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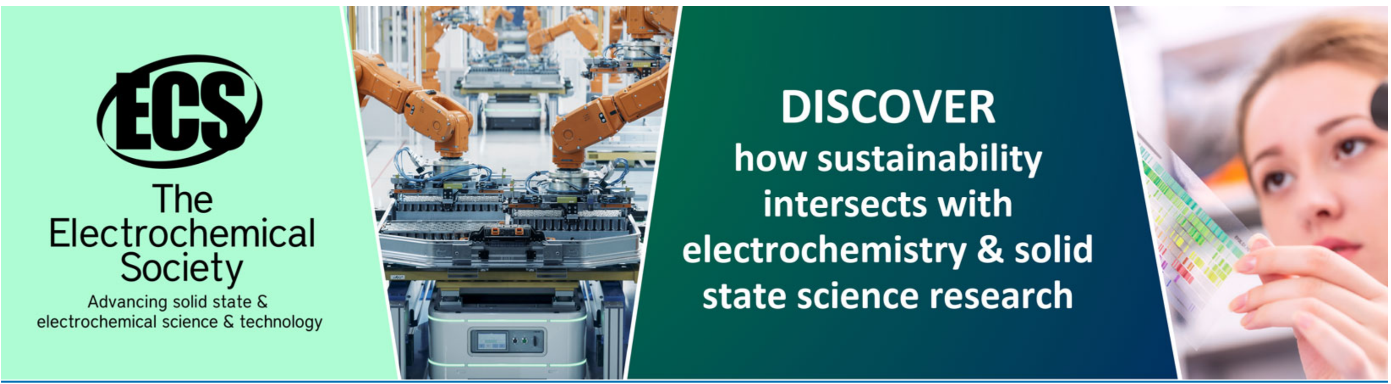

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Correlations for thermal conductivity and viscosity of water based nanofluids

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Abstract: The thermo-physical properties of nanofluids such as thermal conductivity, viscosity, density and specific heat of nanofluids are required for the analysis of convection heat transfer coefficients. The density and specific heat of nanofluids can be estimated with the mixture relations in literature. Information regarding the properties at different volume concentration and temperature is required for the estimation of heat transfer coefficient. The two most fundamental properties which are, experimentally, determined, are viscosity and thermal conductivity. Investigators have been determining the properties of nanofluids at different temperatures and base liquids. The present work is an attempt to analyze the available data to develop a non-linear regression equation for the estimation of thermal conductivity and viscosity of water based nanofluids. In the present study, nanofluids are considered as a homogenous medium and the parameters influencing the thermo physical properties identified. Equations are developed for the analysis of thermo-physical properties of nanofluids as a function of parameters viz., material, concentration, temperature and particle size useful for designer. The opposing nature of thermal conductivity rise and viscosity decrease with temperature; dependence of nanofluid thermal conductivity on material properties alters the range of applicability of nanofluids for heat transfer applications. The thermal conductivity and viscosity of Al_2O_3, ZnO and TiO_2 dispersed in water are measured to validate the proposed equations. The result shows that the equations are able to predict the thermal conductivity and viscosity of different types of nanofluids of different particle diameters closely.

1. Introduction

Experiments are undertaken to determine heat transfer coefficients and pressure drop for flow of viscous liquids in a tube under turbulent flow conditions. The study helped in fixing the dimensions for compactness of heat exchangers used in various process industries and thermal power plants. To achieve compactness and miniaturization of electronic equipment passive and active methods of augmentation have been suggested in heat transfer literature [1, 2] for a wide range of Prandtl numbers of the working medium. The initial studies relevant to the augmentation of heat transfer are mostly related to use of micro sized solid particles of various sizes in the base fluid. However, these techniques became impracticable and obsolete due severe practical problems arising due to erosion and high pumping power requirements in spite of the fact that a certain degree of heat transfer augmentation is achieved. Further, agglomeration and resettlement of particles posed severe maintenance problem. In contrast, recent studies with the reduction of particle size to nano level proved effective in achieving heat transfer augmentation without any substantial increase in pumping power requirements. Results from several investigations have been coming to light from different sources and typical reviews of such literature can be cited.

