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Proposed new equations for calculation of thermophysical properties of nanofluids

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ABSTRACT

A trial-error procedure is applied for the derivation of correlations to estimate the relative thermal conductivity (k_r) and dynamic viscosity (μ_r) of nanofluids using MATLAB. Thermophysical properties of particles and base fluids, particle diameter (d_p), sphericity, capping layer thickness, Brownian motion of a particle, temperature, and volume fraction (φ) are considered. The accuracy of predicting k_r and μ_r of nanofluids is developed using dimensionless parameters involving base fluid and particle characteristics. The results reveal that the estimated values are in a good agreement with the experimental data with a standard deviation of 2.16% and 8.16% for k_r and μ_r of nanofluids, respectively. Besides that, 97.5% of the predicted k_r values suit experimental data of k_r with a mean deviation of ±5%, whereas 90.4% of the estimated μ_r values match the data of μ_r with a mean deviation of ±10%. Therefore, the proposed new equations will be useful for numerical simulation studies and the engineering design of heat transfer devices such as refrigeration systems, solar collectors, and heat exchangers.

1. Introduction

Nanofluids consist of addition of nanometer sized (0-100 nm) particles such as oxides, nitrides, carbides, metal, carbon-based materials and hybrid nanoparticles to base fluids containing water (W), ethylene glycol (EG), ethylene glycol-water (EG-W), oil, etc. Recent review papers on thermophysical properties of nanofluids illustrated that thermal conductivity and dynamic viscosity of nanofluids depend on various parameters including the Brownian velocity, particle size and shape, type of nanoparticle and base fluid, nanofluid temperature (T), particle volume fraction (φ), and surfactants [1-5].

The relative thermal conductivity (k_r) equals thermal conductivity of nanofluids over thermal conductivity of base fluids. Several researchers [6-18] have improved various correlations for predicting k_r of nanofluids. The Maxwell model [6] was improved to predict k_r of dilute suspensions of non-interacting spheres. Hamilton et al. [7] developed a model involving a shape factor by changing the Maxwell model. But both Maxwell's and Hamilton's models do not consider the influence of temperature and particle size on k_r of nanofluids. Since the models considering only the influence of variation of φ fail to estimate k_r of nanofluids, many new models including different properties of nanofluids have been improved in recent decades. Koo et al. [8] and Vajjha et al. [10] used a two-term model considering the conventional static conductivity (Maxwell model) and the thermal conductivity thanks to Brownian effect including particle diameter (d_p), φ, T, and properties of base fluid. Patel et al. [11] suggested an empirical equation including change of thermal conductivity of base fluids and particles, T and d_p using the non-linear regression analysis. Hassani et al. [14] suggested a correlation including the size distribution of nanoparticles, the Brownian motion, φ and T using the Vaschy–Buckingham theorem.

The dynamic viscosity of nanofluids is also important for the heat transfer applications thanks to the internal resistance to fluid flow and a negative impact on the pumping power. The relative dynamic viscosity of

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nanofluids (μ_r) equals dynamic viscosity of nanofluids divided by dynamic viscosity of base fluids.

Various models [19-27] were suggested to predict μ_r of nanofluids. Einstein [19] was the first researcher who developed a theoretical model to estimate μ_r of the solid-liquid suspension for $\varphi < 0.2\%$. Graham [20] presented a model to calculate μ_r depending on d_p and the minimum distance separating the sphere surfaces for low φ. Masoumi et al. [22] described a new correlation involving the Brownian motion of nanoparticles, d_p, particle density, dynamic viscosity of base fluid, and distance between centers of particles. Hosseini et al. [23] improved a model with capping layer thickness, hydrodynamic volume fraction and d_p on the nanoparticle and T. Corcione [12] proposed an equation accounting for d_p, equivalent molecular diameter of the base fluid and φ. Adio et al. [24] suggested a correlation considering d_p, φ, capping layer thickness and T by using dimensional analysis. The goal of the present paper is to represent new empirical correlating equations for predicting k_r and μ_r of W, EG and EG-W based nanofluids including spherical and cylindrical nanoparticles. Most of researchers have developed their models to estimate k_r of nanofluids with spherical particles using only their own data. On other hand, the models for estimating μ_r of nanofluids are relatively few compared to k_r models and most of them deal with only change of φ. But k_r and μ_r of nanofluids are dependent on many factors. Therefore, the suggested correlations will help to improve predicting k_r and μ_r of nanofluids with extending range by using different dimensionless parameters consisting of the Brownian velocity, thermophysical properties of base fluids and nanoparticles, d_p, ψ, T, and φ. A summary of different models on k_r and μ_r of nanofluids is presented in Table 1 and Table 2, respectively.

