EMPIRICAL CORRELATIONS TO PREDICT THERMOPHYSICAL AND HEAT TRANSFER CHARACTERISTICS OF NANOFLUIDS

by

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Nanofluids exhibits larger thermal conductivity due to the presence of suspended nanosized solid particles in them such as Al_2O_3, Cu, CuO,TiO_2, etc. Varieties of models have been proposed by several authors to explain the heat transfer enhancement of fluids such as water, ethylene glycol, engine oil containing these particles. This paper presents a systematic literature survey to exploit the thermophysical characteristics of nanofluids. Based on the experimental data available in the literature empirical correlation to predict the thermal conductivity of Al_2O_3, Cu, CuO, and TiO_2 nanoparticles with water and ethylene glycol as basefluid is developed and presented. Similarly the correlations to predict the Nusselt number under laminar and turbulent flow conditions is also developed and presented. These correlations are useful to predict the heat transfer ability of nanofluids and takes care of variations in volume fraction, nanoparticle size and fluid temperature. The improved thermophysical characteristics of a nanofluid make it excellently suitable for future heat exchange applications.

Key words: *nanofluids, thermal conductivity, heat transfer coefficient, laminar, turbulent*

Introduction

Heat transfer fluids such as water and ethylene glycol play an important role in many industrial sectors including power generation, chemical production, air-conditioning, transportation and micro-electronics. Nanotechnology has been widely used in traditional industry because materials with grain size of nanometers posses unique optical, electrical and chemical properties, but the performance of these convectional heat transfer fluids is limited due to their low thermal conductivities. A recent development is that nanoparticles can be dispersed in conventional heat transfer fluids such as water, glycol, or oil to produce a new class of high efficiency heat exchange media [1-2]. The superior properties of nanoparticle fluid mixtures relative to those of fluids without particle or with large size particle include high thermal conductivities, stability and prevention of clogging in micro channels. Choi *et. al*. [1] at the Argonne National Laboratory proposed to construct a new class of engineered fluids with superior heat transfer capabilities. Wang *et. al*. [3] reported enhanced thermal conductivity for alumina and cupric oxide with a variety of base fluids including water and ethylene glycol. With alumina particles they observed a maximum of 12% increase in the conductivity with a volume fraction of 3%. The viscosity on the other hand showed an increase of 20-30% for the same vol-

ume fraction. Eastman *et. al.* [4] showed that 10 nm copper particles in ethylene glycol could enhance the conductivity by 40% with very small particle loading fraction. With cupric oxide (35 nm) the enhancement was 20% for a volume fraction of 4%. These results clearly show the effect of particle size on the conductivity enhancement. Das *et. al*. [5] measured the conductivities of alumina and cupric oxide at different temperatures ranging from 20 °C to 50 °C and found linear increase in the conductivity ratio with temperature. However for the same loading fraction the ratio of increase was higher for cupric oxide than alumina. Kim *et. al*. [6] conducted experiments on several oxide nanoparticles over a wide range of experimental conditions. They also demonstrated that high-power laser irradiation can result in significant increase in the effective thermal conductivity even at small volume fractions. Xuan and Li [7] studied convective heat transfer of Cu nanoparticle in deionized water and showed remarkable enhancement in heat transfer with smaller volume fraction of Cu particles. Pak and Cho [8] studied heat transfer performance of Al_2O_3 and TiO_2 nanoparticles suspended in water, and expressed that the convective heat transfer coefficient is 12% smaller than that of pure water at 3% volume fraction. Wen and Ding [9] reported experimental results for the Al_2O_3 water based nanofluid flowing through a tube in laminar regime. They found that a significant enhancement in convective heat transfer coefficient with increasing Reynolds number and volume fraction. Heris *et al*. [10] investigated laminar flow of CuO + water and Al_2O_3 + water nanofluids, results showed that the heat transfer coefficient enhanced with increasing volume fraction and Peclet number. Buongiorno [11] reported the convective heat transfer depends on Brownian diffusion and thermophoresis and developed correlation based on them. Hence an attempt is made through this paper to present the correlations to evaluate the various thermophysical and heat transfer properties of nanofluids.

Thermal properties of nanofluids

The thermal conductivity measurement of nanofluids was the main focus in the early stages of nanofluid research. Recently, studies have been carried out on the heat transfer coefficient of nanofluids in natural and forced flow. Most studies carried out to date are limited to the thermal characterization of nanofluids without phase change (boiling, evaporation, or condensation). However, nanoparticles in nanofluids can play a vital role in two-phase heat transfer systems, and there is a great need to characterize nanofluids in boiling and condensation heat transfer. Das *et al.* [12] initiated experiments on the boiling characteristics of nanofluids. In any case the heat transfer coefficient depends not only on the thermal conductivity but also on other properties such as the specific heat, density, and dynamic viscosity of a nanofluid which are discussed. Some of the properties of nanoparticles and base fluids are listed in tab.1 useful for assessing the nanofluid properties.

