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Computer-Aided Simulation of Heat Transfer in Nanofluids

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Abstract_ Numerical simulation and experimental investigation were used for study of laminar forced convective heat transfer of Al_2O_3/water nanofluid. Single phase model with temperature-dependent properties was employed for numerical simulation of transport phenomena in nanofluid. The results of experiments and computer-aided simulation indicated remarkable enhancement of convective heat transfer of base fluid, by adding small amounts of Al_2O_3 nanoparticles. The convective heat transfer in nanofluid enhanced with increasing of nanoparticle concentration and flow Reynolds number. Increasing of ethylene glycol in the base fluid composition resulted in decreasing of heat transfer coefficient.
Keywords: nanofluid, forced convective heat transfer, Al2O3 nanoparticle, single phase model

I. Introduction

Nanofluids are stable suspensions of nano-size particles in convectional fluids which can be used as heat-transfer fluids, tribological fluids, surfactants, chemical agents, process/extractive materials and pharmaceutical materials [1-3]. There are two main methods for preparation of nanofluids [4]; a. The single step method: in this method, the nanoparticles preparation and dispersion to base fluid is performed simultaneously. b. The two-step method: in this method, the nanoparticles are prepared and then dispersed in the base fluid.

There are large numbers of experimental investigations on the convective heat transfer of nanofluids. As it can be seen in table1, the results of these studies show that the convective heat transfer enhances with increasing of nanoparticles concentration. Table1. The experimental investigations on the convective heat transfer of nanofluids. The first numerical study of nanofluid heat transfer has been performed by Choi et al. [10]. Single phase method is the first numerical technique has been used for study of nanofluid convective heat transfer [11]. In this method, nanofluid is assumed as a single phase fluid at thermal equilibrium and the motion slip between nanoparticles and base fluid is not considered.

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Maiga et al. [12] and Palm et al. [13] have been employed single phase method for analysis of convective heat transfer of Al_2O_3/water. Their results exhibit good agreement with the experimental results.

The relative velocity of nanoparticles and base fluid are considered in two phase method [14- 16]. Behzadmehr et al. [17] employed this method for 1 Vol. % Cu nanofluid and reported that the turbulent convective heat transfer in a circular tube increased up to 15%. Bianco et al. [18] studied the forced laminar convection of nanofluid containing 100nm Al_2O_3 nanoparticles. They concluded that single phase and two phase methods exhibited approximated results, especially in the case of using temperature-dependent properties. Xuan and Roetzel [20] employed dispersion method for modeling of nanofluid thermal properties. They considered the chaotic movement of the nanoparticles in nanofluid, similar to dispersion theory in porous media proposed by Bear [21]. Mokmeli et al. [22] used dispersion method for analysis of the effect of volume fraction, average size of ATF-graphite and Al_2O_3 nanoparticles on the convective heat transfer of nanofluid.

Table1. The experimental investigations on the convective heat transfer of nanofluids

Author	Nanofluid composition	Results
Heris et al. [5]	Al_2O_3/water	41% enhancement of heat transfer coefficient at 2.5Vol.% of nanoparticles and Pe=6000
Yang et al. [6]	graphite/ water	22% enhancement of heat transfer coefficient at 2.5 Vol. % nanoparticles
Chen et al. [7]	titanate/water	remarkable increasing of convective heat transfer with increasing of nanoparticles concentration and aspect ratio
Nguyen et al. [8]	Al_2O_3/water	Increasing of heat transfer in the electronic cooling system up to 40% at 6.8 Vol.% of nanoparticles
Ding et al. [9]	CNT/water	Remarkable enhancement of heat transfer coefficient

In this study, the forced laminar convective heat transfer coefficient of nanofluid containing Al_2O_3 nanoparticles flows through a horizontal tube is studied. Single phase method with temperature-dependent properties is used for numerical simulation of nanofluid's thermal behavior. Experimental investigations are used for validation of the results of numerical simulation.