2. Methodology

2.1 Correlations for Relative Thermal Conductivity

The correlation for predicting k_r of nanofluids is derived from the experimental data [28, 29, 31-39] including spherical and cylindrical particles with W, EG and EG-W based nanofluids by trial error method using MATLAB.

A second-degree polynomial is used to describe k_r of nanofluids:

$$k_r = (\beta_2\phi^2 + \beta_1\phi)\Delta_{k_r} + \beta_0 \tag{1}$$

where the terms, β_2, β_1, and β_0 are the empirical constants, and Δ_{k_r} is the dimensionless term, which is multiplied by the constants, β_2, and β_1 to express the impacts of base fluids and particles characteristics on k_r of nanofluids.

The term, Δ_{k_r} in Equation (1) can be written as:

$$\Delta_{k_r} = \left(\frac{k_p}{k_{bf}}\right)^{0.78}\left[ln\left(\frac{k_p}{k_{bf}}\right)^{1.25}\right]\left(\frac{h}{d_p}\right)^{1.12}\left(\frac{T}{T_{\mathrm{ref}}}\right)^{13.9}\left(\frac{c_{p_{bf}}}{c_{p_{ref}}}\right)^{5.35}\left(\frac{1}{\psi}\right)^{0.017(d_p/h)}\mathrm{Re}^{0.1}\mathrm{Pr}^{0.24} \tag{2}$$

where h is capping layer thickness and h =1 nm [23], T_{ref} is a reference temperature and T_{ref} = 293 K, c_{pbf} and c_{pref} are specific heat of base fluid and reference specific heat and c_{pref} is equal to 4182.2 J/kg (specific heat of water at 293 K) [40].

The particle sphericity, ψ in Equation (2) is equal to the sphere surface area including equivalent volume as the actual particle [41]. ψ = 0.5 and ψ = 1 for cylindrical and spherical nanoparticles, respectively.

The nanoparticle Reynolds number is calculated by:

$$Re = \frac{\rho_b u_{Br} d_p}{\mu_{bf}} \tag{3}$$

where u_{Br} is the Brownian velocity, which is computed using the Koo and Kleinstreuer model accounting for the influence of the particle Brownian motion and interaction between particles and fluid molecules [8]:

$$u_{Br} = \sqrt{\frac{18k_bT}{\pi\rho_{bf}d_p^{\,3}}} \tag{4}$$

where k_b is the Boltzmann constant which is equal to $1.3806\text{x}10^{-23}$.

The Prandtl number of the base fluids is calculated as

$$Pr = \frac{c_{p_{bf}}\mu_b}{k_{bf}} \tag{5}$$

The constants, β_2, β_1, and β_0 in Equation (1) and the exponents in Equation (2) are determined based on the experimental data [28, 29, 31-39] using MATLAB. For spherical particle with W based nanofluids and cylindrical particle with W, EG and EG-W based fluids, β_2 = 0.00019, β_1 = 0.0045, and β_0 = 1.033. For spherical particle with EG and EG-W based fluids β_2 = -0.0008, β_1 = 0.0716, and β_0 = 1.011.

2.2 Correlations for Relative Dynamic Viscosity

The correlation for predicting μ_r of nanofluids are derived from experimental data [24, 28, 35, 39, 43-48] including spherical and cylindrical particles with W, EG and EG-W based nanofluids by trial error method using MATLAB.

A second-degree polynomial is used to express μ_r of nanofluids:

$$\mu_r = \left(\eta_2\varphi^2 + \eta_1\varphi\right)\Delta_{\mu_r} + \eta_0 \tag{6}$$

where the terms, η_2, η_1, and η_0 are the empirical constants, and Δ_{μ_r} is the dimensionless term, which is multiplied by the

constants, η_2, and η_1 to express the impacts of base fluids and particles characteristics on k_r of nanofluids.

