Numerical study of heat transfer enhancement with Al_2O_3/Water Nanofluid

L.Saoudi, M.Gareche, F. Iachachene, N.Azril, N.Zeraibi

Abstract— The purpose of this paper is to identify the suitable formulation of the viscosity of laminar forced convection of Al_2O_3 nanofluid through a horizontal circular tube. Four different viscosity models are tested. This paper included thermal behavior for fully developed laminar flow regime in forced convection heat transfer of Al_2O_3 nanoparticle dispersed in water as a base fluid, flowing through a horizontal circular tube under constant heat flux boundary condition at wall. In this investigation, the effects of parameters, such as nanoparticles diameter, nanoparticle volume fraction , and Reynolds number on the enhancement of nanofluid heat transfer have been considered in order to study the behavior of the system in terms of, heat transfer coefficient and temperature field.

Index Terms— Al_2O_3-water, Circular tube, Heat transfer, Laminar flow, Nanofluid, Numerical study, Particles size, Viscosity

1 INTRODUCTION

THE problems of sedimentation, increased pressure drop, fouling and erosion of the flow channel [1], which are caused by addition of milli or micro sized solid particles in a base fluid are resolved by nanofluids, which is a dispersion of nanosized particules in the traditional fluids such as water, ethylene glycol and oil. The term "nanofluids" who designate a new class of heat transfer fluids is coined for the first time by Steve Choi from Argonne National Laboratory USA on 1995[2] . The last decade, transport properties of nanofluids has seen the rapid development of heat transfer devices in many aspects from engineering and science.

Wen and Ding [3] observed in their experimental study that heat transfer increased by increasing the Reynolds number and volumetric ratio of particles, when they investigated the convective heat transfer characteristics in Al_2O_3-water nanofluid along a tube. According to the researches Xuan who experimentally studied the convective heat transfer and friction coefficient for the nanofluid in both laminar and turbulent flows , they noticed that the flow velocity and volume fraction ofnanoparticles affected the heat transfer coefficient [4,5]. Zeinali Heris et al [6-8] found that the 20nm Al_2O_3 nanoparticles showed an improved heat transfer performance compared with the 50nm CuO nanoparticles in circular tubes, especially at high concentrations. Viscosity is an important property due to its very crucial impact on heat transfer.

Therefore, viscosity of nanofluids should be thoroughly investigated before use for practical heat transfer applications.

However, there is a lack of systematical data on this subject and experimental results are sometimes contradictory. The effect of dispersed particles on the viscosity of suspensions was first studied in Einstein's classical work [9]. Considering the motion of a small particle in a fluid, he determined the flow field perturbations caused by it and then calculated the effective stress tensor. To extend formula of Einstein to such particle concentrations within Einstein's concept, it is necessary to take into account the hydrodynamic perturbations due to the mutual influence of closely spaced dispersed particles. This hydrodynamic interaction leads to an increase in the energy dissipation of viscous friction. As a result, the viscosity increases linearly with increasing particle concentration. Theory incorporating these effects was developed by Batchelor [10]. Several equations have been developed in an effort to extend Einstein's formula to suspensions of higher concentrations. Brinkman [11] presented a viscosity correlation that extended Einstein's equation to concentrated suspensions, then Pak and Cho [12] presented some additional data for Al_2O_3/water nanofluids. Maiga et

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al. [13] proposed a viscosity model based on the particle volume fraction for Al_2O_3/water nanofluids, they reported the effective viscosity increases when particle volume fraction is increased.

