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INFLUENCE OF CERTAIN THERMO-PHYSICAL PROPERTIES ON PRANDTL NUMBER OF WATER BASED NANOFLUIDS

W. H. Azmi[1], K. V. Sharma[1], P.K. Sarma[3] and Rizalman Mamat[1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang,
26300 UMP, Kuantan, Pahang, Malaysia; Phone: +6012-9478091, Fax: +609-4242314
E-mail: wanazmi@ump.edu.my
[2]International Director, GITAM University, Rishikonda,
Visakhapatnam 530045, India; Tel./Fax: +91-891-2798899
E-mail: sarmapk@yahoo.com

ABSTRACT

The thermo physical properties such as thermal conductivity, viscosity, density and specific heat are essential for the determination of nanofluid heat transfer coefficients. Experimental data indicate the nanofluid thermal conductivity to increase with temperature and decrease with particle size. However, viscosity is observed to decrease with temperature and increase with particle size. This opposing nature of the two properties along with the nanofluid specific heat which decreases with both temperature and particle size have a significant influence on the values of nanofluid Prandtl number. The forced convective heat transfer coefficients are dependent on Reynolds and Prandtl numbers which in turn are dependent on the nanofluid properties. Regression equations have been developed as a function of concentration, temperature and particle size using the experimental data available in literature useful in the estimation of convective heat transfer coefficients. The analyses of these parameters indicate that the nanofluid heat transfer coefficient need not necessarily predict higher values of heat transfer coefficients when compared with water at all concentrations, contrary to the general expectations. The condition for heat transfer enhancement is explained.

***Keywords**:* Nanofluids, Thermal conductivity, Viscosity, Specific heat, Regression equation, Prandtl number

INTRODUCTION

Thermo-physical properties such as viscosity, specific heat, thermal conductivity and density are essential for the evaluation of nanofluid heat transfer coefficient. Experimental observations indicate the forced convective heat transfer coefficients to increase with increase in volume concentration of the nanofluid. However, Duangthongsuk and Wongwises (2009) have observed with 21nm TiO_2 particles dispersed in water to decrease with increase with concentration. The present work is directed to study the influence of parameters such as particle size, concentration and temperature on Prandtl number and consequently the heat transfer coefficients.

Nanofluids are particle suspensions of size less than 100 nm (Choi, 1995) dispersed in a continuous medium such as water, ethylene glycol, engine oil, etc. The thermo-physical properties of these fluids are higher than those of the base liquids. Nanofluids are found to exhibit higher thermal conductivity even at very low concentration of suspended nanoparticles (Eastman et al. 1997, Lee et al., 1999 and

Wang et al., 1999). The properties of aluminium oxide and copper oxide nanofluids in water and ethylene glycol are widely investigated because of their potential as heat transfer fluid in automotive and electronic cooling applications (Maiga et al., 2006, Wen and Ding, 2004). The determination of effective thermal conductivity of nanofluid is based on the classical analysis of Maxwell (1904) for two phase solid-liquid mixtures given by

$$K_{eff} = K_{bf}\left[\frac{K_p + 2K_{bf} + 2\,\phi\left(K_p - K_{bf}\right)}{K_p + 2K_{bf} - \phi\left(K_p - K_{bf}\right)}\right] \tag{1}$$

The model predicts satisfactorily for spherical shaped particles at low volume concentrations, ϕ and at ambient conditions. The limitation on the particle volume concentration proposed by Maxwell (1904) has been relaxed by Bruggemen (1935). The interactions among the randomly distributed particles is considered and proposed an equation in implicit form as

$$\phi\left[\frac{K_p - K_{eff}}{K_p + 2K_{eff}}\right] + (1-\phi)\left[\frac{K_{bf} - K_{eff}}{K_{bf} + 2K_{neff}}\right] = 0 \tag{2}$$

where K_{eff} is estimated using Eq. (1) and the net effective thermal conductivity K_{neff} of the two phase fluid is determined.

Even though nanoparticles are many orders smaller than micron size solid suspension, modifications and addition of suitable terms and or consideration of dynamic factors associated with nanofluids are made to Maxwell's model by the investigators. Various theoretical models are since being developed to predict the thermal conductivity of nanofluids. Thermo-physical properties of nanofluids are essential for the evaluation of heat transfer coefficient. Viscosity and specific heat of the nanofluids also need to be considered in the evaluation of thermo-physical study. These properties vary with concentration and temperature. The effect of variation of these parameters on thermo-physical properties has been dealt by Duangthongsuk and Wongwises (2009), Vajjha and Das (2009), Das et al. (2003), Nguyen et al. (2007), Murshed et al. (2008), Pak and Cho (1998) and Chen et al. (1995). But not many study about the properties variation with the nanoparticle size. The properties are evaluated at different concentrations in the experimental range useful for the estimation of heat transfer coefficient.

