Heat Transfer Enhancement Using Aluminium Oxide Nanofluid: Effect of the Base Fluid

Meriem Amoura *am_louni@yahoo.fr*
Faculty of Physics/Department of Energetic
University of sciences and Technology Houari Boumedienne
BP.32, Al Alia, Bab Ezzouar, Algiers, 16111, Algeria

Madjid Benmoussa *frank42200@hotmail.fr*
Faculty of Physics/Department of Energetic
University of sciences and Technology Houari Boumedienne
BP.32, Al Alia, Bab Ezzouar, Algiers, 16111, Algeria

Abstract

The flow and heat transfer is an important phenomenon in engineering systems due to its wide application in electronic cooling, heat exchangers, double pane windows etc.. The enhancement of heat transfer in these systems is an essential topic from an energy saving perspective. The lower heat transfer performance when conventional fluids, such as water, engine oil and ethylene glycol are used hinders improvements in performance and a consequent reduction in the size of such systems. The use of solid particles as an additive suspended into the base fluid is a technique for heat transfer enhancement. Therefore, the heat transfer enhancement in a horizontal circular tube that is maintained at a constant temperature under laminar regime has been investigated numerically. A computational code applied to the problem by use of the finite volume method was developed. Nanofluid was made by dispersion of Al_2O_3 nanoparticles in pur water and ethylene glycol. Results illustrate that the suspended nanoparticles increase the heat transfer with an increase in the nanoparticles volume fraction and for a considered range of Reynolds numbers. And in other hand, the heat transfer is very sensitive to the base fluid.

Keywords: Al_2O_3 Nanoparticles, Circular Tube, Heat Transfer enhancement, Numerical Simulation.

1. INTRODUCTION

ONE of the most important needs of modern industries is high performance heat transfer equipment. In the past few decades, many techniques for heat transfer enhancement have been proposed. One idea involves improving the performance of heat transfer fluids by the addition of solid particles [1], [2].

Suspensions of nano-sized (< 100 nm) particles in conventional heat transfer fluids (such as water, ethylene glycol, and engine oil) were named nanofluid by Choi [3]. To understand and describe various features of flow and heat transfer behaviour of nanofluids, numerous investigations have been carried out [4], [5]. Almost all previous investigations show that the thermal conductivity of nanofluids increases significantly over that of the base fluid [5], [6], [7], [8].

Oxide nanoparticles [9], [10], [11], [12], carbon nanotubes [13], [14] and other types of nanoparticles [15], [16], [17], [18] have been used in the preparation of nanofluids. Conventional heat transfer fluids such as water, ethylene glycol and transformer oil have been employed as base fluid. Results of these investigations show that the heat transfer coefficient of nanofluids is considerably higher than that of the base fluid and the enhancement of heat transfer coefficient increases with nanoparticle concentration and nanofluid flow rate.

Most investigators have studied experimentally the heat transfer characteristics of nanofluids, however, very few studies relates to numerical investigations on convective heat transfer.

Therefore, the objective of this work is to numerically simulate the convective heat transfer characteristics of water-Al_2O_3 and ethylene glycol-Al_2O_3 nanofluids in horizontal circular tube maintained at a constant temperature in the laminar flow. A computational code by use of the finite volume method is developed [19]. Laminar model was used to simulate the flow and heat transfer using the SIMPLE scheme for pressure-velocity coupling. This code is validated by comparison to results reported in the literature. The major contribution of this study is to showing the effect of the base fluid on the convective heat transfer performance.

2. FORMULATION OF THE PROBLEM

The geometry under investigation is shown in Fig. 1. We consider a horizontal circular tube with a finite length and a diameter D. The flow will be considered as axi-symmetric and therefore it is two dimensional so that it can be represented by the axial and radial coordinates only. The tube contains water-Al_2O_3 or ethylene glycol-Al_2O_3. These Al_2O_3 particles are assumed to be in the same size and shape. In addition, the solid particles are in thermal equilibrium with the base fluid and they are the same velocity.