For the study of the effect of nanoparticles diameter in the enhancement of heat transfer, Mirmasoumi et al. [14], numerically studied the convective heat transfer in a fully developed flow for Al_2O_3/water nanofluid. They applied two-phase mixture model in their simulation. They found that the convective heat transfer coefficient significantly increased by decreasing the nanoparticles mean diameter. Moraveji et al. [15] simulated Al_2O_3/water nanofluid through a tube under constant heat flux. They found that the heat transfer coefficient increased by increasing the nanoparticle concentration and Reynolds number. Furthermore, the heat transfer coefficient increased by decreasing particle diameter. Davarnejad et al.[16] simulated the convective heat transfer in the developed region of the tube flow containing water and Al_2O_3 nanoparticles with two average diameters of 20nm and 50nm under constant heat flux. It was concluded that heat transfer coefficient increased by increasing the Reynolds number and the concentration of nanoparticles. Furthermore, the two nanofluids showed higher heat transfer than the base fluid (water) although the nanofluid with particles size of 20nm had the highest heat transfer coefficient.

The subject of this work is to investigate the effect of several nanofluid viscosity formulations in heat transfer behavior of Al_2O_3/water nanofluid flowing through a horizontal tube in laminar regime under constant heat flux conditions. Where the effective dynamic viscosity of this nanofluid is calculated by using four models (Batchlor, Brinkman, Pak and Cho and Maiga). The second part of this study aims to investigate the effect of nanoparticles diameter in the heat transfer behavior of Al_2O_3/water nanofluid by using the correlation proposed by Maiga [13] to calculate the effective dynamic viscosity.

2 METHODOLOGY

2.1 Physical model and formulation

The flow configuration of this study is given in Figure 1. The base fluid (i.e. water) and the nanoparticles are in thermal equilibrium, they flow at same velocity and no slip boundary condition occurs between them. As shown in Figure 1, a two-dimensional pipe (with 1 m length and 1cm inner diameter) was spotted in our simulation. The flow is assumed as Newtonian, laminar and stationary through a simple axisymmetric duct. The particles are assumed to be in the same size and shape.

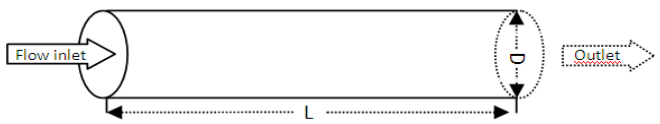

Fig. 1 - Pipe numerical domain

2.2 Physical properties of the nanofluid

Although the nanofluids are solid–liquid mixtures, the approach conventionally used in most studies of forced convection handles the nanofluid as a single-phase (homogenous) fluid. In the single-phase model a nanofluid is treated as a homogenous fluid, but with enhanced properties due to the inclusion of nanoparticles. The thermophysical properties of the nanofluid such as density, viscosity and thermal conductivity which were applied for the simulation are assumed to be independent of temperature but of course are functions of the volume fraction of the suspended nanoparticles. These properties of the base fluid and metal oxide Al2O3 are summarized in Table 1.

TABLE I
THERMOPHYSICAL PROPERTIES OF THE BASE FLUID, AND METAL OXIDE (AL_2O_3)

Fluid	Property			
	k(W/mK)	ρ (kg/m^3)	c_p(J/kgK)	μ10^{-6}(Pa s)
Water	0.613	997.1	4179	1003
Al2O3	40	3970	765	-

The density of the nanofluid is given by Eq. (1) as

$$\rho_{nf} = \rho_p \phi + \rho_{bf}(1-\phi) \quad (1)$$

The effective heat capacity is calculated by (Ghasemi and Aminossadati 2011[17])

$$C_{P_{nf}} = \frac{\rho_p C_{P_p} \phi + \rho_{bf} C_{P_{bf}} (1-\phi)}{\rho_{nf}} \quad (2)$$

The thermal conductivity of nanofluid was evaluated from the model proposed by Maxwell [18], by Eq. (3) as:

$$k_{nf} = k_{bf} + 3\phi \frac{k_p - k_{bf}}{k_p + 2k_{bf} - \phi(k_p - k_{bf})} k_{bf} \quad (3)$$

Nanofluid viscosity is a most important factor for practical applications because it controls the pressure reduction in forced convection. Therefore, for allowing the use of nanofluids in experimental applications, the viscosity augmentation of nanofluids compared to pure

fluids should be systematically explored. The ideal nanofluids must have great thermal conductivity and weak viscosity. In this paper, several viscosity formulations are checked (Table 2).