The purpose of this study is to generate regression equation for thermo-physical properties which are viscosity, specific heat and thermal conductivity. These properties then will be used to evaluate the value of Prandtl number of the nanofluids. Finally establish an equation for nanofluids Prandtl number with a function of temperature, particle size and concentration. The behavior of nanofluids can easily understand with the estimation of Prandtl number for a specific condition.

EVALUATION OF NANOFLUID PROPERTIES

The thermo-physical properties of nanofluid such as density, absolute viscosity, specific heat and thermal conductivity are studied. The experiment data available in the literature from various investigators were collected and used to generate a regression equation for each property. Prandtl number of nanofluids can be estimated from the three important properties. Table 1 shows the regression equation for water properties.

Table 1: Properties of water where T_b in °C ($25 \le T_b \le 100$ and $0.07\% \le AD \le 2.75\%$)

Property	**Regression Equation for water**
Density	$\rho_w = 1000 \times \left[1.0 - \dfrac{(T_b - 4.0)^2}{119000 + 1365 \times T_b - 4 \times (T_b)^2} \right]$ ± 0.07%
Viscosity	$\mu_w = 0.0015 - 3.16325e - 5 \times T_b + 3.04789e - 7 \times (T_b)^2 - 1.1104e - 9 \times (T_b)^3$ ± 2.75%
Thermal conductivity	$K_w = 0.55994 + 0.00216 \times T_b - 1.02749e - 5 \times (T_b)^2 + 6.72794e - 9 \times (T_b)^3$ ± 1.4%
Specific heat	$C_w = 4217.629 - 3.20888 \times T_b + 0.09503 \times (T_b)^2 - 0.00132 \times (T_b)^3 + 9.415e - 6 \times (T_b)^4 - 2.5479e - 8 \times (T_b)^5$ ± 2.46%

Density

The density of nanofluids at different volume concentrations and temperatures are obtained from the literature and shown in Table 2. The nanofluids density calculated with the equation from Pak and Cho (1998)

$$\rho_{nf} = \phi\, \rho_p + (1 - \phi)\, \rho_w \tag{3}$$

Specific Heat

The specific heat of nanofluid at any concentration can be estimated from the relation valid for homogeneous mixtures given by

$$C_{nf} = \frac{(1-\phi)\left(\rho\, C_p\right)_w + \phi\left(\rho C_p\right)_{np}}{(1-\phi)\rho_w + \phi \rho_{np}} \tag{4}$$

The specific heat equation of Pak and Cho (1998) given by

$$C_{nf} = \phi C_p + (1 - \phi) C_w \tag{5}$$

Both equations are able to predict specific heat of nanofluids. The deviation increased with the increase of concentration. Eq. (4) consider heat capacity in the determination of specific heat. Hence, the value of specific heat from the equation is able to estimate the specific heat of nanofluids better than Eq. (5) in the high concentration range. Therefore, Eq. (4) was used in the analysis of specific heat of the nanofluids. Table 2 shows the specific heat and density for various types of nanoparticles.

Table 2: Density and Specific heat of nanoparticles

Particle	Data from Ref	Range	Equation/Data used in the analysis
Al_2O_3	Pak and Cho (1998)	$d_p \approx 13$	$\rho_p = 3880$
	Vajjha and Das (2009)	$d_p \approx 44$ and 53	$\rho_p = 3600$
	Risha et al. (2007)	$d_p \approx 80$	$\rho_p = 3076$
	Present equation	$13 \le d_p \le 80$	$\rho_p = 4009.23 - 11.862 \times d_p$, $C_p = 765$ to 773
CuO and Cu	Namburu et al. (2007)	$d_p \le 29$	$\rho_p = 6300$ to 6500, $C_p = 385$ (bulk)
	Vajjha and Das (2009) Mintsa et al. (2009) Chen et al. (1995)	$46 \le T_b \le 481$	$C_p = 541.54 + 0.42299 \times T_b$ (powders)
TiO_2	Pak and Cho (1998)	$d_p \approx 27$	$\rho_p = 4175$, $C_p = 692$
	He et al. (2009)	$95 \le d_p \le 210$	
	Duangthongsuk and Wongwises (2009)	$d_p \approx 21$	$\rho_p = 4170$
ZrO_2	Williams et al. (2008)	$d_p \approx 60$	$\rho_p = 5500$
		$10 \le T_b \le 100$	$C_p = 475.4 + 0.6883 \times T_b - 0.00131 \times T_b^2$
SiO_2	Vajjha and Das (2009)	$d_p \approx 20$	$\rho_p = 2220$, $C_p = 745$
ZnO	Vajjha and Das (2009)	$29 \le d_p \le 77$	$\rho_p = 5600$, $C_p = 514$
SiC	National Institute of Standards and Technology (NIST)	$20 \le T_b \le 1000$	$\rho_p = 3160.65 - 0.03194 \times T_b - 1.871e-5 \times (T_b)^2$
			$C_p = 694.8 + 1.0196 \times T_b - 4.744e-4 \times (T_b)^2$