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II. Experimental

A design scheme of experimental set-up used at this work is shown in Figure1. This system consists of a flow loop, pipeline system, a 25 liter reservoir tank, pumping and cooling system. Nanofluid flows through a horizontal copper tube with 1m length, 1 cm diameter and 1.7 mm thickness. The tube section is insulated by using a layer of 25 mm of fiberglass which electrically heated at a constant rate of 5000 W/m^2. The tube section is uniformly wounded by Nickel-chrome wire connected to a DC 300 W power supply. Five K-type thermocouples are installed along the tube section and two K-type thermocouples are installed at the tube ends, for measuring of nanofluid bulk temperature. The local temperatures were transferred to a programmed computer system to calculate and store the Nusselt number and convective heat transfer coefficient (Eq's1_3). The nanofluid flowrate is measured by using a flow-meter, installed at tube entrance. The nanofluid flowrate and temperature are measured with uncertainties of 3% and 0.1. The nanolfuid exits the tube section and is stored in a 25 liters tank, cooled and recycled to the tube section. Steady state condition is reached after 35 min. Cooling system is consisted of a tubular heat exchanger with 50 cm length which used cooling water for reducing the nanofluid temperature. The uncertainty of Re number and convective heat transfer coefficient were 3 and 6% in the experiments.

The nanofluid is prepared by addition of 10nm γ-Al_2O_3 nanoparticles (1-10 Vol. %) and 0.1 Vol. % Triton X-100 as stabilizer to distillated water as base fluid. The prepared mixture is homogenized by using an ultrasonic bath (model) for 10 hours. The produced stable nanofluid is used for thermal analysis. In the last step of experiments, for investigation of the effect of base fluid composition, ethylene glycol is mixed with water involving different volume concentrations (10, 20 and 40 Vol. %). The produced mixture is agitated in a flask and used for preparation of nanofluids. The Physical properties of Al_2O_3 nanoparticles (Nanostructured and Amorphous Materials, Inc, USA) and ethylene glycol were illustrated in tables 2 and 3 [23]. The thermal parameters (h_{ave} and Nu_{ave}) are estimated using equations 1- 3. In these equations T_{local}, T_w and T_{input} are local temperature, wall temperature and input temperature, ρ and Cp and u are nanofluid density, specific heat and velocity, L and D are tube length and diameter and x is distance from tube inlet.

Table2. The physical properties of γ-Al_2O_3 nanoparticles

γ- Aluminum Oxide Powder	
Average particle size (nm)	10
Specific surface area(m^2/g)	160
Purity (%)	99
Particle Morphology	Nearly spherical

Table3. The physical properties of Ethylene glycol (at 20°c)

Molecular Formula	$C_2H_6O_2$
Molar mass (kg.kmol^{-1})	62.07
Density (kg/m^3)	1113
Specific heat capacity (kJ.kg^{-1}.K^{-1})	2.381
Viscosity (Pa.s)	0.02
Thermal conductivity(W.m^{-1}.K^{-1})	0.256

III. Numerical simulation

Single phase method was used for numerical simulation of convective heat transfer. The tube geometry is demonstrated in figure2. Nanofluid enters the tube at a uniform velocity (U_0) and temperature (T_0). At the end of the tube section, fully developed condition is assumed. The velocity and thermal fields of nanofluid are assumed symmetrical regarding to the centerline of the tube. The conservation equations for single phase method are illustrated below (Eq's. 4-7) [24].

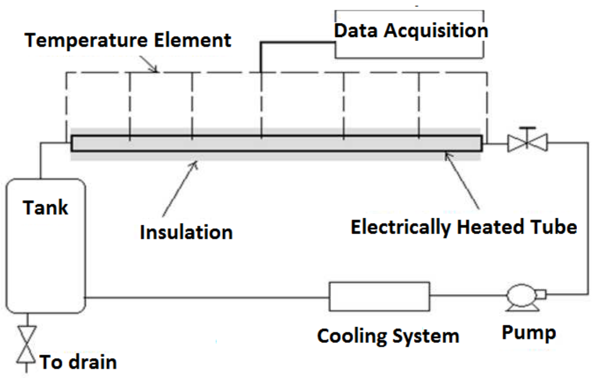

Fig1 .The experimental set-up

$$h_{local} = \frac{(T_{local} - T_{input})\rho c_p u D}{4x(T_w - T_{input})} \quad (1)$$

$$h_{ave} = \frac{1}{L}\int_0^L h(z)dz \quad (2)$$

$$Nu_{ave} = \frac{h_{ave}.D}{K_{nf}} \quad (3)$$

The physical properties of nanofluid are assumed as functions of physical properties of both base fluid and nanoparticles and their volume fraction (Eq's. 8-11) [18]. The physical properties of both nanofluid and base fluid were assumed temperature-dependent. The physical properties of base fluid were obtained by fitting a quadratic function on the NIST data for water (Eq's. 12-15) [25]. The viscosity of nanofluid is assumed as a function of nanoparticles size for ensuring more accurate results (Eq. 10) [14].