TABLE II
SUMMARY OF VISCOSITY MODELS OBTAINED BY SEVERAL AUTHORS

Authors	Effective viscosity
Batchlor	$\mu_{nf} = \mu_{bf}\left(1+2,5\phi+6,5\phi^2\right)$
Brinkman	$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2,5}}$
Maiga	$\mu_{nf} = \mu_{bf}\left(1+7,3\phi+123\phi^2\right)$
Pak and Cho	$\mu_{nf} = \mu_{bf}\left(1+39,11\phi+533,9\phi^2\right)$

2.2.1 Governing equations for nanofluid flow

The governing equations for a homogenous analysis of forced convection are continuity, momentum, and energy equations with their density, specific heat, thermal conductivity and viscosity modified for nanofluid application.

Continuity

$$\frac{\partial\left(\rho_{nf}u\right)}{\partial x}+\frac{1}{r}\frac{\partial\left(\rho_{nf}rv\right)}{\partial r}=0 \qquad (4)$$

Momentum equation in the axial direction is given by

$$\rho_{nf}\frac{\partial\left(uu\right)}{\partial x}+\rho_{nf}\frac{1}{r}\frac{\partial\left(rvu\right)}{\partial x}=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{nf}\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_{nf}\frac{\partial u}{\partial r}\right) \qquad (5)$$

Momentum equation in the radial direction is given by

$$\rho_{nf}\frac{\partial\left(uv\right)}{\partial x}+\rho_{nf}\frac{1}{r}\frac{\partial\left(rvv\right)}{\partial r}=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left(\mu_{nf}\frac{\partial v}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_{nf}\frac{\partial v}{\partial r}\right)-\mu_{nf}\frac{v}{r^2} \qquad (6)$$

The axi-symmetric form of energy equation is as follows:

$$\rho_{nf}\frac{\partial(uT)}{\partial x}+\rho_{nf}\frac{1}{r}\frac{\partial(rvT)}{\partial r}=\frac{\partial(\frac{K_{nf}}{C_{pnf}}\frac{\partial T}{\partial x})}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}(r\frac{K_{nf}}{C_{pnf}}\frac{\partial T}{\partial r}) \qquad (7)$$

2.2.2 Numerical study

The numerical solutions of the governing equations (Eqs. (4)–(7)) are performed by the finite volume Method [19]. The discretization of these equations is achieved on collocated meshes. A second order upwind scheme is chosen for energy and momentum equations. The pressure velocity coupling has been resolved by SIMPLE algorithm (Semi-Implicit Method for Pressure Linked Equation) (Patankar [19]).The solution is considered converged when the normalized residual of each variable is less than 10^{-6}.

2.2.3 Boundary Conditions

The boundary conditions for this flow configuration are specified as follows:

At the inlet of the calculation domain constant values are imposed as: velocity components U =Uin; V = 0; and ambient temperature (Tin=293K).

At the outlet, the fully developed conditions prevail, the static pressure is kept at atmospheric pressure.

On the wall of the pipe no-slip conditions, u = v = 0, and constant heat flux ($q=5000W/m^2$) are imposed.

On the axis of symmetry all axial derivatives are zero.

3 Results and Discussion

In this investigation, the effects of parameters, such as nanoparticles diameter, concentration, and Reynolds number on the enhancement of nanofluid heat transfer have been considered in order to study the behavior of the system in term of, heat transfer coefficient which is calculated using the following equation:

$$h(x)=\frac{q}{\left(T_w(x)-T_b(x)\right)} \qquad (8)$$

where q is the heat flux at the wall, is the axial distance from the inlet to the heat transfer test section, Tw and Tb are the wall and fluid average bulk temperatures, respectively.

