Heat transfer behaviour of nanofluid in a heated tube

Meriem AMOURA[1] and Noureddine Zeraibi[2]

[1] *Université des Sciences et de la Technologie Houari Boumedienne. Faculté de Physique. Dépt. Energétique. B.P. 32 El-Alia, bab-Ezzouar, 16111, Alger, Algeria*

[2]*Université de Boumerdes. Faculté des hydrocarbures dépt. Transport et équipement. 35000 Avenue de l'indépendance, Boumerdes, Algeria.*

[1]am_louni@yahoo.fr

[2]no_zeraibi@yahoo.fr

Abstract-- Convective heat transfer behaviour of CuO-water nanofluid flowing through a heated horizontal tube under laminar regime has been investigated numerically. A computational code applied to the problem by use of the finite volume method was developed. 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.

Keywords**-- Heat transfer, nanofluid, numerical study**

Nomenclature

Cp	Specific heat (J/kg K)
D	Diameter (m)
L	Length of cylinder (m)
q	Heat flux (W/m^2)
Re	Reynolds number
r	Radius
T	Temperature
u, v	Velocity components
x, r	Axial and radial coordinates

Greek symbols

ϕ	Nanoparticle fraction
μ	Dynamic viscosity (kg/m s)
ρ	Density (kg/m^3)

Subscripts

f	fluid
nf	nanofluid

I. 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 behavior of nanofluids, numerous investigations have been carried out [4]. Almost all previous investigations show that the thermal conductivity of nanofluids increases significantly over that of the base fluid [4-6].

Oxide nanoparticles [7-11], carbon nanotubes [12-13] and other types of nanoparticles [14-17] have been used in the preparation of nanofluids. Conventional heat transfer fluids such as water, ethylene glycol and transformer oil have been emplowad 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 nanofluid CuO/water in horizontal circular tube with constant wall heat flux in the laminar flow regime were studied numerically. A computational code by use of the finite volume method is developed [18]. 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 importance of the choice of the correlation to determine the Nusselt number

II. PROBLEM FORMULATION

The geometry under investigation is shown in Fig. 1. We consider an 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 and CuO nanoparticles. These 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. The nanoparticles in the base fluid can be easily fluidized and, thus, the nanofluid mixture is considered as a single phase.

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 thermophysical properties such as density, thermal conductivity of the base fluid and nanoparticle and viscosity are summarized in Table 1.

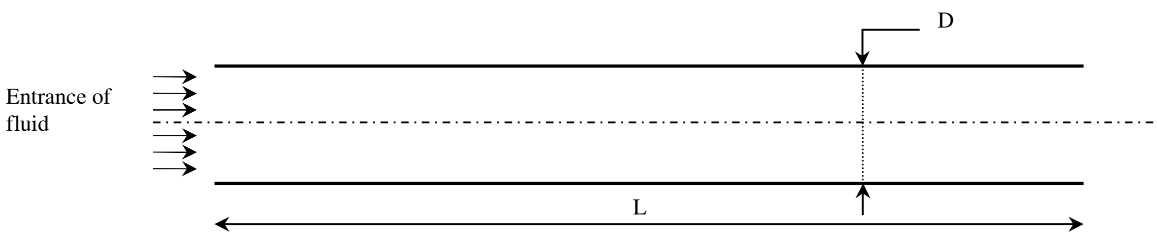

Fig.1 Geometry of the problem

TABLE 1
MATERIAL PROPERTIES OF FLUID AND NANOPARTICLE [19]

	Water	**CuO**
Density (kg/m^3)	1000	6350
Thermal conductivity (W/m K)	0.6	69
Specific heat capacity (J/kg K	4183	535
Dynamic viscosity (Ns/m^2) x 10^{-3}	1.003	-

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:

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

Momentum equations in the axial and radial directions are:

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

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

The axi-symmetric form of energy equation is:

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

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

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

Specific heat is also defined by mixing theory:

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

The thermal conductivity of nanofluid was evaluated from the model proposed by Maxwell [20] namely:

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

The effective viscosity of fluid containing small particules is given by Brinkman [21] as:

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

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

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

The problem is characterized by the following parameters of similarity:

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

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

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

The Nusselt number of the nanofluids is expected to be dependent on a numerous 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. It can be expressed as:

$$Nu=\begin{cases}1.953\left(RePr\frac{D}{x}\right)^{\frac{1}{3}} & \left(RePr\frac{D}{x}\right)\geq 33.3\\ 4.364+0.0722RePr\frac{D}{x} & \left(RePr\frac{D}{x}\right)\leq 33.3\end{cases}\quad [22] \tag{13}$$

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

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

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 figure 2 and table 2.