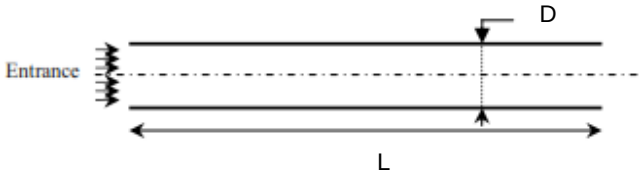

FIGURE 1: Geometry of The Problem.

The physical properties of the nanofluid are assumed to be independent of temperature but of course are functions of the volume fraction ϕ of the suspended nanoparticles. The buoyancy effects are neglected.

The governing equations for nanofluid in axi-symmetric cylinder are the continuity, momentum, and energy equations with their density, thermal conductivity, and viscosity modified for nanofluid application. The continuity written in cylindrical coordinate for an axi-symmetric geometry is:

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

Momentum equations in the axial and radial directions are:

$$\rho_{nf}\frac{\partial\left(uu\right)}{\partial x}+\rho_{nf}\frac{1}{r}\frac{\partial\left(rvu\right)}{\partial x}= -\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{nf}\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_{nf}\frac{\partial u}{\partial r}\right) \tag{2}$$

$$\rho_{nf}\frac{\partial\left(uv\right)}{\partial x}+\rho_{nf}\frac{1}{r}\frac{\partial\left(rvv\right)}{\partial r}= -\frac{\partial P}{\partial r}+\frac{\partial}{\partial x}\left(\mu_{nf}\frac{\partial v}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_{nf}\frac{\partial v}{\partial r}\right)-\mu_{nf}\frac{v}{r^2} \tag{3}$$

The axi-symmetric form of energy equation is:

$$\rho_{nf}\frac{\partial(uT)}{\partial x}+\rho_{nf}\frac{1}{r}\frac{\partial(rvT)}{\partial r}= \frac{\partial}{\partial x}\left(\frac{k_{nf}}{c_{p_{nf}}}\frac{\partial T}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{k_{nf}}{c_{p_{nf}}}\frac{\partial T}{\partial r}\right) \quad (4)$$

As mentioned before, nanofluid properties are combinations of base fluid and particle properties. The effective density of nanofluid is predicted by mixing theory:

$$\rho_{nf}=\rho_{particle}\emptyset+\rho_{bf}(1-\emptyset) \quad (5)$$

Specific heat is also defined by mixing theory:

$$Cp_{nf}=\frac{\rho_{particle}\ Cp_{particle}\ \emptyset\ +\ \rho_{bf}\ Cp_{bf}\ (1-\emptyset)}{\rho_{nf}} \quad (6)$$

The thermal conductivity of nanofluid was evaluated from the model proposed by Maxwell [1873] namely:

$$k_{nf}=k_{bf}+3\emptyset\frac{k_{particle}-k_{bf}}{k_{particle}+2k_{bf}-\emptyset(k_{particle}-k_{bf})}k_{bf} \quad (7)$$

The effective viscosity of fluid containing small particules is given by Brinkman [1952] as:

$$\mu_{nf}=\frac{\mu_{bf}}{(1-\emptyset)^{2.5}} \quad (8)$$

The dimensionless form of the governing equations can be obtained by use of dimensionless variables defined as:

$$U=\frac{u}{U_0}\quad;\quad P=\frac{p}{\rho U_0}\quad;\quad R=\frac{r}{D}\quad;\quad \theta=\frac{T-T_0}{T_{wall}-T_0} \quad (9)$$

The problem is characterized by the following parameters of similarity:

the Reynolds number: $$Re=\frac{\rho_{nf}UD}{\mu_{nf}} \quad (10)$$

the Prandtl number: $$Pr=\frac{\mu_{nf}\ Cp_{nf}}{k_{nf}} \quad (11)$$

the Peclet number: $Pe=Re\ Pr$ (12)