Table 1. Thermophysical properties of nanoparticle and base fluids

Property	Water	Ethylene glycol	Cu	Al_2O_3	CuO	Ti O_2
C [J/kgK]	4179	2415	385	765	535.6	686.2
ρ [kg/m^3]	997.1	1111	8933	3970	6500	4250
k [W/mK]	0.605	0.252	400	40	20	8.9538
α [m^2/s]	1.47	93	1163	1317	57.45	30.7

Density

The density of a nanofluid can be calculated by using mass balance as:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p \tag{1}$$

For typical nanofluids with nanoparticles at a value of volume fraction less than 1%, a change of less than 5% in the fluid density is expected.

Specific heat

The specific heat of a nanofluid can be calculated by using energy balance as:

$$C_{nf} \quad \frac{(1 \quad \phi)\rho_f C_f \quad \phi\rho_p C_p}{\rho_{nf}} \tag{2}$$

Using these equations, one can predict that small decreases in specific heat will typically result when solid particles are dispersed in liquids. For example, adding 3 vol.% Al_2O_3 to water would be predicted to decrease the specific heat by approximately 8% compared with that of water alone. The simple equations above may need to be modified if nanoparticles are found to exhibit a size-dependent specific heat.

Viscosity

Wang *et. al.* [3] measured the viscosity of water-based nanofluids containing Al_2O_3 nanoparticles dispersed by different dispersion techniques and showed that nanofluids exhibit lower viscosities when the particles are better dispersed. They also showed an increase of ~30% in viscosity at 3 vol.% Al_2O_3, compared with that of water alone. However, the viscosity of the Al_2O_3/water nanofluids prepared by Pak & Cho [8] was three times higher than that of water.

Wang *et. al.* [3] gave a correlation as follows.

For Al_2O_3 + water:

$$\mu_{nf} = 123\phi^2 + 7.3\phi + 1 \tag{3}$$

For Al_2O_3 + ethylene glycol:

$$\mu_{nf} = 360\phi^2 - 0.19\phi + 1 \tag{4}$$

Pak and Cho [8] correlation for the viscosity of nanofluids as follows.

For Al_2O_3 + water:

$$\mu_{nf} = \mu_f(1 + 39.11\phi + 533.9\phi^2) \tag{5}$$

For TiO_2 + water:

$$\mu_{nf} = \mu_f(1 + 5.45\phi + 108.2\phi^2) \tag{6}$$

Chen *et. al.* [13] correlation for the viscosity of TiO_2 + ethylene glycol as follows.

For TiO_2 + ethylene glycol:

$$\mu_{nf} = \mu_f(1 + 10.6\phi + 10.6\phi^2) \tag{7}$$

For Cu + water:

$$\mu_{nf} = \mu_f(0.995 + 3.645\phi + 468.72\phi^2) \tag{8}$$

Kulkarni *et. al*. [14] presented the correlation for the viscosity of CuO + water as follows:

$$\ln \mu_{\mathrm{nf}} \quad A \frac{1}{T} \quad B \tag{9}$$

$$A = 20\,587\phi^2 + 15\,857\phi + 1078.3$$

$$B = -107.12\phi^2 + 53.548\phi + 2.8715$$

In the present work the above equations are used wherever necessary and found to be nearer to experimental data available in the literature.

Thermal conductivity models

Many theoretical and empirical models have been proposed to predict the effective thermal conductivity of nanofluids and are presented in graphical form as shown in fig. 1. It is found that the predicted values of various models are far less than experimental observations. Hence present work is aimed at developing a suitable correlation to predict the thermal conductivity of nanofluids.