Viscosity and Thermal Conductivity

The viscosity and thermal conductivity equations from literature at different volume concentrations, temperature and particle size are shown in Table 3. Various types of regression equations were presented to predict the nanofluids viscosity and thermal conductivity for different type of nanofluids. By using the experimental data from all investigators with the different nanofluids, one single equation for estimation of nanofluids viscosity and thermal condcutivity were established. The equation is able to predict the viscosity for different type of nanofluids with small deviation.

Table 3: Viscosity and thermal conductivity of nanofluids

Particle	**Data from Ref**	**Validity**	**Equation/Data used in the analysis (input ϕ in percent)**
Al_2O_3	Pak and Cho (1998)	$d_p \approx 13$ $25 \le T_b \le 70$ $1.34 \le \phi \le 4.33$ $8.5 \le \Pr_{nf} \le 12.3$	$\frac{\mu_{nf}}{\mu_w} = 1.00869 \exp(\phi/1.93595)$ $\frac{K_{nf}}{K_w} = 1.03344 + 0.0514\phi - 0.000453431\phi^2$
	Williams et al. (2008)	$d_p \approx 46$ $21 \le T_b \le 80$ $0.9 \le \phi \le 3.6$	$\frac{\mu_{nf}}{\mu_w} = 0.4914 + 0.5255 \exp[\phi / 2.453]$ $\frac{K_{nf}}{K_w} = 0.975 + 0.07268\phi - 0.00589\phi^2$
	Nguyen et al. (2007)	$36 \le d_p \le 47$ $25 \le T_b \le 55$ $1.0 \le \phi \le 9.0$	$\frac{\mu_{nf}}{\mu_w} = 0.01301\phi^{0.4557} d_p^{\ 1.122}$ (exp data ave dev 6%)
CuO and Cu	Nguyen et al. (2007)	$d_p \approx 29$ $1.0 \le \phi \le 9.0$ $20 \le T_b \le 50$	$\frac{\mu_{nf}}{\mu_w} = 1.475 - 0.319\phi + 0.051\phi^2 + 0.009\phi^3$
	Lee et al. (1999)	$d_p \approx 23.6 \pm 1.0$ $0 \le \phi \le 4.0$ T_b at room temperature	$\frac{K_{nf}}{K_w} = 1 + 0.03904\phi - 0.00127\phi^2$
	Das et al. (2003)	$d_p \approx 28.6$ $0 \le \phi \le 4.0$ T_b at room temperature	$\frac{K_{nf}}{K_w} = 1 + 0.06443\phi - 0.00786\phi^2$
	Xuan and Li (2003)	$d_p \le 100$ $0.3 \le \phi \le 2.0$ T_b at room temperature	$\frac{K_{nf}}{K_w} = 1 - 6.725 \times 10^{-4}\phi + 0.04023\phi^2$

ANALYSIS OF EXISTING DATA FOR REGRESSION EQUATION

It is now fairly established that the viscosity and thermal conductivity of nanofluids are influenced by volume concentration, temperature and particle size. Whereas the specific heat of nanofluids is depend on concentration and temperature by homogenous mixture equation. Regression equations have been developed by various investigators for the estimation of viscosity and thermal conductivity of Al_2O_3, CuO, TiO_2, ZrO_2, SiO_2, ZnO, and SiC nanofluid in water mostly as a function of particle volume concentration and temperature. The experimental data by various investigators were used in the analysis to establish three regression equations for viscosity, thermal conductivity and specific heat. Then, from this three regression equation, the Prandtl number ratio regression equation was developed to determine the value of Prandtl number for nanofluids as a function of particle size, temperature and concentration.