The representative dimensionless coefficient of heat transfer, the Nusselt number, is defined as:

$$Nu(x)=\frac{h(x)\cdot D}{k} \qquad (9)$$

Where D is the diameter of the inner tube and k is the thermal conductivity of the fluid.

3.1 Grid-Independence Analysis

In order to determine the grid independency of the simulated results, different combination of nodes in the radial and axial directions were investigated. In figure 2, it can be observed that the Nusselt number for water increases linearly till an optimum number of cell volumes is reached. Beyond this, any further increase in the number of cell volumes only increases the computational time, without any significant improvement in the Nusselt number. This result shows the number of grid points in the x and r directions are set to 1000 and 50 respectively. Therefore, the mentioned nodes were accepted as the optimal ones.

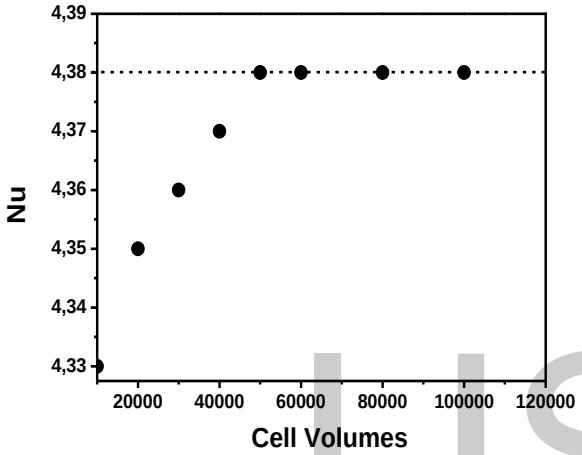

Fig. 2-Grid Independence study

3.2 Validation

In figure 3, the axial profile of the local heat transfer coefficient is compared with experimental data of Lazarus et al. [20] and the predictions of the following well-known Shah equation for laminar flows under the constant heat flux boundary condition (Shah, 1975), given by:

$$Nu_{x_*} = \begin{cases} 3,303x_*^{-1/3} - 1.00 & x_* \le 0.00005 \\ 1.302x_*^{-1/3} - 0.50 & 0.00005 \le x_* \le 0.0015 \\ 4.364 + 8.68(10^3 x_*)^{-0.506} e^{-41x_*} & x_* \succ 0.001 \end{cases} \quad (10)$$

Where x* was calculated from below

$$x_* = \frac{x}{d \cdot \mathrm{Re} \cdot \mathrm{Pr}} \quad (11)$$

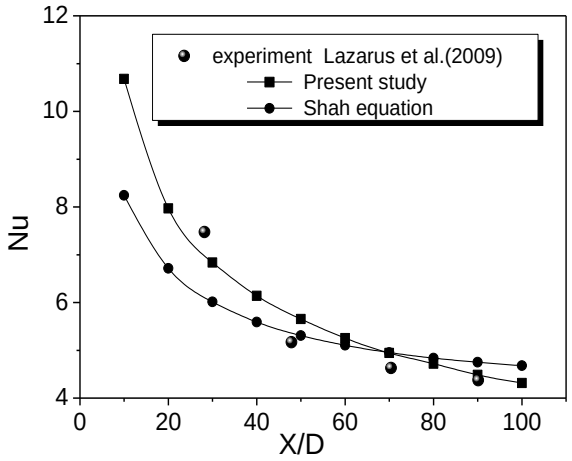

Fig. 3-Comparison of numerical values, experimental values of water Nusselt number with Shah equation versus axial distance for Re=400

As shown in this figure, the experimental and numerical results were found to be in satisfactory agreement with minor discrepancies between the result and the correlation of Shah in the pipe, which can be explained by a difference in the tube size. The Shah equation was developed on the basis of laminar flows in large channels (Celata and al., 2004[21];Guo and Li, 2003[22]), while a tube with 1 cm diameter was used in this study.