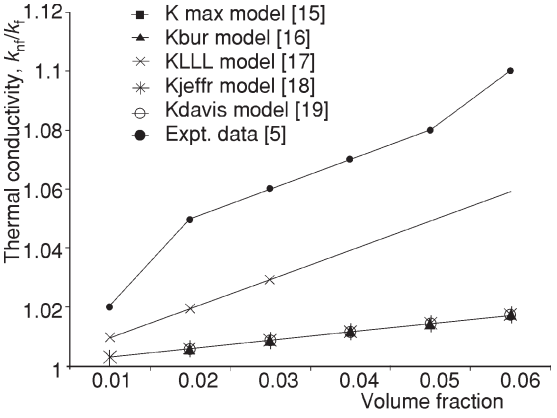

Figure 1. Comparison of the thermal conductivity of nanofluid model with the experimental data [5]

Present model for thermal conductivity

Jang *et. al.* [20] found that the Brownian motion of nanoparticles at the molecular and nanoscale level is a key mechanism governing the thermal behavior of nanofluids. They theoretically derived a model which considers effect of the concentration, temperature, and nanoparticles size.

Thus from the above analysis one can conclude that the thermal conductivity of a nanofluid, k_{nf}, is a function of:

$$\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}} \quad \mathrm{f}[\nu, d, \rho, T, k_{\mathrm{p}}, k_{\mathrm{f}}, \phi] \tag{10}$$

These variables can be grouped and can be expressed in non-dimensional terms as:

$$\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}} \quad \mathrm{f}\ \mathrm{Re}_{\mathrm{m}}, \phi, \frac{k_{\mathrm{p}}}{k_{\mathrm{f}}} \tag{11}$$

where Re_m is modified Reynolds number of nanofluids equal to $(1/v_f)(18k_bT/\Pi\rho_p d_p)^{1/2}$

Therefore, the correlation can be expressed as:

$$\frac{k_{nf}}{k_f} = c\,\mathrm{Re}_m^{p}\,\phi^{q}\left(\frac{k_p}{k_f}\right)^{r} \tag{12}$$

The data available in the literature for different nanoparticle sizes at different volume fraction and at different temperature is used to evaluate the constants. Using nonlinear regression analysis the constants are obtained as p = 0.175, q = 0.05, and r = 0.2324. Further the constant *c* for different nanofluids is listed in tab. 2. The correlations developed suits the data with a maximum average deviation of 2% and standard deviation of 4%.

The above equation takes care of diameter of the nanoparticle, concentration, and temperature effects. The correlations give good agreement with the experimental results as shown in fig. 2.

Table 2. Value of constant *c* for different nanofluids in $k_{nf}/k_f = c\mathrm{Re}_m^{0.175}\phi^{0.05}k_p/k_f^{0.2324}$

Nanofluids	C
$Al_2O_3 + H_2O$	1
Al_2O_3 + ethylene glycol	1.32
$CuO + H_2O$	1.298
CuO + ethylene glycol	1.72
$Cu + H_2O$	0.74
Cu + ethylene glycol	0.82
$TiO_2 + H_2O$	1.5
TiO_2 + ethylene glycol	1.98

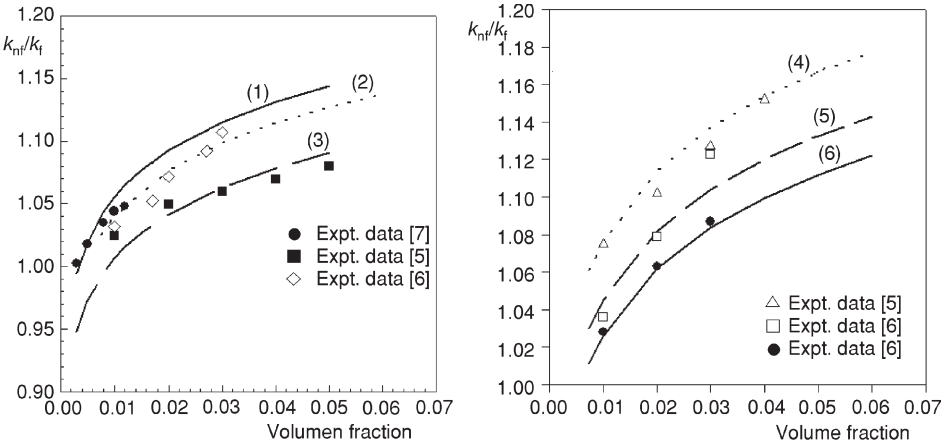

Figure 2. Comparison of the present correlations for thermal conductivity of nanofluids with experimental data

(1) Present correlation for Cu + H_2O (d = 100 nm), (2) Present correlation for Al_2O_3 + ethylene glycol (d = 38.4 nm), (3) Present correlation for $Al_2O_3 + H_2O$ (d = 38.4 nm), (4) Present correlation CuO + H_2O (d = 23.6 nm), (5) Present correlation $Ti_2O + H_2O$ (d = 34 nm), (6) Present correlation Ti_2O + ethylene glycol (d = 34 nm)