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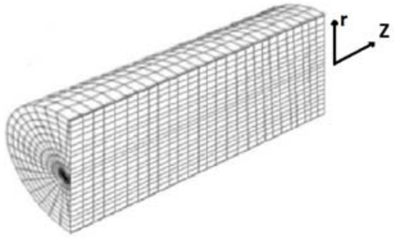

Fig2. Geometrical configuration under study

Continuity equation:

$$\frac{\partial\rho}{\partial t} + (\nabla.\rho U) = 0 \qquad (4)$$

Momentum equation:

$$\rho\frac{DU}{Dt} = -\nabla p + \mu\nabla^2 U \qquad (5)$$

Energy equation:

$$\rho C_p \frac{DT}{\partial t} = k\nabla^2 T \qquad (6)$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + (U.V) \qquad (7)$$

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_{np} \qquad (8)$$

$$C_{p,nf} = (1-\varphi)C_{p,bf} + \varphi C_{p,np} \qquad (9)$$

$$\mu_{nf} = \mu_{bf} + \frac{\rho_{np}\vartheta_B d_{np}^2}{72\delta C} \qquad (10)$$

$$\frac{k_{nf}}{k_{bf}} = 4.97\varphi^2 + 2.7\varphi + 1 \qquad (11)$$

$$\rho_{bf}\left(\frac{kg}{m^3}\right) = -3.668\times10^{-3}T^2 - 6.867\times10^{-2}T + 1001,\ T(^\circ C) \qquad (12)$$

$$Cp_{bf}\left(\frac{J}{kg.K}\right) = -7.798\times10^{-6}T^2 - 2.892\times10^{-4}T + 0.0124 lnT + 4.224,\ T(^\circ C) \qquad (13)$$

$$\mu_{bf}(pa.s) = -5.051\times10^{-4}\ln(T+2.459) + 2.567\times10^{-3},\ T(^\circ C) \qquad (14)$$

$$k_{bf}\left({}^{W}/_{m.k}\right) = -9.751\times10^{-6}T^2 - 2.163\times10^{-3}T + 0.5596,\ T(^\circ C) \qquad (15)$$

The boundary conditions at the tube input is assumed relevant to the nanofluid input properties ($U=U_0$, $V=V_0$, $T=T_0$ and $P=P_0$) and the fully developed condition is assumed at the tube exit($\frac{\partial}{\partial z} = 0$). No slip condition and constant heat flux were assumed at tube wall ($U=V=0$, $\frac{\partial p}{\partial r} = 0$, q_w=cte).

Several non-uniform grids have been tested for ensuring that the model results are grid independent (100×125, 200×250, 400×500, 800×1000). The accuracy of model results increases by increasing the number of grids up to 200×250 nodes along the radial and axial directions (the thermal field was assumed symmetrical regarding the tube centerline using no tangential). No significant enhancement has been observed after this point. The non-uniform grids including 200×250 nodes have been used. The number of nodes near to tube wall is higher.

The conservation equations for steady state conditions in two-dimensional system were discretized using finite difference method. The obtained algebraic (discretized) equations were solved using computer aided programming. Matlab version R2010a was used for computational processing (implemented by a 2.53 GHZ Intel Core2 Duo CPU processor with 4 GB RAM) of numerical model. The first trial values for the operational variables are illustrated in table4.The intended convergence for velocity, temperature and pressure are10-5 m/s, 0.01˚c and 1 Pa respectively.

The model was employed for comprehensive analysis of the effects of Al_2O_3 concentration (0, 1, 2, 5 and 10 Vol. %), Reynolds number (250-500 and 1000), nanofluid inlet temperature (20, 30, 40 and 60 ˚c) and base fluid composition (0, 10, 20, 30 and 40 Vol. % of EG).