The Nusselt number of the nanofluids is expected to depend on a number of factors such as thermal conductivity and specific heat capacity, the volume fraction of the suspendes particles, the flow structure and the viscosity of the nanofluid. The Nusselt number of the nanofluid can be expressed as [20]:

$$Nu=\begin{cases}1.953\left(RePr\frac{D}{x}\right)^{\frac{1}{3}} & \left(RePr\frac{D}{x}\right)\geq 33.3\\ 4.364+0.0722RePr\frac{D}{x} & \left(RePr\frac{D}{x}\right)\leq 33.3\end{cases} \quad (13)$$

The mean temperature of the fluid for an axi-symmetric case at any cross-section of the tube is:

$$T_{mean} = \frac{\int_0^{D/2} 2\pi\rho C_p Turdr}{\int_0^{D/2} 2\pi\rho urdr} = \frac{2}{U_{mean}(D/2)^2}\int_0^{D/2} T(r,x)u(r,x)rdr \quad (14)$$

where *T* is the temperature at a distance *r* from the axis where the axial velocity is *u*.

The boundary conditions in this geometry are summarized in Fig. 2 and Table I.

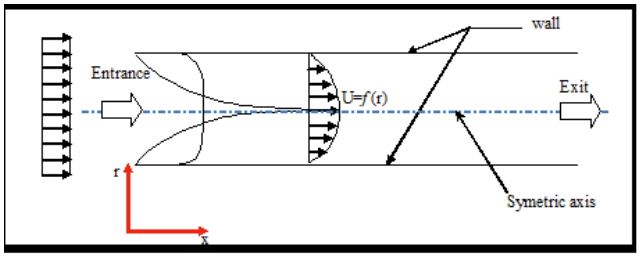

FIGURE 2: Boundary Conditions.

The condition	Entrance	Wall	Symetric axis
Axial velocity *U*	$U_0 = \frac{\mathrm{Re}\,\mu}{\rho D}$	*U = 0*	$\frac{\partial U}{\partial r} = 0$
Radial velocity *V*	*V = 0*	*V = 0*	*V = 0*
Temperature T	T_0= 288 K	T= T_{wall}=320K	$\frac{\partial T}{\partial r} = 0$

TABLE 1: Boundary Conditions.

The numerical simulation is based on the finite volume formulation. The governing equations are integrated over each control volume to obtain a set of linear algebraic equations. These equations were solved by employing SIMPLE algorithm for the pressure correction processes, and convective and diffusive terms were discretized by upwind and central difference schemes, respectively. Second order discretization scheme were employed for all simulation. For cylinder's diameter less than 10 cm and a length equal to 5 m, a grid independence study was carried out with three different (301x31, 401x31 and 421x31) grid sizes. These studies are performed for 10% volume fraction of CuO. Mean temperature profiles along of the cylinder are plotted for Reynolds number equal at 25 as shown in Fig. 3.

From Fig. 3 it is very clear that grid size 401x31 and 421x31 gave same results. The 401x31 and non-uniform grid is chosen for computation, allowing fine grid spacing near the wall of cylinder (Fig. 4).

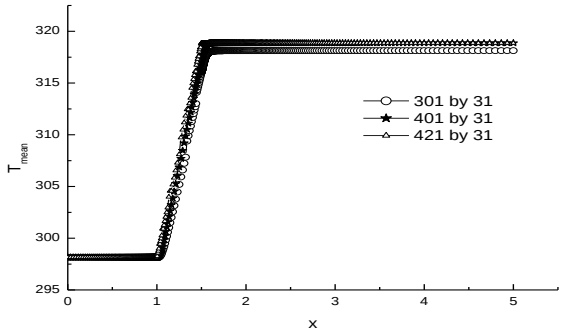

FIGURE 3: Temperature profiles at Re=25 for 10% volume fraction of CuO.