Convective heat transfer characteristics of nanofluids

Convective heat transfer analysis of nanofluid flowing inside a straight tube of circular cross-section under laminar and turbulent conditions is taken up. The flow and the thermal field

are assumed symmetrical with respect to the vertical plane passing through the main axis. Further there exists no formulated theory known to date that could reasonably predict the flow and heat transfer behaviors of a nanofluid by considering it as multi-component model. Therefore, it has been suggested that the particles may be easily fluidized and consequently, can be considered as conventional single-phase fluid, which posses effective physical properties being function of the properties of both constituents and their respective concentrations (Pak and Cho [8]; Xuan and Li [7]). As a result, a direct extension from a conventional fluid to nanofluid appears feasible, and one may then expect that the classical theory developed for a conventional single-phase fluid can be applied to nanofluid as well. Thus, all the equations of conservation (mass, momentum, and energy) as well known for single-phase fluid can be directly applied to nanofluids.

$$\frac{\partial u}{\partial x} \quad \frac{\partial v}{\partial y} \quad 0 \tag{13}$$

$$u\frac{\partial u}{\partial x} \quad v\frac{\partial v}{\partial y} \quad \frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}x} \quad v\frac{\partial^2 u}{\partial y^2} \quad \frac{\partial}{\partial y}(\overline{u\,v}) \tag{14}$$

$$u\frac{\partial T}{\partial x} \quad v\frac{\partial T}{\partial y} \quad \alpha\frac{\partial^2 T}{\partial x^2} \quad \frac{\partial}{\partial y}(\overline{v\,T}) \tag{15}$$

However, J. Buongiorno [11] proposed Brownian diffusion and thermophoresis effects for the enhancement of heat transfer coefficient of nanofluids as:

$$D_{\mathrm{B}} \quad \frac{\mathrm{k}_{\mathrm{B}}T}{3\pi\mu d_{\mathrm{p}}} \tag{16}$$

$$D_{\mathrm{T}} \quad \beta\frac{\mu}{\rho}\phi \tag{17}$$

Turbulent flow

Maiga *et. al*. [21] considered the turbulent convection and obtained the Nusselt number by using computational fluid dynamics (CFD) based *k-ε* model applying genetic algorithm as:

$$\mathrm{Nu}_{\mathrm{nf}} \quad 0.085\,\mathrm{Re}_{\mathrm{f}}^{0.71}\,\mathrm{Pr}_{\mathrm{f}}^{0.35} \tag{18}$$

Pak and Cho [8] and Xuan and Li [7] has developed correlations of a form similar to that of well known Dittus-Boelter formula to characterize nanofluids heat transfer. Pak and Cho[8] and Xuan and Li [7] proposed correlation for the calculation of nanofluid Nusselt number as given in eqs. (19) and (20). In these correlations the Reynolds number and Prandtl numbers are calculated by considering the base fluid properties which will give under estimate results compared with experimental values.

$$\mathrm{Nu}_{\mathrm{nf}} \quad 0.021(\mathrm{Re}_{\mathrm{f}})^{0.8}(\mathrm{Pr}_{\mathrm{f}})^{0.5} \tag{19}$$

$$\mathrm{Nu}_{\mathrm{nf}} \quad 0.059\,1 \quad 7.6286\phi^{0.6886}\,\mathrm{Re}_{\mathrm{f}}\,\mathrm{Pr}_{\mathrm{f}}\frac{d_{\mathrm{p}}}{D}^{0.001} \quad \mathrm{Re}_{\mathrm{f}}^{0.9238}\,\mathrm{Pr}_{\mathrm{f}}^{0.4} \tag{20}$$

Hence in this paper, the above "single phase fluid" approach is adopted to study the thermal behaviors of nanofluids. The thermophysical properties of the nanofluid itself are considered while evaluating the non dimensional numbers. The convective heat transfer coefficient and Nusselt number are related as:

$$\mathrm{Nu}_{\mathrm{nf}} \quad \frac{h_{\mathrm{nf}} D}{k_{\mathrm{nf}}} \tag{21}$$

The heat transfer coefficient of turbulent flow through circular tube can be calculated from equation in the following form:

$$\mathrm{Nu}_{\mathrm{nf}} = a(\mathrm{Re}_{\mathrm{nf}})^{0.8}(\mathrm{Pr}_{\mathrm{nf}})^{0.4} \tag{22}$$

where $\mathrm{Re}_{\mathrm{nf}}$ and $\mathrm{Pr}_{\mathrm{nf}}$ as defined as:

$$\mathrm{Re}_{\mathrm{nf}} \quad \frac{\rho_{\mathrm{nf}} u D}{\mu_{\mathrm{nf}}} \tag{23}$$

$$\mathrm{Pr}_{\mathrm{nf}} \quad \frac{C_{\mathrm{nf}} \mu_{\mathrm{nf}}}{k_{\mathrm{nf}}} \tag{24}$$