The term, Δ_{μ_r} in Equation (6) can be written as:

$$\Delta_{\mu_r} = \left(\frac{\rho_p}{\rho_{bf}}\right)^{2.4}\left(\frac{h}{d_p}\right)^{1.8}\left(\frac{T_{ref}}{T}\right)^{8}\left(\frac{1}{\psi}\right)^{6} Re^{-0.11} \quad (7)$$

where ρ_p and ρ_{bf} are particle and base fluid density. The constants, η_2, η_1, and η_0 in Equation (6) and the exponents in Equation (7) are determined based on the experimental data [24, 28, 35, 39, 43-48] using MATLAB. For spherical particle with W based nanofluids and cylindrical particle with W, EG and EG-W based fluids, $\eta_2 = 0.3136$, $\eta_1 = 0.5165$, and $\eta_0 = 1.064$. For spherical particle with EG and EG-W based fluids, $\eta_2 = 0.1167$, $\eta_1 = 0.4717$, and $\eta_0 = 1.064$.

The thermophysical properties of the base fluids in Equations (2) and (7) are evaluated using the data taken from [40, 42] at the nanofluid temperature. The thermophysical properties of the nanoparticles used for all the calculations are given in Table 3.

Table 1. Various correlations on k_r nanofluids

Authors	Correlations	Remarks
Maxwell [6]	$k_r = \frac{2k_{bf} + 2(k_p - k_{bf})\varphi + k_p}{2k_{bf} - (k_p - k_{bf})\varphi + k_p}$	Nanofluids with spherical particles for low φ.
Hamilton et al. [7]	$k_r = \frac{(n-1)k_{bf} + (n-1)(k_p - k_{bf})\varphi + k_p}{(n-1)k_{bf} + -(k_p - k_{bf})\varphi + k_p}$	n is a shape factor and $n = 3/\psi$.
Koo et al. [8]	$k_r = \frac{2k_{bf} + 2(k_p - k_{bf})\varphi + k_p}{2k_{bf} - (k_p - k_{bf})\varphi + k_p} + \frac{5\text{x}10^4 \beta \rho_{bf} c_{p_{bf}} \varphi}{k_{bf}}\sqrt{\frac{k_b T}{\rho_p d_p}} f(T, \varphi)$ $\beta = 0.0137(100\varphi)^{-0.8229} \ (\varphi < 1\%), \ \beta = 0.0011(100\varphi)^{-0.7272} \ (\varphi > 1\%),$ $f(T,\varphi) = (0.4705 - 6.04\varphi)T + 1722.3\varphi - 134.63 \ \ for\ CuO-W\ mixture.$	$f(T, \varphi)$ is obtained the measured data of Das et al. [9].
Vajjha et al. [10]	$k_r = \frac{2k_{bf} + 2(k_p - k_{bf})\varphi + k_p}{2k_{bf} - (k_p - k_{bf})\varphi + k_p} + \frac{5\text{x}10^4 \beta \rho_{bf} c_{p_{bf}} \varphi}{k_{bf}}\sqrt{\frac{k_b T}{\rho_p d_p}} f(T, \varphi)$ $\beta = 8.4407(100\varphi)^{-1.07304} \ (\varphi = 1-10\%) \ \ for\ Al_2O_3\ and \ (\varphi = 1-7\%) \ \ for\ ZnO$ $\beta = 9.881(100\varphi)^{-0.9446} \ (\varphi = 1-6\%) \ \ for\ CuO\ with\ 60-40\%\ EG-W$ $f(T, \varphi) = (2.8217\text{x}10^{-2}\varphi + 3.917\text{x}10^{-3})\frac{T}{T_0} - 3.069\text{x}10^{-2}\varphi - 3.91123\text{x}10^{-3}$	The ranges of d_p, T and φ are 29-77 nm, 298-363 K and 1-10%.