Experiments are conducted for the determination of viscosity and thermal conductivity of nanofluids. Choi [3] conducted experiments with Carbon Nano Tubes (CNT) in motor oil at 1.0% volume concentration. The thermal conductivity enhancement obtained is up to 60% of the base liquid value. Various investigators [4-17] determined the properties of nanofluids dispersed with Cu and metal oxides such as Al_2O_3, TiO_2, CuO, SiO_2, etc in different base fluids, concentrations and temperatures. All these investigators observed greater values of thermal conductivity when compared to base fluid, water. The nanofluid thermal conductivity increased and viscosity decreased with temperature. Besides, the techniques employed for dispersion of particle suspension with surfactant and the pH, affect the values of thermal conductivity and the thermal stability of the nanofluid. The experimental values obtained by these investigators deviate from the theoretical models of Maxwell [18] and Hamilton and Crosser [19].

The primary consideration of the article is to review the salient physical properties of nanofluids and establish generalized correlations for different nano-base fluid combination for particle sizes ranging between 20 to 170 nm. It is fairly established from the regression analysis that the thermal conductivities and absolute viscosities of nanofluids are dependent on volumetric concentrations and temperature of the medium. The influence of particle size hither to not considered might also be an influencing factor.

2. Evaluation of thermo physical properties of nanofluid

2.1. Density, ρ_{nf}

Applying the principle of mass conservation of the two species in a finite control volume of the nano fluid, the nanofluid density ρ_{nf} can be obtained from the relation

$$\rho_{nf} = \varphi \rho_p + (1-\varphi)\rho_w \tag{1}$$

where φ is the volumetric fraction of nano particles in the base fluid.

2.2. Specific heat, C_{nf}

The thermal conservation of energy of the two species in a finite control volume will yield the overall specific heat C_{nf} of the nano fluid as

$$C_{nf} = \frac{(1-\phi)(\rho\, C)_w + \phi\,(\rho C)_p}{(1-\phi)\rho_w + \phi\rho_p} \tag{2}$$

2.3. Thermal conductivity, k_{nf}

The thermal conductivity of various nanofluids is determined experimentally by many [5-10]. The experiments are conducted mostly with spherical shape particles having diameters in the range of 20 – 170 nm, temperature of 20 – 70^{o}C and volume concentration of less than 4.0% with Al_2O_3, Cu, CuO, SiC, TiO_2, ZrO_2 particles dispersed in water. The thermal conductivity data of metal and metal oxide nanofluids available in the literature are used in the development of regression equations. Pak and Cho [20], Williams et al. [13], Lee et al. [4], Murshed et al. [8], Das et al. [7], Chon and Kihm [21], Mintsa et al [22], Beck et al. [23], Avsec [24], Duangthongsuk and Wongwises [25], Sundar et al. [26] and Hong et al. [27] conducted experiments for the determination of thermal conductivity of nanofluids. The value of thermal conductivity depends primarily on the choice of material, concentration, and temperature and particle size. The influence of material on nanofluid thermal conductivity data is affected through the thermal diffusivity ratio of particle to water ($\alpha_{p/}\ \alpha_w$). Experimental values consisting of 252 data points are used in the regression analysis, to develop a correlation for the determination of thermal conductivity k_{nf}, given by

$$k_{nf} = k_w 0.8938 \left(1+\frac{\phi}{100}\right)^{1.37} \left(1+\frac{T_{nf}}{70}\right)^{0.2777} \left(1+\frac{d_p}{150}\right)^{-0.0336} \left(\frac{\alpha_p}{\alpha_w}\right)^{0.01737} \tag{3}$$

where $\o$ is volumetric concentration in %, temperature T_{nf} in ^{o}C and particle diameter d_p in nm.

2.4. Viscosity of nanofluid, μ_{nf}

Nguyen et al. [28] conducted experiments for the determination of viscosity of Al_2O_3 and CuO nanofluids in water at different concentrations and particle sizes under ambient conditions. The authors have stated the viscosity of Al_2O_3 nanofluid with particle size of 36 and 47nm and CuO of 29nm size predicted close values for volume concentration less than 4% and deviated at higher concentrations. Hence the experimental viscosity data of Nguyen et al. [28], Hwang et al. [29], Wang et al. [30], Zeinali Heris et al. [31], Nguyen et al. [32], Lee et al. [33], Pak and Cho [20], He et al. [34], Duangthongsuk and Wongwises [35] and Lee et al. [36] for volume concentration less than 4% consisting of 233 data points are subjected to regression and obtained the following correlation

$$\mu_{nf} = \mu_w \left(1+\frac{\phi}{100}\right)^{11.3} \left(1+\frac{T_{nf}}{70}\right)^{-0.038} \left(1+\frac{d_p}{170}\right)^{-0.061} \tag{4}$$

The properties of water are estimated with the aid of equations listed in equations (5) – (8) having a maximum deviation of 3.5 % applicable in the range $0 \le T_w \le 100$ where T_w is the temperature of water in ^{o}C.