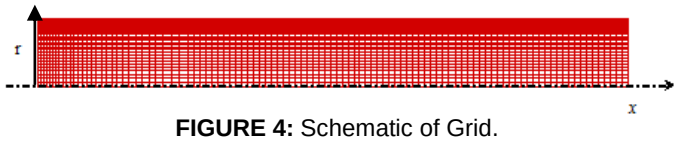

FIGURE 4: Schematic of Grid.

The convergence of the numerical solution is based on residuals of governing equations that were summed over all cells in the computational domain. Convergence was achieved when the summation of residuals decreased to less than 10^{-8} for all equations.

Furthermore, in order to validate the numerical code used for the present study, the steady-state solutions obtained as time-asymptotic solutions for an vertical square cavity with differentially heated sidewalls and adiabatic top and bottom walls, have been compared with the results of Hadjisophocleous [21], Tiwari [22] and Kuang [23]. In particular, the average Nusselt numbers, the maximum horizontal and vertical velocity components obtained at Rayleigh numbers in the range between 10^3 and 10^6 are summarized in the Table II. A very agreement has been obtained.

	Hadjisophocleous [21]	Tiwari [22]	Kuang [23]	Present study
Ra=10^3				
u_{max}	3.544	3.642	3.597	3.643
y	0.814	0.804	0.819	0.818
v_{max}	3.586	3.702	3.669	3.690
x	0.186	0.178	0.181	0.179
$\overline{Nu}$	1.141	1.087	1.118	1.108
Ra=10^4				
u_{max}	15.995	16.144	16.185	16.164
y	0.814	0.822	0.819	0.821
v_{max}	18.894	19.665	19.648	19.665
x	0.103	0.110	0.112	0.111
$\overline{Nu}$	2.29	2.195	2.243	2.228
Ra=10^5				
u_{max}	37.144	34.30	36.732	36.720
y	0.855	0.856	0.858	0.857
v_{max}	68.91	68.77	68.288	68.260
x	0.061	0.059	0.063	0.060
$\overline{Nu}$	4.964	4.450	4.511	4.489
Ra=10^6				
u_{max}	66.42	65.59	66.47	66.48
y	0.897	0.839	0.869	0.890
v_{max}	226.4	219.73	222.34	219.55
x	0.0206	0.04237	0.03804	0.0399
$\overline{Nu}$	10.39	8.803	8.758	8.765

TABLE 2: Comparison between present study and results reported in the literature.

3. RESULTS

Reynolds number range 25<Re<600 and for different volume fractions. The Nusselt number and the pressure loss coefficient profiles are presented for the different cases.

Fig. 5 represents variation of mean Nusselt number with Reynolds number at different nanoparticle volume fractions (1%, 3%, 5%, and 10%). We have seen that Nusselt number is a increasing function of Reynolods number for all nanoparticle volume fractions. Also, ethylene glycol base fluid enhances its heat transfer significantly comparatively to the water. These results are in agreement with the experimental study of Ramesh R. et al. [24.]

In order to show the importance of the ethylene glycol base fluid on heat transfer, we have calculated the Nusselt number enhancement by the following equation:

$$Nu(\%) = \frac{Nu_{nf(EG)} - Nu_{nf(water)}}{Nu_{nf(water)}} \quad (15)$$

We observe in figure 6, that the Nusselt number enhancements calculated for the ethylene glycol base fluid are much higher than those calculated for water base fluid and are a increasing function of Reynolods number for all nanoparticle volume fractions. These results show that the heat transfer is very sensitive to the base fluid. From this, for calculate and for the disign the thermal systems using nanoparticle, it is desirable to give an importance to the base fluid.