Patel et al. [11]	$k_r = 1 + 0.135\left(\frac{k_p}{k_{bf}}\right)^{0.273}\varphi^{0.467}\left(\frac{T}{20}\right)^{0.547}\left(\frac{100}{d_p}\right)^{0.234}$	The ranges of d_p, T and φ are 10-150 nm, 293-343 K and 0.1-3% for nanoparticles with W, EG and transformer oil.
Corcione [12]	$k_r = 4.4Re^{0.4}Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_{bf}}\right)^{0.03}\varphi^{0.66} + 1, \ Re = \frac{\rho_{bf} u_{Br} d_p}{\mu_{bf}}, \ Pr = \frac{c_{p_{bf}} \mu_{bf}}{k_{bf}}$	The ranges of d_p, T and φ are 10-150 nm, 294-324 K and 0.2-9% for Al_2O_3, CuO-W and EG, TiO_2-W and Cu-EG.
Azmi et al. [13]	$k_r = 0.8938\left(1 + \frac{\varphi}{100}\right)^{1.37}\left(1 + \frac{T}{70}\right)^{0.2777}\left(1 + \frac{d_p}{150}\right)^{-0.0336}\left(\frac{\alpha_p}{\alpha_w}\right)^{0.01737}$	T is 394.5 K and the range of φ is 0-4% nm for Al_2O_3 (50 nm), ZnO (100 nm) with W.
Hassani et al. [14]	$k_r = 1.04 + \varphi^{1.11}\pi_3^{0.33}\pi_4^{-1.7}\left[\pi_4^{1.7} - 262\pi_3^{-0.33} + \left(135\pi_5^{0.23}\pi_6^{0.82}\pi_7^{-0.1}\pi_8^{-7}\right)\right]$ $\pi_3 = \frac{k_p}{k_{bf}}, \ \pi_4 = \frac{c_{p_{bf}} \mu_{bf}}{k_{bf}}, \ \pi_5 = \frac{d_{ref}}{d_p}, \ \pi_6 = \frac{v_{bf}}{d_p u_{Br}}, \ \pi_7 = \frac{c_{p_{bf}}}{T^{-1}u_{Br}^2}, \ \pi_8 = \frac{T_b}{T}$	The ranges of d_p, T and φ are 15-200 nm, 293-393 K and 0.005-14% for various nanofluids.
Garoosi [17]	$k_r = \frac{2k_{bf} + 2(k_p - k_{bf})\varphi + k_p}{2k_{bf} - (k_p - k_{bf})\varphi + k_p} + 3.762\left(\frac{T}{T_0}\right)^{8.661}\left(\frac{d_p}{d_{bf}}\right)^{-0.4351}\left(\frac{k_p}{k_{bf}}\right)^{0.08235}\varphi^{0.64}e^{(-5.742\varphi)}$ $\omega = (1 + 0.8946 \times \varphi)$	Empirical correlation is valid for $0 \le \varphi \le 0.12$, $10\text{nm} \le d_p \le 5\mu\text{m}$ and $288\ \text{K} \le T \le 360\ \text{K}$.
Arasu et al. [18]	$k_r = 0.9472 - 0.052\varphi + 0.001482T + 0.00663(\varphi T)$	The ranges of T and φ are 308-333 K and 0.1-0.4% for TiO_2 with W.