3.3 Effect of Viscosity Formulation

To attain the best prediction in laminar flow, four different nanofluid viscosity models (Batchlor[10], Brinkman[11], Pak and Cho [12] and Maiga[13]) illustrated in Table 2 based on low nanoparticle volume fraction have been investigated and compared in Figure 4. This comparison, shows that the Maiga model used in the numerical simulation to calculate the dynamic viscosity in prediction of Nusselt number, convective heat transfer coefficient ratio and viscosity ratio on the fully developed flow of Al2O3/water nanofluid (figures 4.a, 4.b and 4.c) respectively, gives closer values of experimental values[23,24], so for the remainder of this work, we will use the correlation proposed by Maiga in the calculation of the effective viscosity.

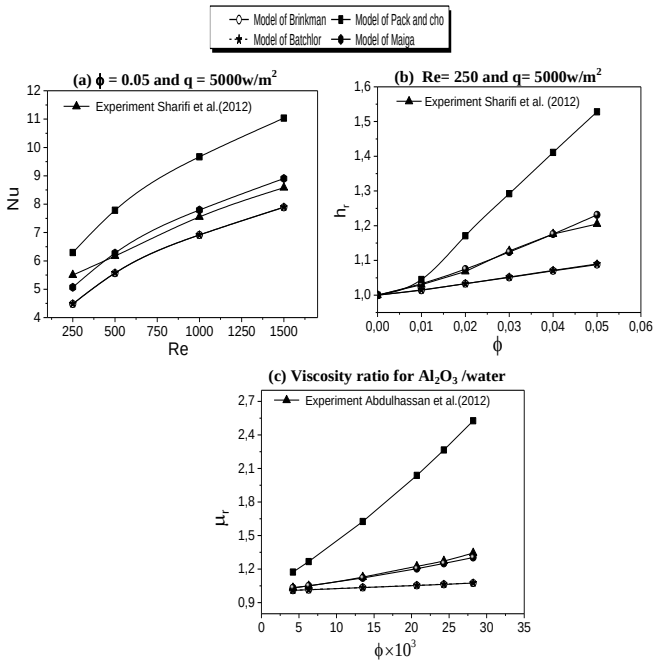

Fig. 4 - Comparison between the different models and experimental results in prediction of the Nusselt number(Fig.a), the convective heat transfer coefficient ratio(Fig.b) and Viscosity ratio(Fig.c) of nanofluid Al_2O_3/water

3.4 Heat transfer enhancement

In the second part of this investigation, the effects of parameters, such as, nanoparticle volume fraction, Reynolds number and nanoparticles diameter on the enhancement of Al_2O_3/Water nanofluid heat transfer have been considered in order to study the behavior of the system in terms of heat transfer coefficient and temperature fields. Four particle sizes with average size of 10, 20, 30 and 50 nm were used in this research with volume fractions in the range of 0 and 0.02 in the various Reynolds numbers (250≤Re≤ 2500), by using the correlation proposed by Maiga[13] to calculate the effective dynamic viscosity, and the thermal conductivity of nanofluid was evaluated from the Stationary model[30] , by Eq. (12) as:

$$k_{nf} = k_{bf}\left(1+\frac{k_p \phi d_{bf}}{k_{bf}(1-\phi)d_{np}}\right) \quad (12)$$

3.4.1 Effects of nanoparticle volume fraction and Reynolds number on the heat transfer

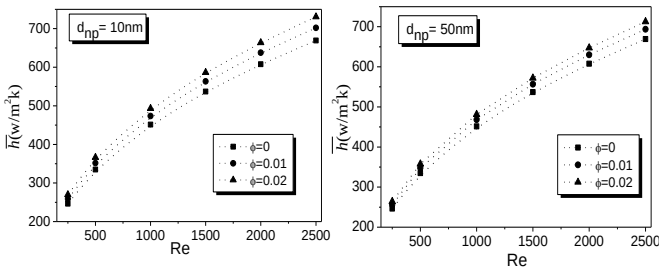

Fig. 5 - The influence of Al2O3 nanoparticles' volume concentration on the average heat transfer coefficient over a range of Reynolds numbers with dnp = 10nm and 50nm