Table4. First trial values for operational variables

parameter Initial value	parameter Initial value
Axial velocity (U)	Nanofluid inlet velocity (U_0)
Radial velocity (v)	0
Temperature (T)	Nanofluid inlet temperature (T_0)
Pressure (P)	Nanofluid inlet pressure with 1% loss along the tube $P_i=P_0(1-0.01Z/L)$; Z=distance from tube inlet, L=tube length

Model validation

The results of Numerical simulation were initially validated by implementing of model and experimental investigation for the forced convection heat transfer of pure water flows (Re number=250) through a horizontal tube exposed to constant heat of 5000 W/m^2. As can be seen in table5, the results of model are in good agreement with experimental results. According to the Perry's handbook, the Values of limiting Nusselt number in laminar flow in closed ducts is 4.36[23].

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Table5. The results of model and experimental investigations for pure water

Thermal properties	Model results	Experimental results
Nu_{ave}	4.37	4.51
h_{ave}	261.81	272.31

IV. Results and discussions

3.1. The effect of Al_2O_3 nanoparticles concentration

The nanoparticles concentration was adjusted at 1, 2, 3, 4, 5 and 10 Vol. % and the convective heat transfer was studied at Re=250 and q_w=5000 w/m^2. The convective heat transfer of nanofluid (h_r=h nanofluid /h base fluid) is shown in figure3. The temperature and velocity fields of nanofluid containing 5 Vol. % Al_2O_3 nanoparticles are shown in figures 4 and 5. The forced convective heat transfer coefficient increases with increasing of nanoparticles concentration. The convective heat transfer coefficient of nanofluid containing 5 Vol. % Al_2O_3 was observed 26% higher than water. At similar operating conditions, the fluids with higher conductive heat transfer coefficient have higher convective heat transfer coefficient. The thermal conductivity of nanofluid is a function of thermal conductivity of both base fluid and nanoparticles. Increasing of nanoparticles concentration, results in increasing of conductive heat transfer coefficient and consequently convective heat transfer [18].

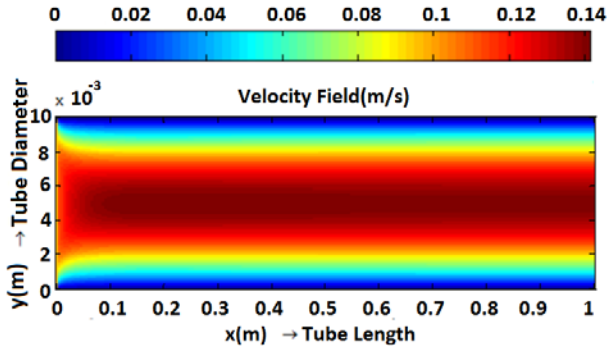

Fig5. The velocity field of nanofluid flow contains 5 Vol. % Al_2O_3 at Re=250, T_0= 20˚c and q_w=5000 w/m^2

3.2. The effect of nanofluid flow Reynolds number:

The effect of Re number on the heat transfer is illustrated in figure6. The velocity and temperature fields of nanofluid flows at Re=1000 are demonstrated in figures7 and 8. The forced convective heat transfer increases with increasing of nanofluid flow Reynolds number. Increasing of flow Reynolds number, results in increasing of turbulent eddies. This event causes increasing of effective thermal conductivity of nanofluid and consequently increasing of convective heat transfer [26].

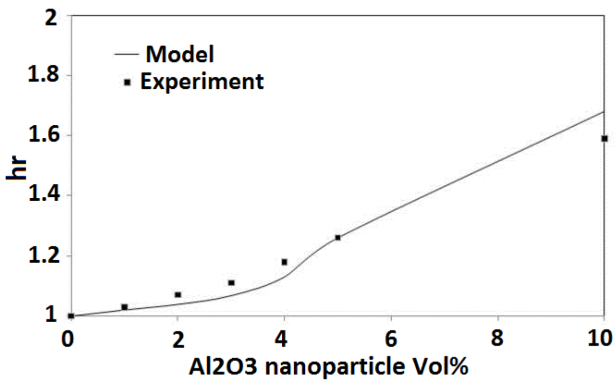

Fig3. The effect of Al_2O_3 nanoparticles concentration on the convective heat transfer coefficient of nanofluid at Re=250 and q_w=5000 w/m^2