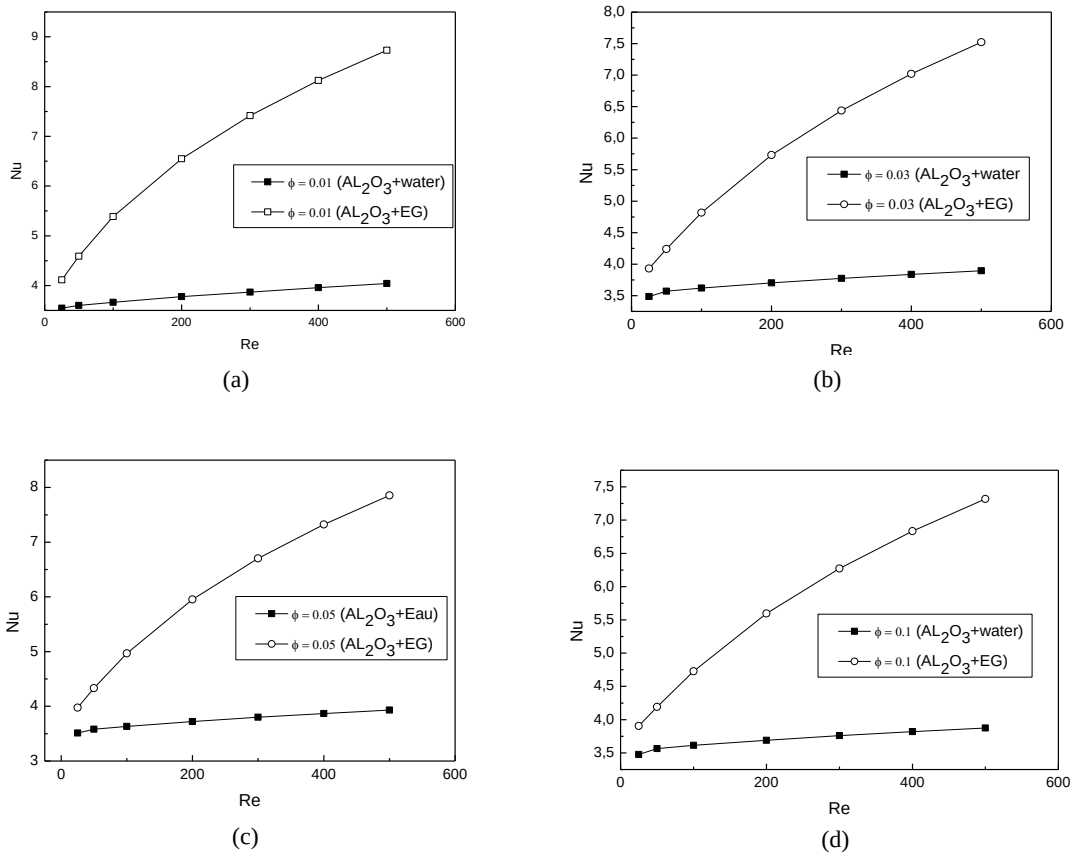

FIGURE 5: Nusselt number for different Reynolds number and different particle volume fractions: ((a) ϕ=0.01; (b) ϕ=0.03; (c) ϕ=0.05; (d) ϕ=0.1).

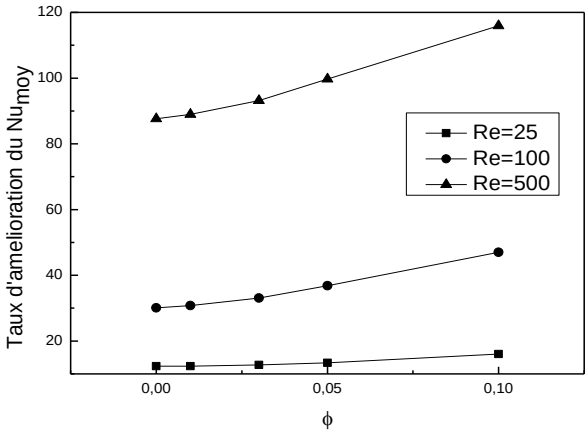

FIGURE 6: Nusselt number enhancement for different Reynolds number and different particle volume fractions.