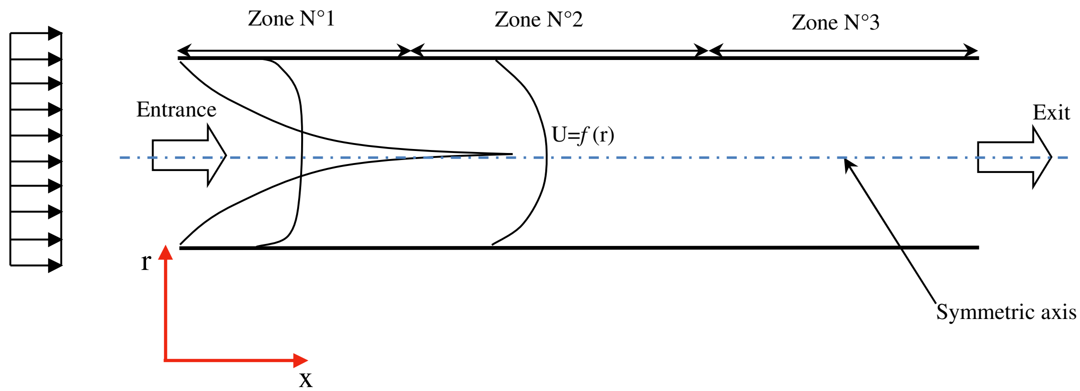

Fig. 2 Boundary conditions

TABLE 2
BOUNDARY CONDITIONS

The condition	Entrance	Zone N°1 $0 \leq x \leq 1m$	Zone N°2 $1 \leq x \leq 1{,}5m$	Zone N°3 $1{,}5m \leq x \leq 5m$ 1m	Symmetric axis
Axial velocity *U*	$U_0 = \frac{\mathrm{Re}\,\mu}{\rho D}$	$U = 0$	$U = 0$	$U = 0$	$\frac{\partial U}{\partial r} = 0$
Radial velocity *V*	$V = 0$	$V = 0$	$V = 0$	$V = 0$	$\frac{\partial V}{\partial r} = 0$
Temperature T	T_0= 288 K	T= T_{wall}	q=900W/m^2	$\frac{\partial T}{\partial r} = 0$	$\frac{\partial T}{\partial r} = 0$

III. NUMERICAL RESOLUTION

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 used for all simulation. For cylinder's diameter less than 2mm and a length equal to 5 m, a independence grid test 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 and in the second zone (starting about a quarter of the way and ending about half way) (Figure 4).

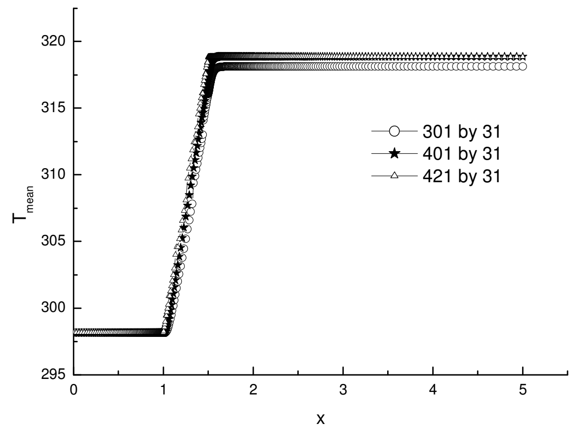

Fig. 3 Temperature profiles at Re=25 for 10% volume fraction of CuO

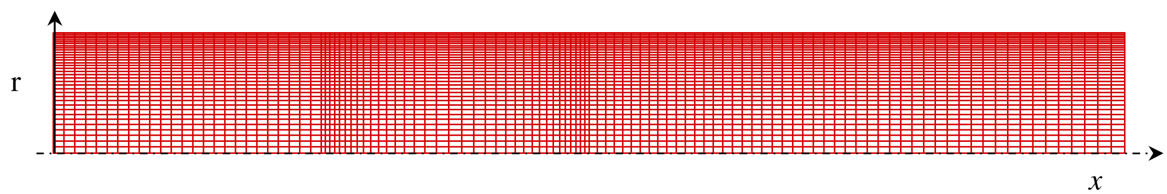

Fig. 4 Schematic of grid

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.

Furthemore, 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 [23], Tiwari [24] and Kuang [25]. 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 3. A very agreement has been obtained.

TABLE 3

COMPARISON BETWEEN PRESENT STUDY AND RESULTS REPORTED IN THE LITERATURE

	Hadjisophocleous [23]	**Tiwari [24]**	**Kuang [25]**	**Present study**
		Ra=10³		
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=10⁴		
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=10⁵		
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=10⁶		
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

IV. RESULTS AND DISCUSSION

The heat transfer performance has been investigated for the Reynolds number range 25<Re<800 and for different volume fractions. The temperature and Nusselt number profiles are presented for the different cases.