The thermal conductivity equation developed with experimental values from various investigators taking into consideration the particle size, temperature and concentration applicable for $13 < d_p < 150\,nm$, $0 < \phi < 20\,\%$, $20 < T_{nf} < 70$ is given by

$$K_r = \frac{K_{nf}}{K_w} = 0.9808 + 0.0142\,[\phi] + 0.2718\left[\frac{T_{nf}}{70}\right] - 0.1020\left[\frac{d_p}{150}\right] \tag{6}$$

obtained with AD of 2.8% and SD of 3.5% where ϕ is percent volume concentration, T_{nf} is the temperature of the nanofluid in ^{o}C and d_p is the diameter of the particle in nanometer.

The viscosity equation developed with experimental values from various investigators taking into consideration the particle size, temperature and concentration applicable for $20 < d_p < 170\,nm$, $0.03 < \phi < 4\,\%$, $15 < T_{nf} < 72$ is given by

$$\mu_r = \frac{\mu_{nf}}{\mu_w} = 0.9042 + 0.1245\,[\phi] - 0.08445\left[\frac{T_{nf}}{72}\right] + 0.6436\left[\frac{d_p}{170}\right] \tag{7}$$

obtained with AD of 4.2% and SD of 5.6% where ϕ is percent volume concentration, T_{nf} is the temperature of the nanofluid in ^{o}C and d_p is the diameter of the particle in nanometer.

The specific heat equation developed with the values from various investigators taking into consideration the temperature and concentration applicable for $0 < \phi < 6\%$, $20 < T_{nf} < 70$ is given by

$$C_{pr} = \frac{C_{pnf}}{C_{pw}} = 1.036 - 0.0298\,[\phi] - 0.07261\left[\frac{T_{nf}}{70}\right] \tag{8}$$

obtained with AD of 3.6 % and SD of 5.5 % where ϕ is percent volume concentration, and T_{nf} is the temperature of the nanofluid in ^{o}C

The Prandtl number ratio developed with the values from three property ratio equations (Eqs. 6-8) taking into consideration the particle size, temperature and concentration applicable for $20 < d_p < 150\ nm$, $0 < \phi < 4\ \%$, $25 < T_{nf} < 70$ is given by

$$\mathrm{Pr}_r = \frac{\mathrm{Pr}_{nf}}{\mathrm{Pr}_w} = 1.063 + 0.03492\left[1+\phi\right] - 0.4306\left[\frac{T_{nf}}{70}\right] + 0.5309\left[\frac{d_p}{150}\right] \tag{9}$$

obtained with AD of 2.3 % and SD of 5.5 % where ϕ is percent volume concentration, T_{nf} is the temperature of the nanofluid in °C and d_p is the diameter of the particle in nanometer.