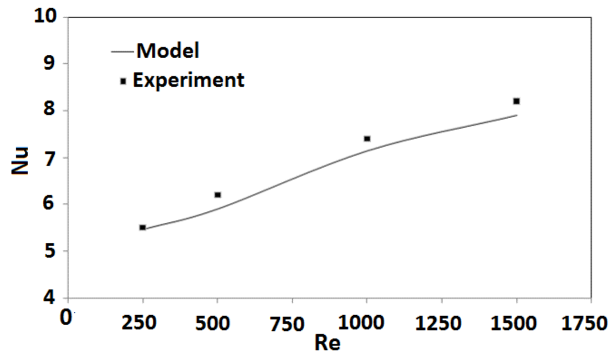

Fig6. The effect of nanofluid flow Reynolds number on the Nusselt number at 5 Vol. % of Al_2O_3 nanoparticles and q_w=5000 w/m^2

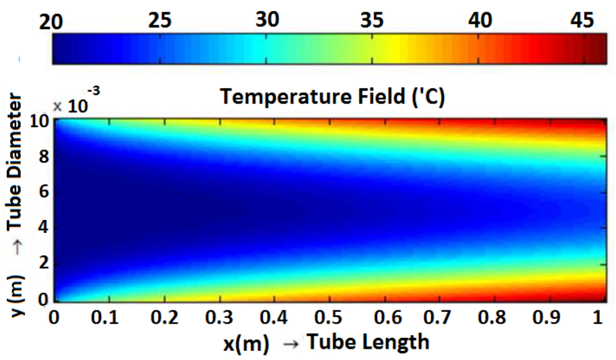

Fig4. The temperature field of nanofluid flow, contains 5 Vol. % Al_2O_3 at Re=250, T0= 20˚c and q_w=5000 w/m^2

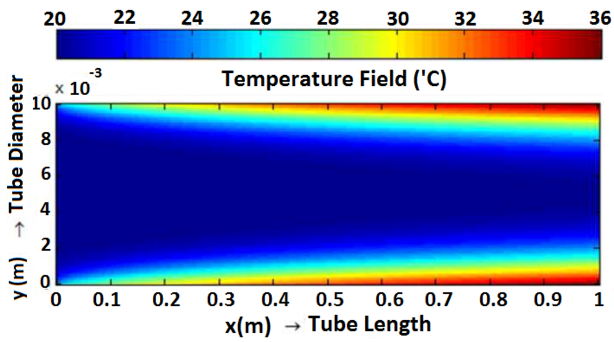

Fig7. The temperature field of nanofluid flow at Re=1000, 5 Vol.%of Al_2O_3 nanoparticles and q_w=5000 w/m^2

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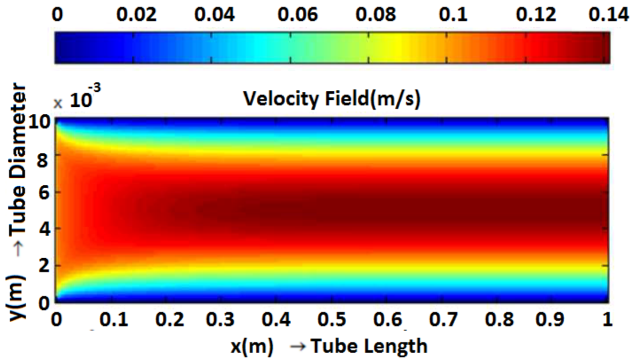

Fig8. The velocity field of nanofluid flow at Re=1000, 5 Vol. % of Al_2O_3 nanoparticles and q_w=5000 w/m^2

3.2. The effect of nanofluid input temperature

As can be seen in figure9, similar to conventional fluids the convective heat transfer coefficient of nanofluid increases with increasing of input temperature. This may be due to increasing of Brownian motions of nanoparticles. Similar results has been reported by Keblinski et al. [27].

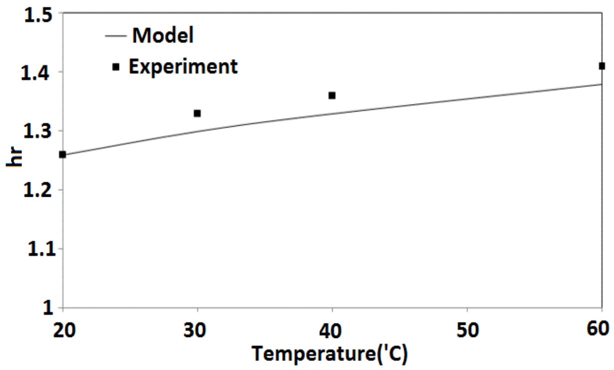

Fig9. The effect of nanofluid input temperature on the convective heat transfer coefficient at Re=250, 5 Vol. % of Al_2O_3 nanoparticles and q_w=5000 w/m^2