$$\rho_w = 1000 \times \left[1.0 - \frac{(T_w - 4.0)^2}{119000 + 1365 \times T_w - 4 \times (T_w)^2}\right] \tag{5}$$

$$k_w = 0.56112 + 0.00193 \times T_w - 2.60152749e-6 \times (T_w)^2 - 6.08803e-8 \times (T_w)^3 \tag{6}$$

$$\mu_w = 0.00169 - 4.25263e-5 \times T_w + 4.9255e-7 \times (T_w)^2 - 2.09935e-9 \times (T_w)^3 \tag{7}$$

$$C_w = 4217.629 - 3.20888 \times T_w + 0.09503 \times (T_w)^2 - 0.00132 \times (T_w)^3 + 9.415e-6 \times (T_w)^4 - 2.5479e-8 \times (T_w)^5 \tag{8}$$

3. Thermal conductivity and viscosity measurement

The thermal conductivity of nanofluid was measured using KD2 Pro thermal property analyzer (Decagon Devices, Inc., USA). The viscosity of the nanofluid was measured using Brookfield LVDV-III Ultra Rheometer. Al_2O_3/water, ZnO/water and TiO2/water nanofluids having particle diameters of 50nm, 100nm and 150nm, respectively and up to 6% volume concentrations were used for thermal conductivity and viscosity measurements. The nanofluids are prepared by dilution process using mechanical homogenizer for uniform dispersion and stability. The measurements are taken at the room temperature.

4. Results and discussion

The salient observations from the regression modelling and experimental analysis on thermal conductivity and viscosity of nanofluids with different materials, particle sizes, temperatures and concentration can be listed as:

- The thermal conductivity and viscosity increases with volume concentration
- The thermal conductivity increases whereas viscosity decreases with temperature
- The thermal conductivity and viscosity increases as particle size decreases

The correlation for nanofluid thermal conductivity in equation (3) is validated with data taken from different sources and shown in the legend of figure 1 obtained with average deviation of 2.73%, standard deviation of 3.55% and maximum deviation of 10.96%. Equation (4) is validated with the data taken from various sources shown in the legend of figure 2 with $C_1 = 1.4$ for SiC and $C_1 = 1.0$ for other water based nanofluids. The data could be correlated with an average deviation of 2.89%, standard deviation of 3.8% with a maximum deviation of 12.96%. It can be observed that the present equation can predict the experimental data of water based nanofluids with a single equation.

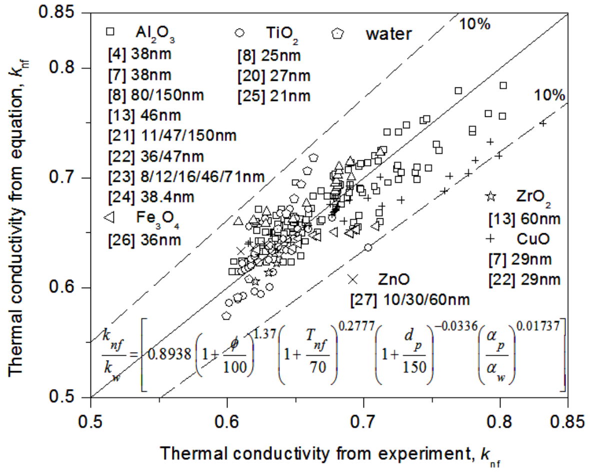

Figure 1. Validation of equation (3) using data from literature

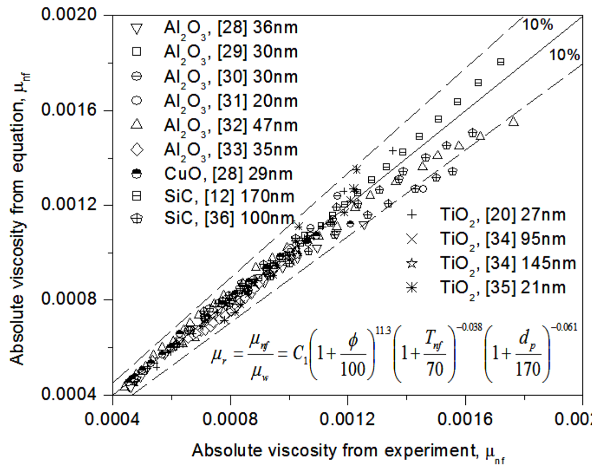

Figure 2. Validation of equation (4) using data from literature

The present thermal conductivity equation is compared with other equations from literature shown as in figure 3. It can be observed that the proposed equation is in satisfactory agreement with the equation by Corcione [37], Vajjha and Das [38] and Prasher et al. [39].