The Nusselt number data of the nanofluids obtained from [4-7] is subjected to non-linear regression analysis and the constant "a" is obtained as 0.0256 for $Al_2O_3 + H_2O$ and 0.027 for $Cu + H_2O$ Nanofluids. Thus the correlations for calculation of Nusselt number are developed as follows with an average deviation of 5% and standard deviation of 6.4%:

$$\mathrm{Nu}_{\mathrm{mf}} \quad 0.0256\,\mathrm{Re}_{\mathrm{nf}}^{0.8}\,\mathrm{Pr}_{\mathrm{nf}}^{0.4} \quad \text{for} \quad \mathrm{Al_2O_3} \quad \mathrm{H_2O} \tag{25}$$

$$\mathrm{Nu}_{\mathrm{nf}} \quad 0.027\,\mathrm{Re}_{\mathrm{nf}}^{0.8}\,\mathrm{Pr}_{\mathrm{nf}}^{0.4} \quad \text{for} \quad \mathrm{Cu} \quad \mathrm{H_2O} \tag{26}$$

The above equation takes care of diameter of the nanoparticle, concentration, and temperature effects. The correlations give good agreement with the experimental results as shown in figs. 3 and 4. The values of $\mathrm{Re}_{\mathrm{nf}}$ and $\mathrm{Pr}_{\mathrm{nf}}$ are to be calculated using the properties of nanofluids as developed and presented in eqs. (5), (12), (23), and (24).

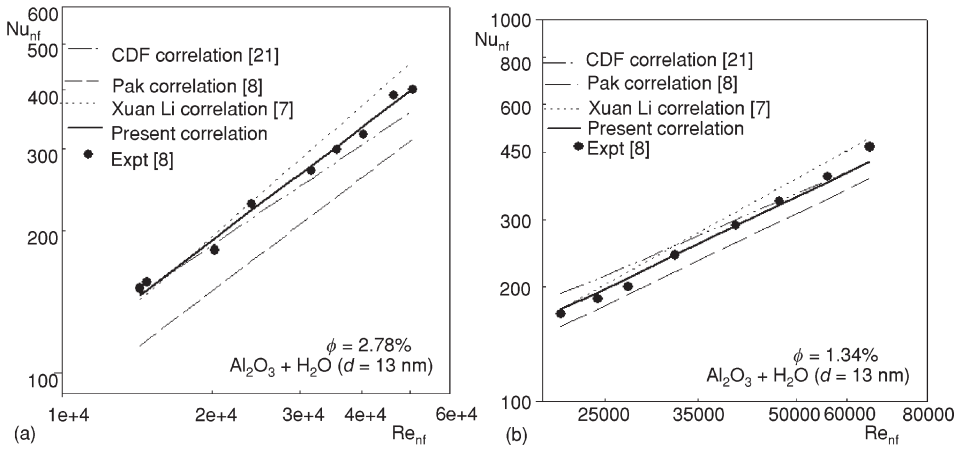

Figure 3. Comparison of the heat transfer alumina/water nanofluid correlation with the experimental data turbulent flow

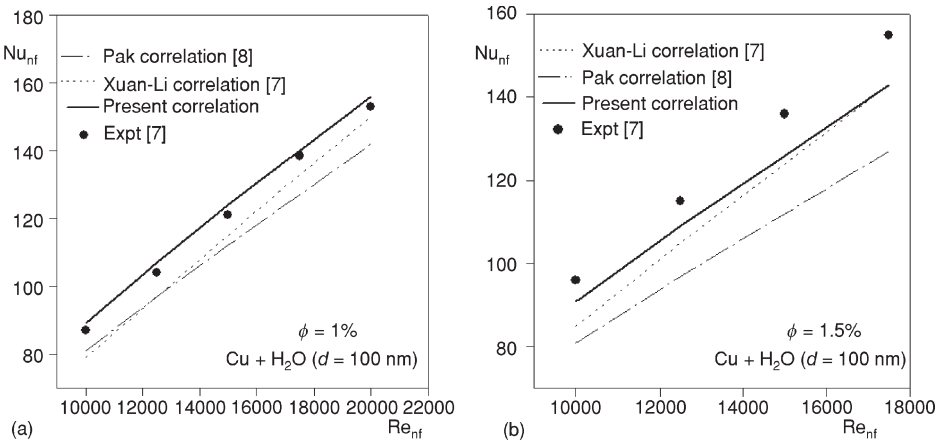

Figure 4. Comparison of the heat transfer Cu/water nanofluid correlation with the experimental data turbulent flow