3.3. The effect of base fluid composition

Ethylene glycol (EG) is an ordinary additive for enhancing of thermal properties of water. The effect of EG concentration in the base fluid composition (10, 20 and 40 Vol. %.) on the nanofluid heat transfer coefficient was investigated. As it can be observed in figure10, increasing of EG concentration in the base fluid composition results in decreasing of convective heat transfer. Ethylene glycol has lower conductivity regarding the water (K_{water} at 20ºc =0.58W.m.K^{-1}) [23] and increasing of its concentration in the EG/water mixture, results in increasing of base fluid conductivity and consequently enhancement of nanofluid convective heat transfer [28].

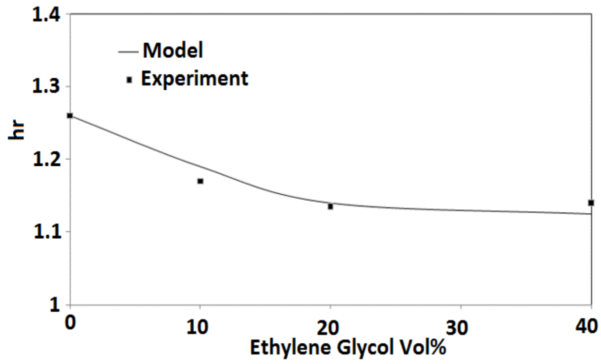

Fig10. The effect of EG concentration in the base fluid composition on the convective heat transfer coefficient at Re=250, 5 Vol. % of Al_2O_3 nanoparticle and q_w=5000 w/m^2

V. Conclusions

Numerical simulation and experimental investigation were employed for study of laminar forced convective heat transfer of nanofluid containing 10nm Al_2O_3 nanoparticles at constant heat flux. The results of both numerical and experimental investigations indicate that the convective heat transfer of water increased significantly by adding Al_2O_3 nanoparticles. The convective heat transfer of nanofluid increases with increasing of nanoparticle concentration, Reynolds number and inlet temperature. Increasing of EG concentration in the base fluid composition, results in decreasing of nanofluid convective heat transfer coefficient. Increasing of flow Reynolds number results in later formation of fully developed region and decreasing of tube wall temperature.

References

[1] Eastman, J. A., Choi, U. S., Li, S., Thompson, L. J., and Lee, S., "Enhanced Thermal Conductivity through the Development of NanofluidsY Proc. of the Symposium on Nanophase and Nanocomposite Materials H, Materials Research Society, Boston, Vol. 457, pp. 3-11. 1995.

[2] Stephen U. S. Choi, Energy technology division, Argonne national laboratory, Northern Illinois University, January 15, DeKalb, IL, 2005.

[3] Choi, U. S., "Enhancing Thermal Conductivity of Fluids with Nanoparticles, Developments and Applications of Non-Newtonian Flows, eds. D. A. Siginer and H. P. Wang, The American Society of Mechanical Engineers, New York, FED 23 VM.D, VO1.66, pp.99-105, 1995.

[4] Eastman, J.A., Mechanisms of Enhanced Heat Transfer in Nanofluids, Materials Science Division, Argonne National Laboratory, Fluctuations and Noise in Out of Equilibrium Systems, Sep 14-16, 2005.

[5] Zeinali Heris, S., Nasr Esfahany, Etemad, M. S.Gh., Experimental investigation of convective heat transfer of Al2O3/water nanofluid in circular tube International Journal of Heat and Fluid Flow, Vol.28, pp.203–210, 2007.

[6] Yang Y, Zhang ZG, Grulke EA, Anderson WB, Wu G. Heat Transfer Properties of Nanoparticle-in-Fluid Dispersions (Nanofluids) in Laminar Flow. Int J Heat Mass Transfer, Vol.48, No.6, pp.1107–1116, 2005.

[7] Chen, H., Yang W., He, Y., Ding, Y., Zhang, L., Tan, C., Lapkin, A., Bavykin, V. D., Heat transfer and flow behavior

of aqueous suspensions of titanate nanotubes (nanofluids), Powder Technology Vol.183, pp.63–72, 2008.