Figure 7 illustrates the pressure loss coefficient as a function of Reynolds number for different volume fraction and for Reynolds number Re=200. The figure shows that the Al2O3-EG nanofluid and the Al2O3-water nanofluid give the same pressure loss coefficient. From this result, we can say that the base fluid don't have any effect on the pressure loss.

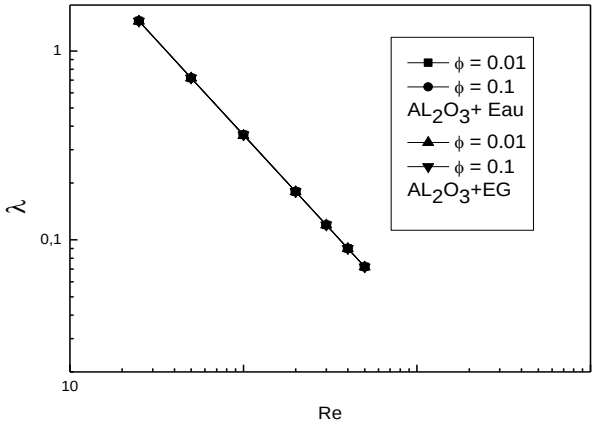

FIGURE 6: Pressure loss coefficient for Re=200 as a function of Reynolds number as particle volume fraction.

4. CONCLUSION

The effect of using two different base fluids on the heat transfer in a horizontal cylinder was studied numerically for a range of Reynolds numbers and nanoparticles volume fraction.

Indeed, the results revealed that the suspended nanoparticles increase the heat transfer with an increase in the nanoparticles volume fraction and for a considered range of Reynolds number. The results show the influence of the base fluid on the heat transfer and the pressure drop identified the kind of base fluid that gives better heat transfer and a minimum pressure drop. Numerical simulations were compared with the experimental résults which show similar trend and are in reasonable agreement. This computational code can be effctively implemented for simulations of nanofluid with further improvement over theoretical models that can account for

temperature effects. More accurate results can be obtained by taking into account the presence of nanoparticles in consideration.

5. REFERENCES

[1] S.U.S Choi, Z.G Zhang, W Yu, F.E Lockwood and E.A Grulke**.** "Anomalous thermal conductivity enhancement in nano-tube suspensions", Applied Physics Letters*,* No. 79, pp. 2252–2254, 2001.

[2] S.K Das, N Putta, P Thiesen and W Roetzel. "Temperature dependence of thermal conductivity enhancement for nanofluids", ASME Trans. J. Heat Transfer, No. 125, pp 567–574, 2003.

[3] S.U.S Choi. "Developments and Applications of Non-Newtonian Flows", Fluids Engineering Division FED, No. 231, pp 99-112, 1995.

[4] E.Abu-Nada, Z.Masoud, H Oztop and A Campo. "Effect of nanofluid variable properties on natural convection in enclosures", Int. J. Thermal Sci., No 49, pp 479-491, 2010.

[5] L.Godson, B.Raja, D.Mohan and S.Wongwises. "Enhancement of heat transfer using nanofluids", Renew. Sustainable Energy Rev., Vol. 14, No2, pp 629-641, 2009.

[6] W.Yu, D.M. France, J.L. Routbort and S.U.S. Choi. "Review and comparison of nanofluid thermal conductivity and heat transfer enhancement", Heat transf. Eng., Vol. 29, No 5, pp 432-460, 2008.

[7] Y.Li, J.Zhou, S.Tung, E.Schneider and S.Xi, "A review on development of nanofluid preparation and characterization", PowderTechnol., Vol. 196, No 2, pp 89-101, 2009.

[8] B.C. Pak and Y. I. Cho. "Hydrodynamic and heat transfer study of dispersed fluids", Int. J. Heat Mass Transf., Vol. 11, pp 5181-5201, 1998.