Laminar flow

Wen & Ding [9] reported experimental results of the convective heat transfer of Al_2O_3 water nanofluid flowing through a copper tube in laminar regime. They compared their experimental results with Shah correlation for laminar flow and found the theoretical results are far less than the experimental values. This may be due to considering the base fluid properties instead of nanofluid properties. Heris *et. al*. [10] conducted experiments on laminar flow of CuO/water and Al_2O_3/water nanofluids through copper tube and proposed Seider-Tate equation to compare experimental results and found to be far less than experimental results. This could be due to wrong estimation of thermal conductivity and viscosity of nanofluids. Thus in this paper we propose a modified Seider-Tate equation in the following form for laminar flow as:

$$\mathrm{Nu}_{nf} \quad b \ \mathrm{Re}_{nf} \mathrm{Pr}_{nf} \frac{D}{L}^{0.333} \tag{27}$$

The constant *b* is evaluated from the regression analysis of the data obtained from [8, 9] and calculated as 1.98. Thus the correlation for calculation of Nusselt number for laminar flow are developed as follows with an average deviation of 6% and standard deviation of 7.4% for all nanofluids:

$$\mathrm{Nu}_{nf} \quad 1.98 \ \mathrm{Re}_{nf} \mathrm{Pr}_{nf} \frac{D}{L}^{0.333} \tag{28}$$

The correlation gives good agreement with the experimental results as shown in the fig. 5. The values of Re_{nf} and Pr_{nf} are to be calculated using the properties of nanofluids as developed and presented in *Thermal properties of nanofluids* and *Present model for thermal conductivity*. The variation of Nusselt number with respect to Reynolds number, volume fraction, and *L/D* ratio are presented in graphical form as shown in fig. 6(a-d).

Conclusions

Correlation to calculate thermal conductivity and heat transfer coefficient of various nanofluids are presented.

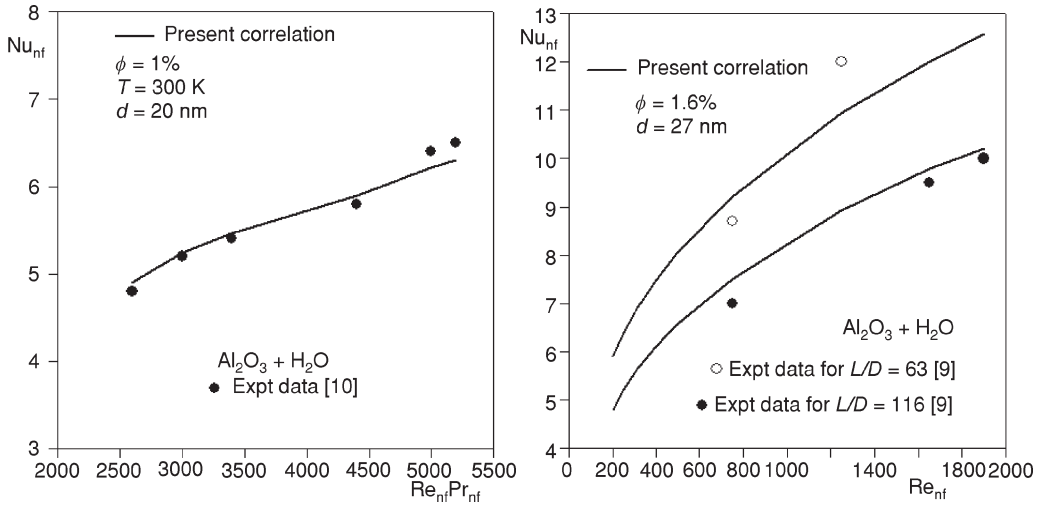

Figure 5. Comparison of the alumina/water nanofluid correlation with the experimental data [9, 10] in laminar flow