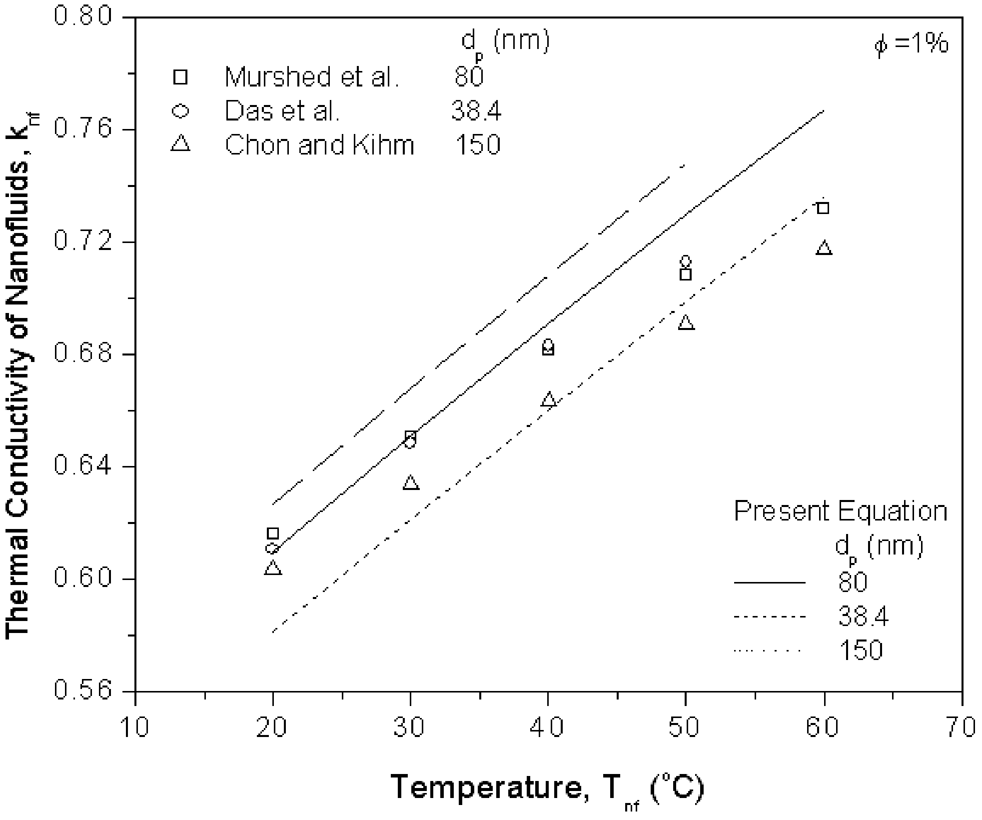


Figure 1: Comparison between regression equation and experiment data