoparticles dispersed in deionized water. All the experimental results show that the addition of Al_2O_3 nanoparticles to a base fluid leads to dramatic enhancement of thermal conductivity. The fluent XY plot help us plot.

Pressure Drop for Nanofluid

In order to validate the computational model, the numerical results were compared with the theoretical data available for the conventional fluids. The Darcy friction factor given by Blasius is presented:

$$f = 0.079\mathrm{Re}^{-0.25} \qquad (7)$$

$$\Delta P = f\left(\frac{L}{D}\right)\left(\frac{\rho V^2}{2}\right) \qquad (8)$$

Contours of static pressure for nanofluid in the volume concentration 0.4% to the base fluid are represented in the Figure 5, 6. Pressure drop of 0.4% volume concentration is obtained 1.42 times of the base fluid. Obviously, the pressure drop of the diluted nanofluid is almost equal to those of the water under the same Reynolds number. Compare the water no significant enhancement in pressure drop for nanofluid is found.

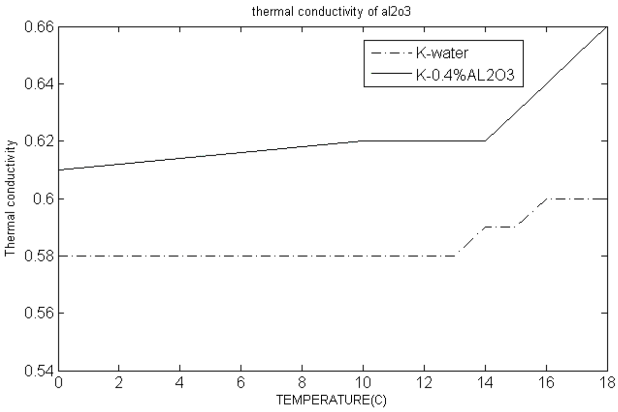

Fig. 4. thermal condutivity of Al_2O_3/water nanofluid.