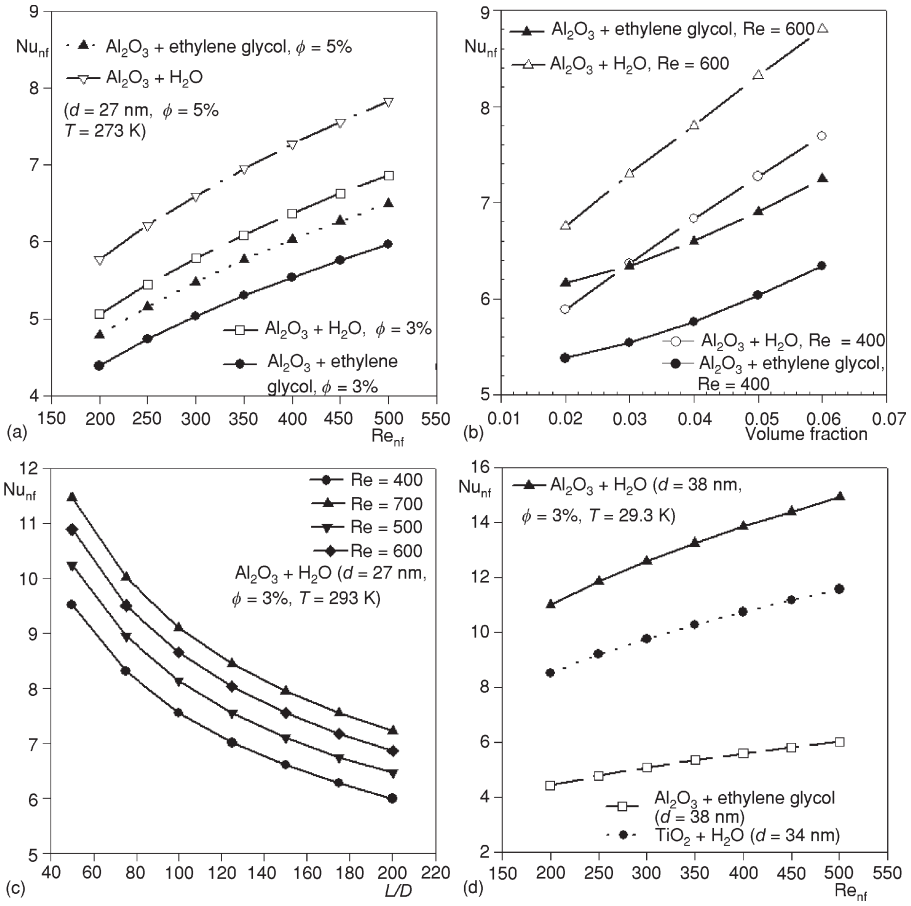

Figure 6. Effect of Nusselt number with (a) Reynolds number, (b) volume fraction, (c) L /D, and (d) $Al_2O_3 + H_2O$, Al_2O_3 + ethylene glycol and $TiO_2 + H_2O$ in laminar flow

Simple empirical correlation to predict thermal conductivity of $Al_2O_3 + H_2O$, Al_2O_3 + ethylene glycol, $Cu + H_2O$, $CuO + H_2O$, $Ti_2O + H_2O$ and Ti_2O + ethylene glycol nanofluid mixtures considering the effect of temperature, volume fraction and particle size is presented and found to be in good agreement with experimental results.

Correlation to predict Nusselt number in turbulent flow for $Al_2O_3 + H_2O$, and $Cu + H_2O$ nanofluids mixture is presented and found to be in good agreement with experimental results.

Correlation to predict Nusselt number in laminar flow for all nanofluids is presented.

The above correlations are suitable only for the specified nanofluids and a general correlation is yet to be developed.

Nomenclature

C – specific heat, [$kJkg^{-1}K^{-1}$]
D – diameter of tube, [m]
D_B – Brownian diffusion coefficient, [m^2s^{-1}]
D_T – thermal diffusion coefficient, [m^2s^{-1}]
d – particle diameter, [nm]
k – thermal conductivity, [$Wm^{-1}K^{-1}$]
k_B – Boltzman constant ($1.3807 \cdot 10^{-23}$), [JK^{-1}]
Nu – Nusselt number, [–]
Re_m – modified Reynolds number $(1/\nu_f)(18k_BT/\Pi\rho_p d_p)^{1/2}$ [–]
Re – Reynolds number ($\rho vD/\mu$), [–]
T – temperature, [K]
u, v – velocity component in x direction, [ms^{-1}]

Greek letter

ρ – density, [kgm^{-3}]
μ – viscosity, [Nsm^{-1}]
β – thermophoretic coefficient, [–]
ϕ – volume fraction, [–]
α – molecular thermal diffusivity, [m^2s^{-1}]