Table 2. Various correlations on μ_r nanofluids

Authors	Correlations	Remarks
Einstein [19]	$\mu_r = 1 + 2.5\varphi$	The model is valid for low φ ($\varphi < 2\%$).
Graham [20]	$\mu_r = 1 + 2.\varphi + \dfrac{4.5}{\left(\frac{h}{a}\right)\left(2+\frac{h}{a}\right)\left(1+\frac{h}{a}\right)^2}$ $h/a = (2)[(1-(\varphi/\varphi_m)^{1/3})/(\varphi/\varphi_m)^{1/3}]$	h is minimum distance separating two spheres. a is radius of particle. φ_m is maximum packing spheres.
Chen et al. [21]	$\mu_r = \left(1 - \dfrac{\varphi}{0.605}\left(\dfrac{a_a}{a}\right)^{1.2}\right)^{-1.5125}$	d_p is 25 nm. The ranges of T and φ are 293-333 K and 0-2% for TiO_2-EG.
Masoumi et al. [22]	$\mu_r = 1 + \dfrac{\rho_p v_{Br} d_p^2}{72C\delta\mu_{bf}}$	d_p is 13 and 28 nm. The ranges of T and φ are 290-340 K and 1-5% for Al_2O_3-W.
Hosseini et al. [23]	$\mu_r = \exp\left[m + \alpha\left(\dfrac{T}{T_0}\right) + \beta(\varphi_h) + \gamma\left(\dfrac{d_p}{1+r}\right)\right]$, $\varphi_h = \varphi\left[\dfrac{d_p + 2s}{d_p}\right]^3$	T_0 = 20 °C. d_p is 36 and 47 nm. The ranges of T and φ are 293-333 K and 0-10% for Al_2O_3-W.
Corcione [12]	$\mu_r = \dfrac{1}{1 - 34.87\left(\dfrac{d_p}{d_{bf}}\right)^{-0.3}\varphi^{1.03}}$, $d_{bf} = 0.1\left(\dfrac{6M}{N\pi\rho_{bf0}}\right)^{1/3}$	The ranges of d_p, T and φ are 25-200 nm, 293-333 K and 0.01-7% for Al_2O_3-W and propylene glycol, TiO_2-W and EG, SiO_2-ethanol and Cu-EG.
Adio et al. [24]	$\mu_r = 1 + \left[a_0 + a_1\left(\dfrac{T}{T_0}\right) + a_2\left(\dfrac{d_p}{h}\right)\right]\varphi + \left[a_3\left(\dfrac{d_p}{h}\right)^2 + a_4\left(\dfrac{T}{T_0}\right)^2 + a_5\right]\varphi^2 + a_6\left(\dfrac{T}{T_0}\right)^2 \varphi^{\frac{1}{3}}$ $a_0 = 7.0764,\ a_1 = -0.1246,\ a_2 = -0.0346,\ a_3 = -0.0024,\ a_4 = -1.2357,$ $a_5 = 53.6946,\ a_6 = 0.0436$	d_p is 21, 105 and 125 nm. The range of T is 293-343 K and $\varphi \le 5\%$ for MgO-EG.
Garossi [17]	$\mu_r = 1 + 49.6 \times \left(\dfrac{d_p}{d_{bf}}\right)^{-0.414} \varphi^{0.908} e^{(10.8\varphi)}$	Empirical correlation is valid for $0 \le \varphi \le 0.12$, 10 nm $\le d_p \le$ 5 μm.
Esfe et al. [27]	$\mu_r = 1.01171 + 0.0387\varphi + 6.35\times10^{-5}T - 0.0010096\varphi T - 0.00466\varphi^2 + 2.127\times10^{-5}T^2 + 0.000107\varphi^2 T + 4.527\times10^{-5}\varphi T^2$	The ranges of T and φ are 298-323 K and 1-4% for AIN (Aluminium nitride) with EG.

Table 3. Thermophysical properties of nanoparticles

Nanoparticles	k (W/m K)	ρ (kg/m^3)
Al_2O_3 [14]	40	3970
CuO [14]	20	6400
SiO_2 [14]	1.2	2200
TiO_2 [49]	8.95	4250
MgO [50]	48.4	3580
ZnO [51]	13	5600
Ag [17]	429	10500
Al [36]	237	2700
CNT, MWCNT [30, 52]	2000	2100

3. Results and Discussion

Figure 1 shows comparison of the predicted k_r values obtained from Equation (1) with experimental data including Al_2O_3-W [28, 29, 33], CuO-W [33], TiO_2-W [32], Ag-W [35] and CNT-W [31] with a d_p range of 13-150 nm, a T range of 295-323 K, a φ range of 0-18.1%.

Figure 2 illustrates comparison of the predicted k_r values obtained from Equation (1) with experimental data containing SiO_2-EG [39], ZnO-EG [34], Al-EG [36], Al_2O_3 -20:80%, 40-60%, 60:40% EG-W [38], MWCNT-30:70% EG-W [37] with a d_p range of 5-50 nm, a T range of 293-303 K, a φ range of 0-5%.