Figure 5 show the temperature profiles along of the cylinder at different Reynolds numbers for pure water and for different nanoparticle concentrations (2%, 5% and 10%). It is clear that addition of nanoparticles to the base fluid enhances its heat transfer significantly. The temperature increases with the volume fraction.

In addition, we also note that the curves of average temperature are almost confused because of the equality of temperatures at the entrance and at the wall for area $0 \leq x \leq 1$m. In the second area (1m ≤ x ≤ 1,5m), there is a sudden increase of the temperature due to the thermal developed regime that is not yet reached. The last zone (x≥2m), where the wall is adiabatic, we observe increasing levels of average temperature proportional to the volume fraction and inversely proportional to the Reynolds number.

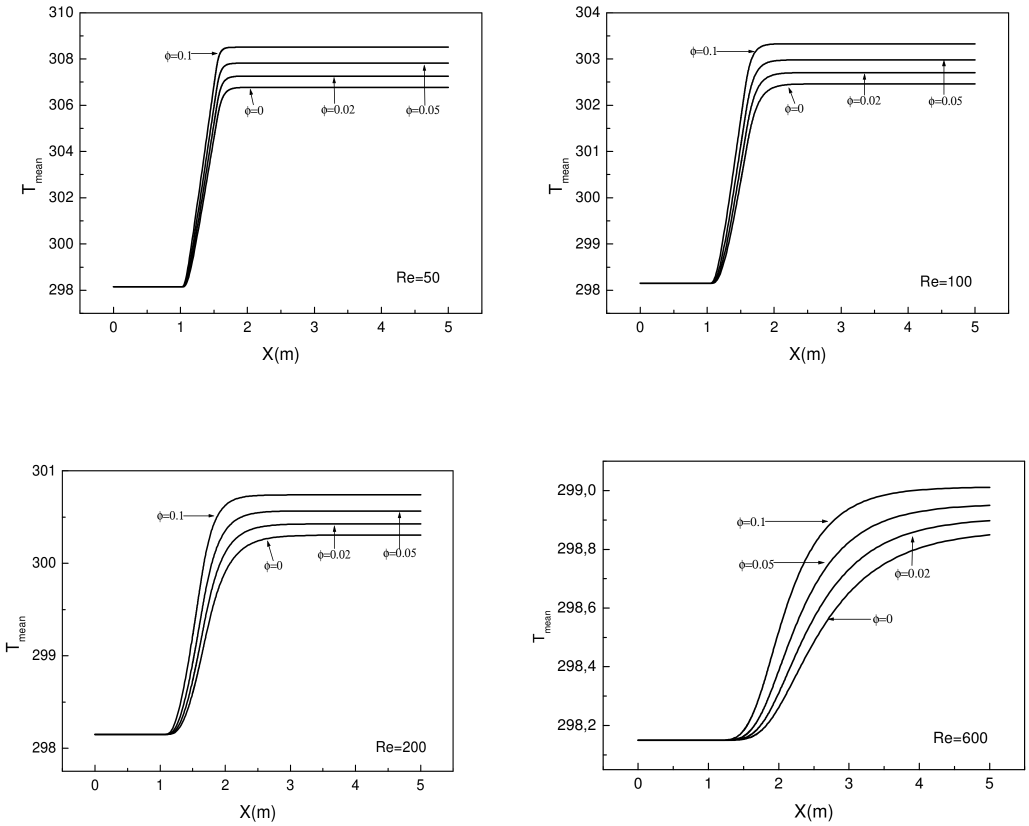

Fig. 5 Temperature profiles at different Reynolds number and for different volume fraction of CuO

The effect of the nanofluid volume fraction on the Nusselt number for heat transfer in the flow in the tube is shown in Figure 6. It can be seen that the Nusselt number increases with the volume fraction. This implies that the nanofluid heat transfer rate has some dependency on particle concentration or volume fraction and it increase with the volume fraction.
Figure 7 represents variation of mean Nusselt number with Reynolds number at different nanoparticle concentrations (2%, 5% and 10%). To calculate specific heat capacity *Cp*, we have used two correlations:

$$Cp_{nf} = (1-\emptyset)Cp_{bf} + \emptyset Cp_{particle} \quad [26] \tag{14}$$

$$Cp_{nf} = \frac{(1-\emptyset)\rho_{bf}Cp_{bf} + \emptyset\rho_{particle}Cp_{particle}}{\rho_{nf}} \quad [27] \tag{15}$$

We seen that the Nusselt number calculated by using the correlation of Xuan gives better results than the correlation of Xing for all nanoparticle concentrations.