[8] Nguyen, C. T., Roy, G., Gauthier, C., Galanis, N., Heat transfer enhancement using Al2O3–water nanofluid for an electronic liquid cooling system, Applied Thermal Engineering ,Vol.27pp.1501–1506, 2007.

[9] Ding, H. Alias, D. Wen, R.A. Williams, Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids), International Journal of Heat and Mass Transfer Vol.49 No.1 pp. 240–250, 2005.

[10] Choi S, Zhang Z, Yu W, Lockwood F, Grulke E. Anomalously thermal conductivity enhancement of in nanotube suspensions. Applied Physics Letters, Vol.79 No.14, pp.2252– 2254, 2001.

[11] Pak, B.C., Cho, Y.I., Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. Experiment. Heat Transfer, Vol.11, No.2, pp.151–170, 1998.

[12] Maiga, S. B., Palm, S. J., Nguyen, C. T., Roy, G., Galanis, N., Heat transfer enhancement by using nanofluids in forced convection flows, International Journal of Heat and Fluid Flow, Vol.26, pp.530–546, 2005.

[13] Palm, S. J., Roy, G., Nguyen C. T., Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties. Applied Thermal Engineering Vol.26, No.17–18, pp.2209–2210, 2006.

[14] Izadi, M., Behzadmehr, A. D., Jalali, V., Numerical study of developing laminar forced convection of a nanofluid in an Annulus, International Journal of Thermal Sciences, Vol.48 2119–2129, 2009.

[15] Lotfi, R., Saboohi, Y., Rashidi, A.M., Numerical study of forced convective heat transfer of Nanofluids: Comparison of different approaches, International Communications in Heat and Mass Transfer Vol.37, pp.74–78, 2010.

[16] Mirmasoumi, S., Behzadmehr, A., Effect of nanoparticles mean diameter on mixed convection heat transfer of a nanofluid in a horizontal tube, International Journal of Heat and Fluid Flow Vol.29, pp.557–566, 2008

[17] Behzadmehr, M., Saffar-Avval, N., Galanis, Prediction of turbulent forced convection of a nanofluid in a tube with uniform heat flux using a two phase approach, International Journal of Heat and Fluid Flow Vol.28, pp.211–219, 2007.

[18] Bianco, V., Chiacchio, F., Manca, O., Nardini, S., Numerical investigation of nanofluids forced convection in circular tubes, Applied Thermal Engineering, Vol.29, pp.3632–3642, 2009.

[19] Yurong, H., Yubin, M., Yunhua, Z., Huilin, L., Yulong, D., Numerical investigation into the convective heat transfer of TiO2 nanofluids flowing through a straight tube under the laminar flow conditions, Applied Thermal Engineering, Vol.29, pp.1965–1972, 2009.

[20] Xuan, Y., Roetzel, W., Conceptions for heat transfer correlation of nanofluids, Int. J. Heat Mass Transfer Vol.43, pp.3701–3707, 2003.

[21] Bear, J., Dynamics of Fluids in Porous Media Second printing. American Elsevier Publishing Company, 1975.

[22] Mokmeli, A., Saffar-Avval, M., Prediction of nanofluid convective heat transfer using the dispersion model, International Journal of Thermal Sciences, Vol.49, pp.471–478, 2010.

[23] Perry, R. H., Green, D. W., Perry's chemical engineers' handbook; 7th edition, McGraw-Hill, New York, 1997.

[24] Bird, R.B., Stewart, W.E., Lightfoot, E.N., Transport Phenomena; 2nd edition, John Wiley & Sons, Inc., New York, 2002.

[25] http://webbook.NIST.gov/chemistry/fluid (2010).

[26] Xuan, Y., Li, Q., Heat transfer enhancement of nanofluids. International Journal of Heat and Fluid Flow, Vol.21, pp.58–64, 2000.

[27] Keblinski, P., Phillpot, S. R., Choi, S. U. S., Eastman, J. A., Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids), International Journal of Heat and Mass Transfer, Vol.45, pp.855–863, 2002.

[28] Al-Amayreh, M., Experimental Study of Thermal Conductivity of Ethylene Glycol Water Mixtures, Vol.44, No.2, pp. 300-313, 2010.