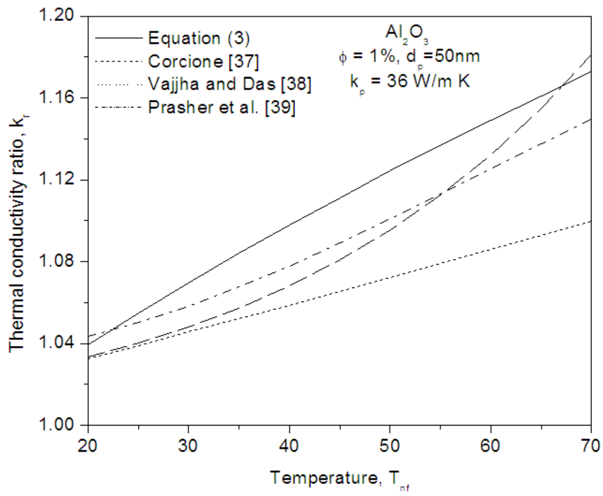

Figure 3. Comparison of equation (3) with the equation from literature

Comparison of the experimental data of measured thermal conductivity of Al_2O_3/water and ZnO/water nanofluids with values evaluated with equation (3) shown in figure 4. The figure shows the measured data of 50nm Al_2O_3/water nanofluid with a maximum deviation of 1.0%. Also the experimental data of ZnO/water nanofluids with 100nm particle diameter gives an average deviation of 0.9%. A satisfactory agreement between the two can be observed from the figure indicating the validity of the equations proposed for thermal conductivity estimation.

Comparison of the measured viscosity of water based nanofluids with the proposed correlation equation (4) is shown as figure 5. The figure shows Al_2O_3/water, ZnO/water and TiO_2/water nanofluids for particle diameters of 50nm, 100nm and 150nm, respectively. The measured data shows the effect of different materials, particle size and volume concentration to the values of viscosity at ambient temperature of 21.5°C. The viscosity estimated using the proposed equation is in a good agreement with the measured data for different nanofluids tested.

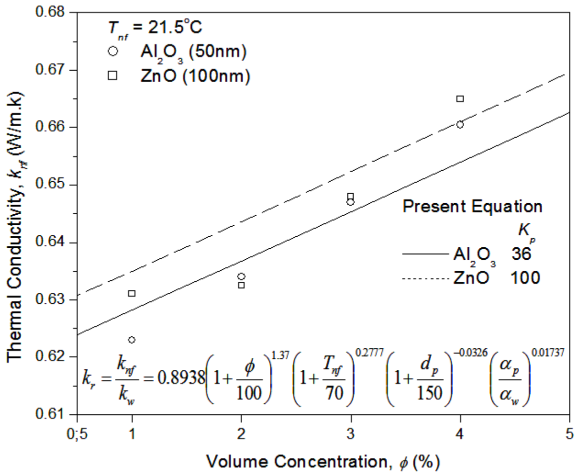

Figure 4. Comparison of measured thermal conductivity with proposed correlation

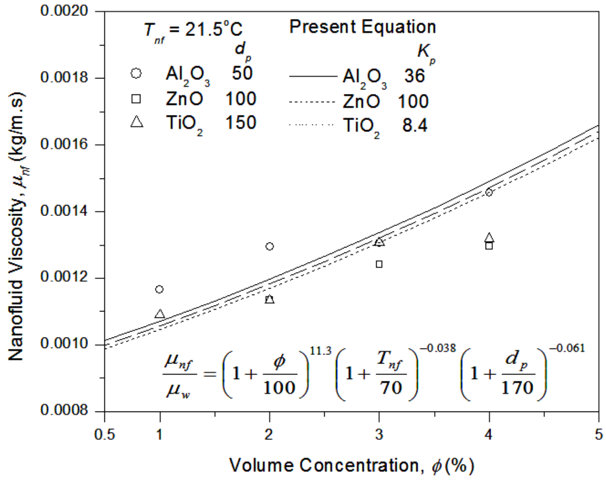

Figure 5. Comparison of measured viscosity with proposed correlation

5. Conclusion

The thermal conductivity and viscosity of metal and metal oxide nanofluids dispersed in water can be estimated using equations (3) and (4) respectively valid for volume concentration less than 4.0%. The proposed correlations predict good agreement with the experimental results. The material concentration, temperature and particle size are be considered simultaneously for evaluating the nanofluid thermal conductivity.

Acknowledgments

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