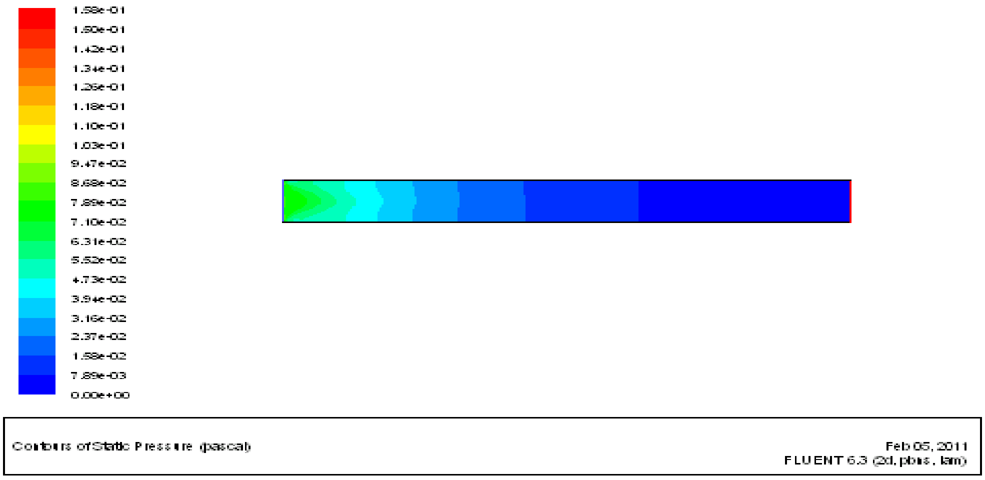

Fig.5.contours of static pressure for water-based alumina

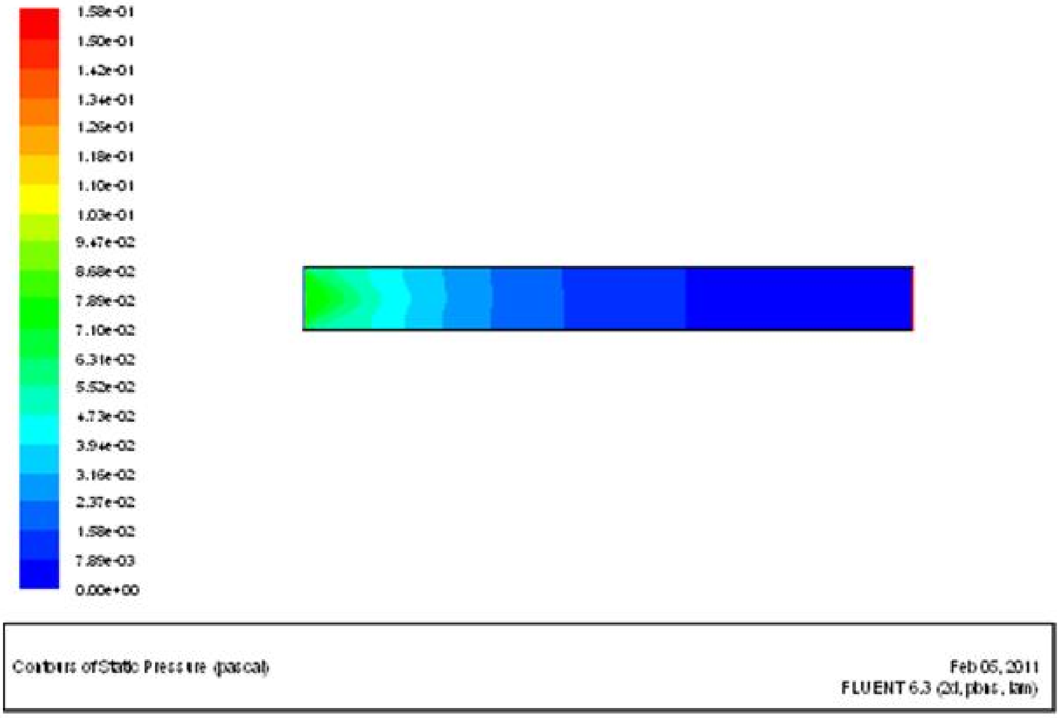

Fig.6. Contours of static pressure for water

Nusselt Number (Nu)

The nanofluid behaves more like a fluid than the conventional solid-fluid mixtures in which relatively larger particles with micrometer or millimeter size are suspended. But the nanofluid is a two phase fluid in nature and has some common features of the solid-fluid mixtures. The local Nusselt number in a circular tube for a constant heat flux condition according to the Reynolds number for the fully developed laminar flow regime, obtained by :

$$Nu_x = \begin{cases} 1.302x_*^{-\frac{1}{3}} - 1 & x_* < 0.0005 \\ 1.302x_*^{-\frac{1}{3}} - 0.5 & 0.00005 < x_* < 0.0015 \\ 4.364 + 8.68(10^3 x_*)^{-0.506} \exp(-41x_*) & x_* > 0.001 \end{cases} \quad (9)$$

$$Nu_x = \frac{h(x)d_{tube}}{k} \quad (10)$$

$$x_* = \left[\frac{\frac{x}{d_{tube}}}{Re_{d_{tube}} Pr}\right] \quad (11)$$

With the measured wall temperature at the aluminium tube, the mean temperature of fluids at inlet, heat flux, and flow rate, the local heat transfer coefficient of nanofluids under the fully developed condition of laminar flow is calculated by :

$$h(x) = \frac{q''}{T_s(x) - T_{m(x)}} \quad (12)$$

Where Tm(x), Ts(x) and h(x) are the mean temperature of fluid, the wall temperature of tube and the heat transfer coefficient respectively. The heat transfer coefficients calculated by equation 12 of the local Nusselt number in a circular tube illustrated for a constant heat flux equal to 5000 condition according to the Reynolds number in Figure 7.

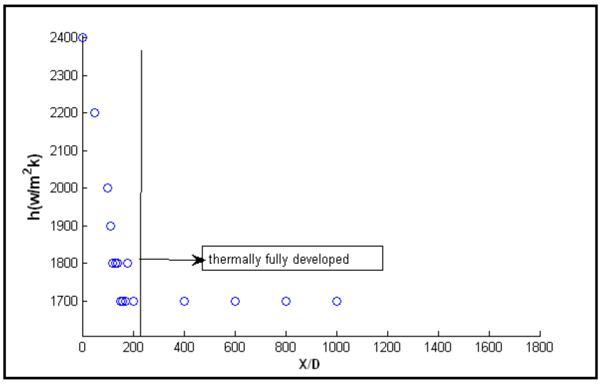

Fig.7. The heat transfer coefficients calculated according to the reynolds number

CONCLUSION

Heat transfer and friction factor characteristics of Al_2O_3 nanofluid in circular tube is studied numerically. At a same Reynolds number of 700 Nusselt number for 0.4% Al_2O_3 nanofluids increases by 1.24 times over the base fluid. The presence of nanoparticles increases the convective heat transfer coefficient by 8% than that of the original base fluid under the same Reynolds number; and the increase is significant even though the concentration is less. At a given concentration the enhancement of heat transfer coefficient increases in the entrance region and decreases with the axial distance. In conclusion, this study has provided a clear insight into the thermal behaviour of a nanofluid under convective conditions in the context of a confined tube flow. The findings of this study can easily be leveraged for various practical heat transfer and thermal applications to bring about a dynamic advancement in the field of nano scale heat transfer.

NOMENCLATURE

A: cross sectional area, m^2
Cp: specific heat, J/kg K
d: tube diameter, m
h: heat transfer coefficient, W/m^2 K
k: thermal conductivity, W/m K
m: mass flow rate, kg/s
Nu: Nusselt number,
Pr: Prandtl number,
q": heat flux, W/m^2
Re: Reynolds number
T: Temperature °C

Greek Symbols:
β: thermal dispersion coefficient, N/m^2 K
φ: volume fraction
ρ: density, kg/m^3
μ: dynamic viscosity, kg/ms
Subscripts:
nf: nanofluid
w: tube wall
x: axial distance
bf: base fluid
i: inner wall
o: outer wall

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