[9] D.Wen and Y.Ding [2004], "Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions", Int. J. Heat Mass Transfer, No. 47, pp 5181–5188, 2004.

[10] S.Z.Heris, S. G. Etemad and M.N. Esfahany . "Experimental investigation of oxide nanofluids laminar flow convective heat transfer", Int. Commun. Heat Mass Transf, Vol. 33, No 4, pp 529-535, 2006.

[11] Y.He, Y.Jin, H.Chen, Y.Ding, D.Cang and H.Lu . "Heat transfer and flow behaviour of aqueous suspensions of TiO2 nanoparticles", Int. J. Heat Mass Transf., Vol. 50, No 11, pp 2272-2281, 2007.

[12] C.T.Nguyen, G.Roy, C.Gauthier and N.Galaris . "Heat transfer enhancement using Al2O3-water nanofluid for an electronic liquid cooling system", App. Therm. Eng., Vol. 27, No 8, pp 1501-1506, 2007.

[13] Y.Ding, H.Alias, D.Wen and R. A. Williams . Heat transfer of aqueous suspensions of Carbon nanotubes", Int. Commun. Heat Mass Transf, Vol. 49, pp 240-250, 2006.

[14] P.Garg, J.L.Alvarado, C.Marsh, T.A. Carlson, D.A.Kessler and K. Annamalai. "An experimental study on the effect of ultrasonication on viscosity and heat transfer performance of multiwall carbon nanotube-based aqueeous nanofluids", Int. J. Heat Mass Transf., Vol 52, No 21, pp 5090-5101, 2009.

[15] Y Xuan and Q.Li . “Investigation on convective heat transfer and flow features of nanofluids”, Int. J. Heat Mass Transfer, Vol. 125, pp 151-155, 2003.

[16] Y.Yang, Z.G.Zhang, E.A.Grulke, W. B. Anderson and G.Wu . “Heat transfer properties of nanoparticle in fluid dispersions”, Int. J. Heat Mass Transfer, Vol. 48, No. 6, pp 1107-1116, 2005.

[17] W.Yu, D. M.France, D. S.Smith, E. V. Timofeeva and J.L. Routbort . “Heat transfer to a Silicon Carbide/water nanofluid” , Int. J. Heat Mass Transfer, Vol. 52, No. 15, pp 3606-3612, 2009.

[18] S.Torii and W. J. Yang . “Heat transfer augmentation of aqueous suspensions of nano-diamonds in turbulent pipe flow”, J. Heat Transf., Vol. 131, pp 1-5, 2009.

[19] S.V. Patankar . Computation of Conduction and Duct Flow Heat Transfer, Hemisphere Publishing Corporation, New York, 1988.

[20] R.K. Shah., “Thermal entry length solutions for the circular tube and parallel plates” Proceedings of 3rd National Heat and Mass Transfer Conference, vol. 1, Indian Institute of Technology, Bombay, p. HMT-11-75, 1975.

[21] Hadjisophocleous, G.V. Sousa and J.E.S. Venart, “Predicting the transientnatural convection in enclosures of arbitrary geometry using a nonorthogonal numerical model” Numer. Heat Transfer A, No. 13, pp 373–392, 1998.

[22] R.K. Tiwari and M.K. Das, “Heat transfer augmentation in a two-sided lid-driven differentially heated square cavity utilizing nanofluids”, Int. J. Heat Mass Transfer, No. 50, pp 2002–2018, 2007.

[23] C.L. Kuang and A. Violi, “Natural convection heat transfer of nanofluids in a vertical cavity: Effects of non-uniform particle diameter and temperature on thermal conductivity”, International Journal of Heat and Fluid Flow, No 31, pp 236–245, 2010.

[24] R. Remesh and R. Vivekananthan, “Application of Al2O3 nanofluid for enhance heat transfer rate in shell and tube heat exchanger”, IOSR Journal of Mechanical and Civil Engineering, Volume 11, Issue 2, pp 29-33, 2014.