for thermal conductivity

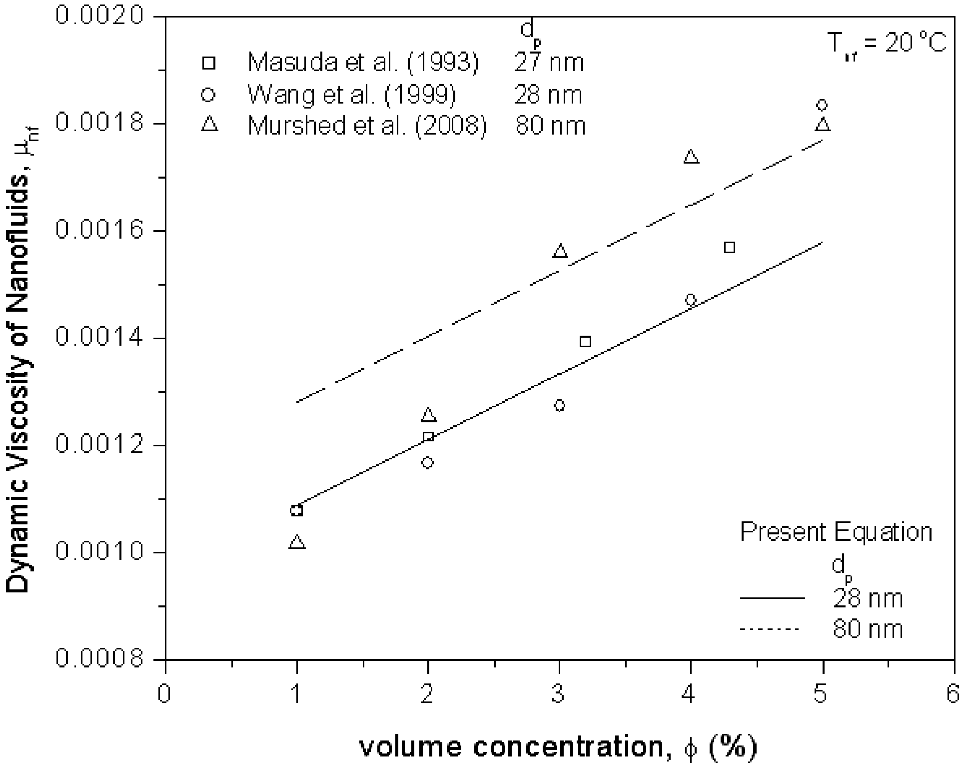
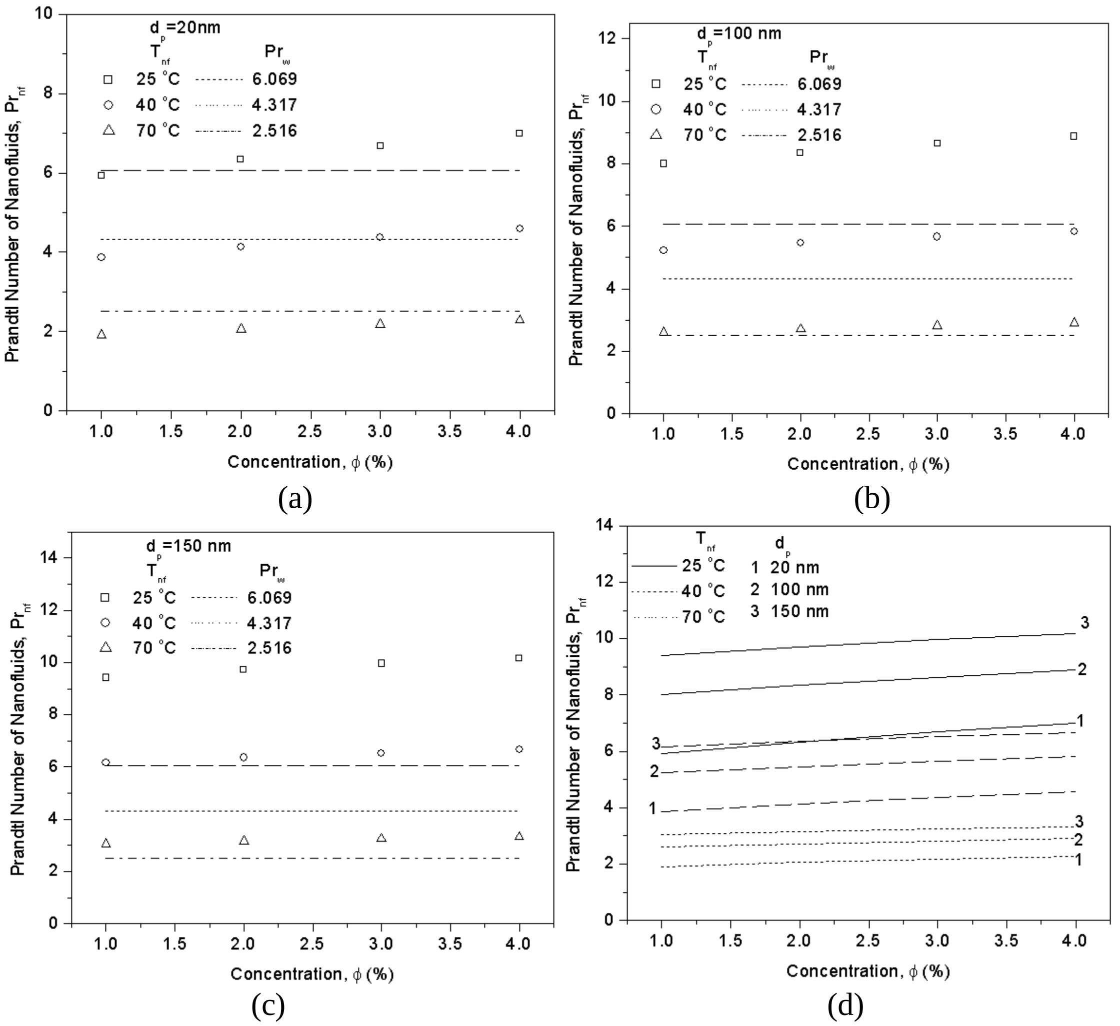