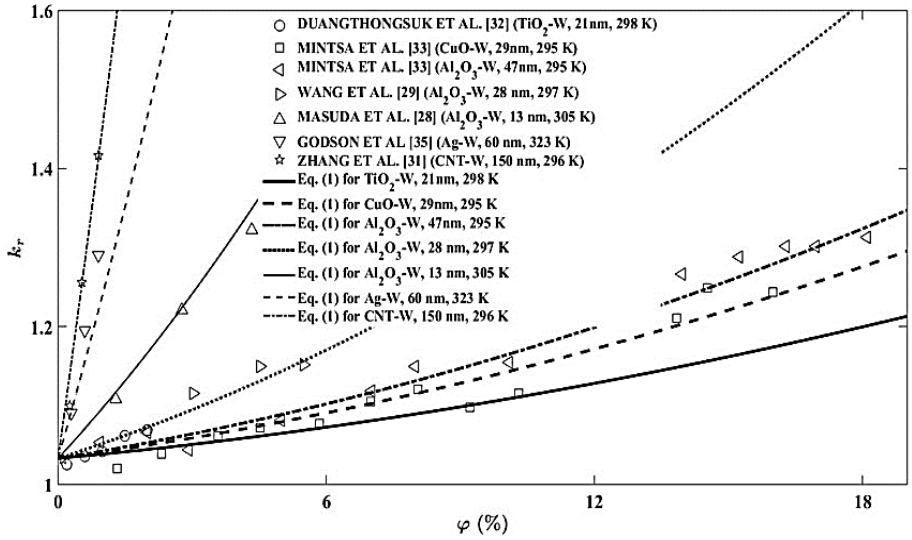

Figure 1. Comparison between the predicted values of k_r produced using Equation (1) and the values obtained by the experimental data of W based nanofluids

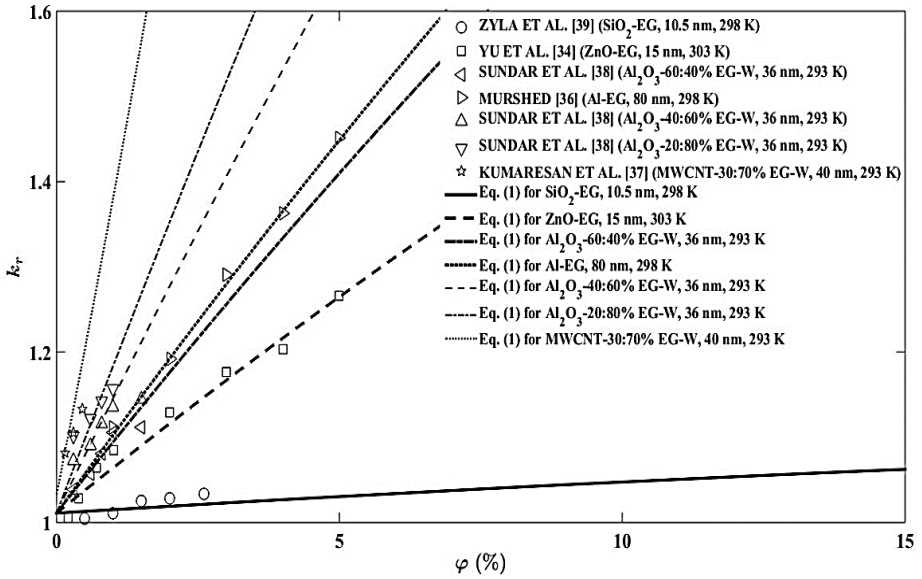

Figure 2. Comparison between the predicted values of k_r produced using Equation (1) and the values obtained by the experimental data of EG / EG-W based nanofluids

It is clear from Figures 1 and 2 that the predicted k_r values found using Equation (1) agree well with experimental data. Previous experimental studies illustrate that the type, shape, and size of nanoparticles affect k_r of nanofluids which generally increases with a reduction of nanoparticle's size. Figures 1 and 2 show that the suggested correlation estimates well k_r of nanofluids with different nanoparticle shapes, sizes, and types. The dimensionless parameters containing h, d_p, and ψ in Equation (2) improve estimation of different size of spherical and cylindrical nanoparticles. The maximum values of k_r are gained by nanofluids with higher thermal conductive particles such as Ag, CNT and MWCNT as shown in Table 3.