Subscripts

nf – nanofluids
p – nanoparticle
f – basefluid

References

[1] Choi, S. U. S., Development and Applications of Non-Newtonian Flows, Vol. 66 (Ed. D. A. Singiner & H. P. Wang), *ASME*, 1995, pp. 99-105
[2] Wang, Q. X., Mujumdar, S. A., Heat Transfer Characteristics of Nanofluids: a Review, *International Journal of Thermal Sciences, 46* (2007), 1, pp. 1-19
[3] Wang, X., Xu, X., Choi, S. U. S., Thermal Conductivity of Nanoparticles Fluid Mixture, *Journal of ThermoPhysic Heat Transfer, 13* (1999), 4, pp. 474-80
[4] Eastman, J. A., *et al*., Anomalously Increased Effective Thermal Conductivities of Ethylene Glycol Based Nanofluids Containing Copper Nanoparticles, *Applied Physic Letters, 78* (2001), 6, pp. 718-720
[5] Das, S. K., *et al*., Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids, *Journal of Heat Transfer, 125* (2003), 4, pp. 567-574
[6] Kim, H. S., Choi, R. S., Kim, D., Thermal Conductivity of Metal-Oxide Nanofluids: Particle Size Dependence and Effect of Laser Irradiation, *Journal of Heat Transfer, 129* (2007), 4, pp. 298-307
[7] Xuan, Y., Li, Q., Investigation of Convective Heat Transfer and Flow Features of Nanofluids, *Journal of Heat Transfer, 125* (2003), 1, pp. 151-153
[8] Pak, B. C., Cho,Y. I., Hydrodynamic and Heat Transfer Study of Dispersed Fluids with Submicron Metallic Oxide Particle, *Experimental Heat Transfer, 11* (1998), 2, pp. 151-170
[9] Wen, D., Ding, Y., Experimental Investigation Into Convective Heat Transfer of Nanofluids at the Entrance Region under Laminar Flow Conditions, *International Journal Heat and Mass Transfer, 47* (2004), 24, pp. 5181-5188
[10] Heris, W. S., Esfahany, N. M., Etemad, Gh. S., Experimental Investigation of Convective Heat Transfer of Al_2O_3/Water Nanofluid in Circular Tube, *International Journal of Heat and Fluid Flow, 28* (2007), 2, pp. 203-210
[11] Buongiorno, J., Convective Transport in Nanofluids, *Journal of Heat and Mass Transfer 128* (2006), 3, pp. 240-250

[12] Das, S. K., Putra, N., Roetzel, W., Pooling Boiling Characteristics of Nanofluids, *International Journal of Heat and Mass Transfer, 46* (2003), 5, pp. 851-862
[13] Chen, H., Ding, Y., He, Y., Tan, C., Rheological Behaviour of Ethylene Glycol Based Titania Nanofluids, *Chemical Physics Letters, 444* (2007), 4, pp. 333-337
[14] Kukarni, P. D., Das, K. D., Chukwu, A. G., Temperature Dependent Rheological Property of Copper Oxide Nanoparticle Suspension (Nanofluid), *Journal of Nanoscience and Nanotechnology, 6* (2006), 4, pp. 1150-1154
[15] Hamilton, R. L., Crosser, O. K., Thermal Conductivity of Heterogeneous Two Component Systems, *Industrial and Engineering Chemistry Fundamentals, 1* (1962), 3, pp. 187-191
[16] Bruggeman, D. A. G., Calculation of Various Physical Constants of Heterogenous Substances, II Dielectricity Constants and Conductivity of non Regular Multi Crystal Systems (in German), Annalen der Physik, Leipzig, Germany, 430 (1935), pp. 285-313
[17] Spanier, E. J., Herman, P. I., Use of Hydrid Phenomenological and Statistical Effective-Medium Theories of Dielectric Functions to Model the Infrared Reflectance of Porous SIC Films, *Physical Review, 61* (2000), 15, pp. 10437-10450
[18] Jeffrey, D. J., Conduction through a Random Suspension of Spheres, *Proceedings of the Royal Society of London*, Series A, 335, 1973, pp. 355-367
[19] Davis, R. H., Effective Thermal Conductivity of a Composites Material with Spherical Inclusions, *International Journal of Thermophysics, 7* (1986), 3, pp. 609-620
[20] Jang, S. P., Choi, S. U. S., Role of Brownian Motion in the Enhanced Thermal Conductivity of Nanofluid, *Applied Physic Letters, 84* (2004), 24, pp. 4316-4318
[21] Maiga, S. B., *et al.*, Heat Transfer Enhancement in Turbulent Tube Flow Using Al_2O_3 Nanoparticle Suspension, *International Journal of Numerical Methods for Heat and Fluid Flow, 16* (2006), 3, pp. 275-292

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