Figure 2: Comparison between regression equation and experiment data for dynamic viscosity

Figure 1 and 2 show a good agreement between the properties calculated from regression equation and experiment data from other sources. There is a small deviation between the regression equation and experiment data. The deviation is less than 5%. Therefore, the developed regression equations are able to predict certain nanofluids properties effectively. Small deviation proves that the equation gives a significant value of nanofluids properties.

RESULTS AND DISCUSSION

Figure 3 shows the variation of Prandtl number of nanofluids with the effect of temperature for different particle diameters. The Prandtl number of nanofluids is found to increase with particle size and decrease with temperature shown through Figs. 3(a) – 3(c). The Prandtl number of nanofluids was compared with Prandtl number of water at the same temperature. Small particle size gives the equal value of Prandtl number for both nanofluids and water. Meanwhile when the particle size increased, the Prandtl number of nanofluids is drastically higher than the Prandtl number of water at the same temperature. However, with particle sizes of the order of 20nm, it can be observed that Prandtl number at low concentrations can be lower than water resulting in obtaining lesser values of heat transfer coefficients. Fig. 3(d) shows the effect of temperature, particle size and concentration to the Prandtl number of nanofluids.



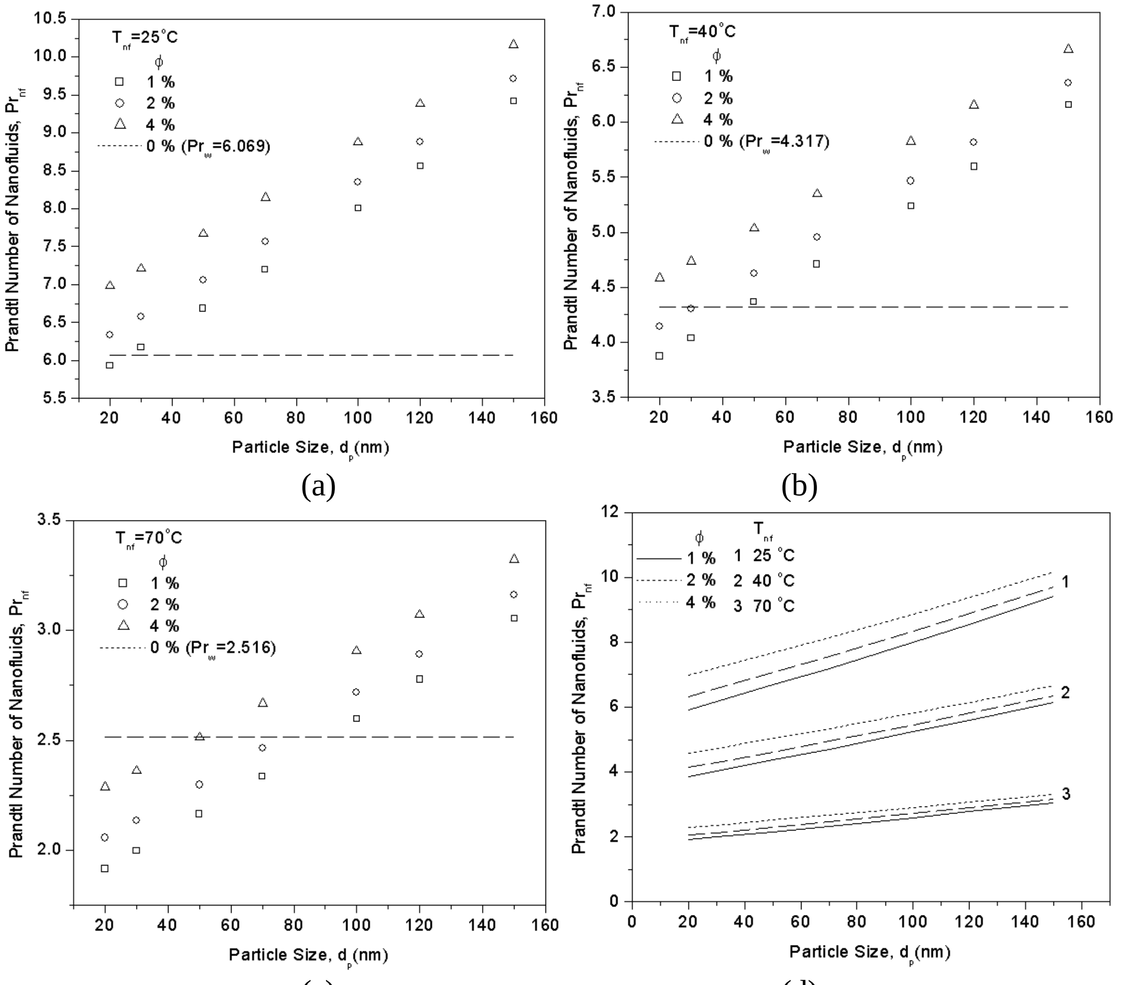
(a) (b)

(c) (d)

Figure 3: Variation of Prandtl number of nanofluids with concentration – Effect of temperature for different particle diameters

Figure 4 shows the variation of Prandtl number of nanofluids with the effect of concentration for different temperature. The Prandtl number of nanofluids is found to increase with concentration and decrease with temperature shown through Figs. 4(a) – 4(c). The Prandtl number of nanofluids was compared with Prandtl number of water at the same temperature. At low temperature, the Prandtl number for nanofluids is higher than water. Meanwhile, the Prandtl number of nanofluids is equal or less than water at low concentration when the temperature increased. Fig. 4(d) shows the effect of temperature, particle size and concentration to the Prandtl number of nanofluids.

Figure 5 shows the variation of Prandtl number of nanofluids with the effect of concentration for different particle size. The Prandtl number of nanofluids is found to increase with concentration and particle size shown through Figs. 5(a) – 5(c). At high concentration, the Prandtl number for nanofluids is increased. Meanwhile when the particle size increased, the Prandtl number of nanofluids is increased. Fig. 5(d) shows the effect of temperature, particle size and concentration to the Prandtl number of nanofluids.