In order to show the importance of the CuO nanoparticle in the water on heat transfer, we have calculated the Nusselt number enhancement by the following equation:

$$Nu(\%) = \frac{Nu_{correlation} - Nu_{water}}{Nu_{water}} \tag{16}$$

We observe that the Nusselt number enhancements calculated by the correlation of Xuan [26] are much higher than those calculated by the correlation of Xing [27] (see table 4).

These results show that the Nusselt number is very sensitive to the method used to calculate specific heat *Cp*. From this, for calculate and for the thermal systems design using nanoparticle, it is recommended to give an importance to the method of determination of specific heat *Cp*.

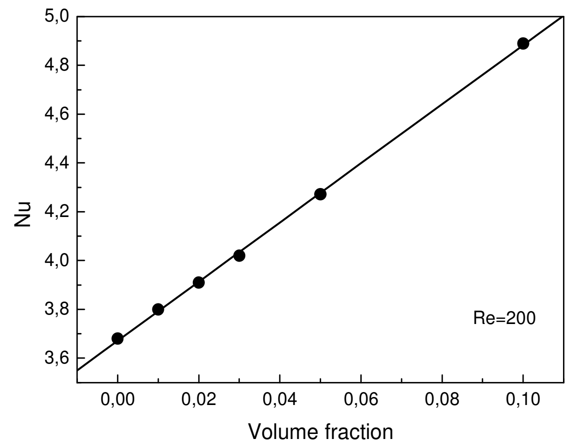

Fig. 6 Effect of volume fraction on the Nusselt number

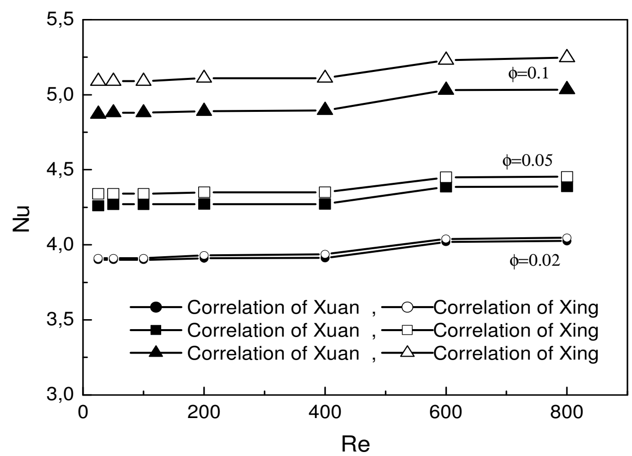

Fig. 7 .Nusselt number versus Reynolds number

TABLE 4

THE NUSSELT NUMBER ENHANCEMENT NU (%)

	Correlation of Xuan [26]			**Correlation of Xing** [27]		
Re	$\phi=0.02$	$\phi=0.05$	$\phi=0.1$	$\phi=0.02$	$\phi=0.05$	$\phi=0.1$
25	6.6	16.5	33.1	6.9	18.6	39.1
50	6.6	16.7	33.3	6.8	18.6	39.1
100	6.4	16.5	33.2	6.7	18.4	38.9
200	6.3	16.1	32.9	6.8	18.2	38.9
400	6.0	15.8	32.7	6.7	17.9	38.5
600	8.9	18.9	36.3	9.5	20.6	41.7
800	8.8	18.6	36.1	9.4	20.4	41.8
$\mathbf{Nu_{mean}}$	7.09	17.01	33.94	7.54	18.96	39.71

V. CONCLUSION

Heat transfer enhancement of nanofluid for CuO/water in a horizontal cylinder has been numerically studied. It was found that suspended nanoparticles in the base fluid causes a remarkable increase in the heat transfer performance in pipe flow compared to the base fluid. From these results it was found that Nusselt number increases with nanofluids volume fraction increases.

It was also seen that the choice of the correlation to determine the Nusselt number is very important for calculate and for the design of the thermal systems using nanoparticles.

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

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] 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.

[5] 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.

[6] 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.

[7] 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.

[8] D.Wen and Y.Ding , 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

[17] 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.

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

[19] 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.

[20] J.C. Maxwell, *Treatise on electricity and Magnesium*, Oxlarendon Press, 1873.

[21] H. Brinkman, *The viscosity of concentrated suspensions and solutions*, J. Chem.. Phys., N° 20, pp. 571-581, 1952.

[22] 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.

[23] 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.

[24] 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.

[25] 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.

[26] Y. Xuan and W. Roetzel, *Conceptions for heat transfer correlation of nanofluids,* Int. J. Heat Mass Transfer, Volume 43, pp 3701-3707, 2000.

*[27]*Z. Xing, H. Gu and M. Fujii, *Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles,* Experimental Thermal and Fluid Science, N° 31, pp 593-599, 2007.