Figure 5 shows the plots of the average heat transfer coefficient versus Reynolds number at various nanoparticle volume fraction of Al_2O_3/water for diameter of nanoparticles 10 and 50 nm. This figure indicates that the average heat transfer coefficient increases with the volume fraction of nanoparticles, and better enhancement is seen at higher Reynolds numbers. The average heat transfer coefficient at the same diameter and Reynolds number increases according to volume concentration. The results illustrate that by increasing volume concentration of Al_2O_3/water from 0.01 to 0.02 for Reynolds number of 500 at dnp=50nm, an improvement of about 6.82% was observed on the average heat transfer coefficient for the nanofluid with ϕ = 0.02. Whereas the enhancement is found to be less (3.75%) for the nanofluid with ϕ =0.01.

An increase in the volume fraction of the nanoparticles intensifies the interaction and collision of the nanoparticles. Also, diffusion and relative movement of these particles near the pipe walls lead to the rapid heat transfer from the walls to the nanofluid. In other words, increasing the volume concentration of the nanoparticles intensifies the mechanisms responsible for the enhanced heat transfer.

3.4.2 Effects of nanoparticle diameter on the heat transfer

Figure 6 reflected the effects of diameter and nanoparticle volume fraction on heat transfer via the value of average heat transfer coefficient in the pipe. The average heat transfer coefficient of the pipe augments moderately with decreasing particle diameter. The analysis of the shape of this curve can confirm, at least qualitatively, that the evolution of heat transfer coefficient in the pipe versus the diameter of nanoparticle is consistent with the numerical study of Davarnejad et al.[16].The difference observed in the value of the average heat transfer coefficient is due to the value of the flux at the wall taken by Davarnejad et al.[16] (q = 18000W / m2), but in our study (q = 5000W/m²). The energy exchange of the nanoparticle-fluid contacts

increases as the flux increases. This rise in flux influences the particle collisions in the nanofluid resulting in an enhancement of thermal conductivity and in turn brings about higher heat transfer coefficient.

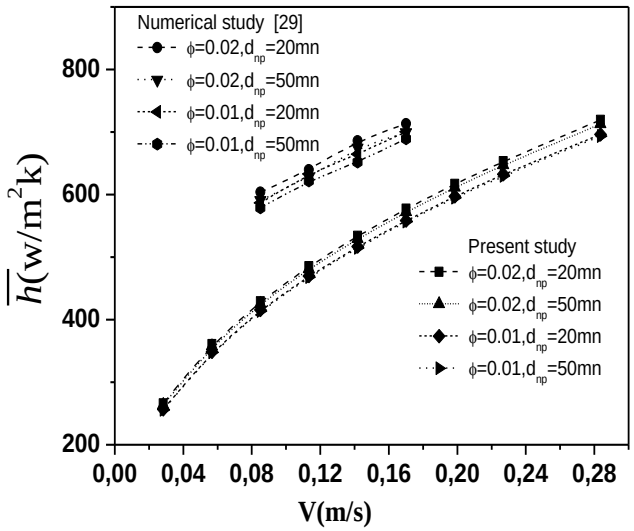

Fig. 6 - Comparative results of average convective heat transfer coefficient in the pipe with different diameters of nanoparticles

Based on obtained data in the current study two correlations for the average heat-transfer coefficient

$\bar{h}$ has been proposed, respectively, for $\phi = 0.01$ and $\phi = 0.02$

$$\bar{h} = \frac{23.75 \times Re^{0.431}}{\left(1 - 0.143 d_{np}^{-1}\right)}, \quad for\ \phi = 0.01$$

$$\bar{h} = \frac{24.5 \times Re^{0.43}}{\left(1 - 0.303 d_{np}^{-1}\right)}, \quad for\ \phi = 0.02$$

Where $\bar{h}$ in (w/m²k) and d_{np} in (nm)

These correlations were obtained following the curve fitting technique using least-squares method. Very well prediction of the average heat-transfer with a maximum error of 2% as shown in Figure 7.