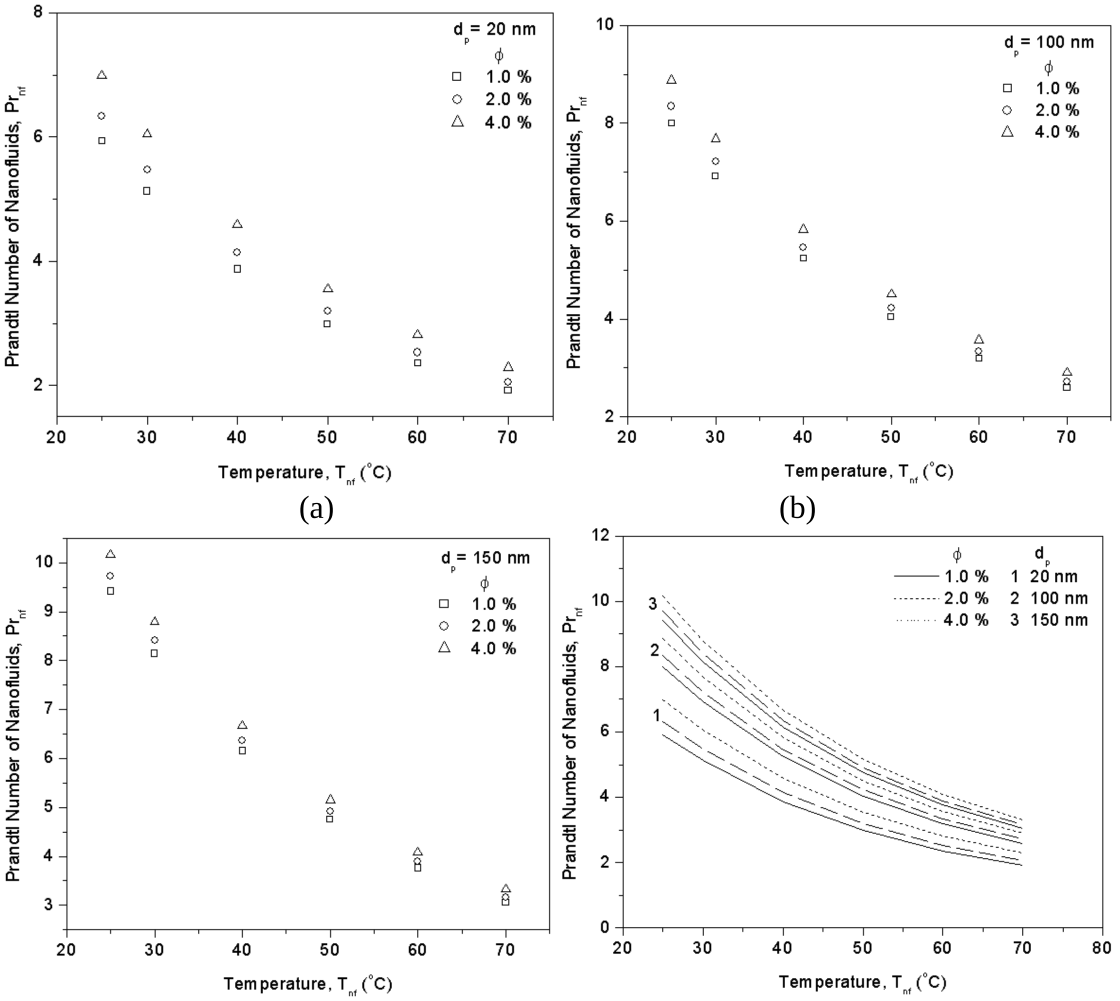
(a)

(b)

(c)

(d)

Figure 4: Variation of Prandtl number of nanofluids with particle diameter – Effect of concentration for different temperature.



(a) (b)

(c) (d)

Figure 5: Variation of Prandtl number of nanofluids with temperature – Effect of concentration for different particle diameter

CONCLUSION

It is required to select a proper particle size based on the operating temperature and concentration for obtaining the desired heat transfer enhancement. Finally, the influences of thermal conductivity, viscosity, density and specific heat on Prandtl number were shown and contributed to the determination of nanofluid heat transfer coefficients.

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Nomenclature

K	thermal conductivity, J/ (K m)
T	temperature, ^{o}C
C	specific heat at constant pressure, J/ (K kg)
d	diameter, m
Pr	Prandtl number

Greek symbols

ϕ	volume fraction of nanoparticles in percent
ρ	density, (kg/m^3)
μ	absolute viscosity, kg/(ms)

Subscripts

bf	basefluid
eff	effective
p	nanoparticle
$neff$	net effective
b	bulk
w	water
nf	nanofluid
r	ratio

Abbreviation

AD	average deviation
NIST	National Institute of Standards and Technology
SD	standard deviation