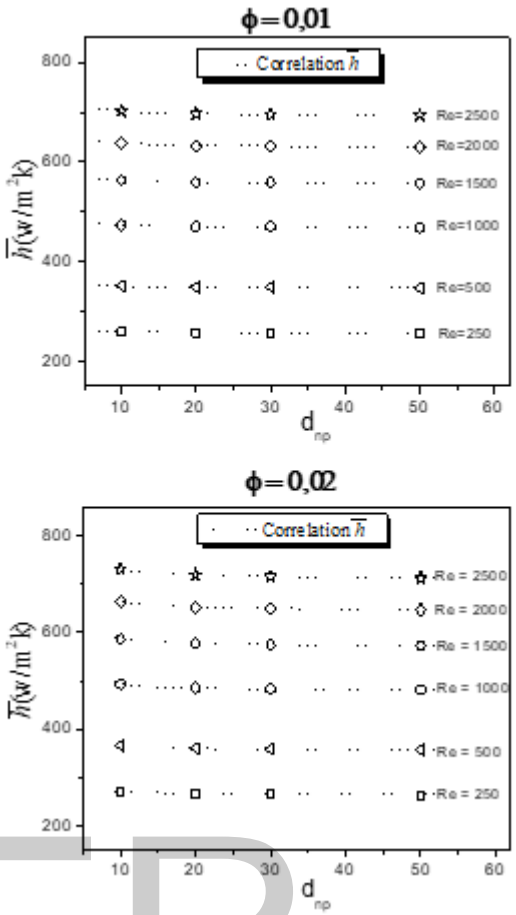

Fig. 7 - Average convective heat transfer coefficient for Al2O3 versus diameters of nanopaeticles for ϕ =0.01 and ϕ =0.02

Figure 8 and 9 respectively exhibit nanofluid bulk temperature versus Reynolds number for particles size of 50 nm, for different volume fractions, and for particles size of 10 and 50 nm for ϕ=0.02 . The results indicates that the bulk nanofluid temperature decreased by increasing the volume fraction of nanopartilcles(see fig.8), although a change in the particle size had no significant effect on the nanofluid bulk temperature(see fig.9) .

4 Conclusions

The laminar flow-forced convection of Al2O3/water nanofluid over a horizontal circular tube under constant heat flux boundary condition at wall was numerically investigated, using a finite volume method. Several models of nanofluid viscosity formulations are tested and compared with experimental data. The results show that Maiga model predicted the heat transfer rates accurately.

Thereafter, this viscosity formulation and the Stationary model for calculation the thermal conductivity of nanofluid were used for study the effect of particle size of Al2O3 and Reynolds number on the heat transfer behavior for two volume concentrations (ϕ=0.01 and ϕ=0.02). The results revealed that Al2O3 nanofluid with nanoparticle diameter of 10 nm had the highest heat transfer coefficient compared to water and nanofluids with nanoparticle diameter (20, 30 and 50 nm). This heat transfer coefficient increased by increasing the particle volume concentration and Reynolds number. The bulk temperature of nanofluid decreased by increasing the volume fraction of nanopartilcles, although a change in the particle size had no significant effect. Based on obtained data in the current study the evolution of the average heat transfer coefficient is correlated according to the nanoparticle diameter and Reynolds number $\overline{h} = f(\mathrm{Re}, d_{np})$, where two correlations for the average heat-transfer coefficient $\overline{h}$ has been proposed, respectively, for $\phi = 0.01$ and $\phi = 0.02$.

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