Like the experimental data in Figures 1 and 2, the predicted k_r values obtained by Equation (1) increase when decreasing d_p and increasing T and φ. Moreover, dimensionless parameters including the nanoparticle's Brownian velocity and thermophysical properties of base fluids enhance predicting k_r of nanofluids with different weight ratios of EG-W mixtures as indicated in Figure 2.

In Figure 3, the predicted k_r values obtained using Equation (1) are compared with experimental k_r values of W, EG / EG-W based nanofluids. As shown in Figure 3, the estimated kr values are very close to experimental kr values with standard deviations of 2.16%.

In addition, 97.5% of the predicted data match experimental data with a mean deviation of ±5% as demonstrated in Figure 3.

Figures 4 shows comparison of the estimated values obtained from Equation (6) with experimental data including Al_2O_3-W [28, 46], ZnO-W [44], Ag-W [35] and

MWCNT-W [45] with a d_p range of 9.2-75 nm, a T range of 293-323 K, a φ range of 0-20.4%.

Figures 5 illustrates comparison of the estimated values obtained from Equation (6) with experimental data containing SiO_2-EG [39], MgO-EG, [24] ZnO-EG [47], CuO -60:40% EG-W [43], MWCNT-50:50% EG-W [48] with a d_p range of 10.5-70 nm, a T range of 293-323 K, a φ range of 0-6.2%, respectively. Figures 4 and 5 indicate that the calculated μ_r values obtained Equation (6) are in good agreement with the experimental μ_r values. As demonstrated in Figures 4 and 5, the estimated μ_r values gained by Equation (6) confirm the general trends of μ_r of nanofluids that the values of μ_r increase when increasing φ and decreasing d_p and T.

The present correlation also takes account of the impact of particle shape on μ_r of nanofluids using ψ in Equation (7). Like the experimental data of μ_r in Figures 4 and 5, the maximum μ_r values are obtained by nanofluids with cylindrical particles such as CNT and MWCNT. As demonstrated in Figure 5, the relative dynamic viscosity of nanofluids with different weight ratios of EG-W mixtures are predicted by using dimensionless parameters including u_{Br}, ρ_{bf}, and μ_{bf}.

In Figure 6, the predicted μ_r values obtained from Equation (6) are compared with experimental μ_r values of W, EG / EG-W based nanofluids. The predicted μ_r values calculated using Equation (6) match closely with experimental μ_r values of W, EG / EG-W based nanofluids with standard deviations of 8.16% as demonstrated in Figure 6. 90.4% and 96.2% of the predicted data suit experimental data with a mean deviation of ±10% and ±20%, respectively. Two points of the calculated data are above a 20% of deviation.

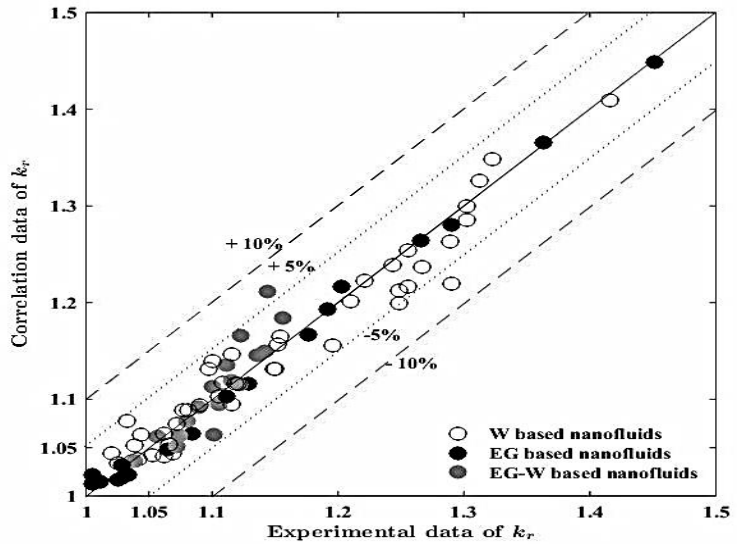

Figure 3. Comparison between the estimated values of k_r calculated using Equation (1) and the measured values of k_r for W, EG / EG-W based nanofluids

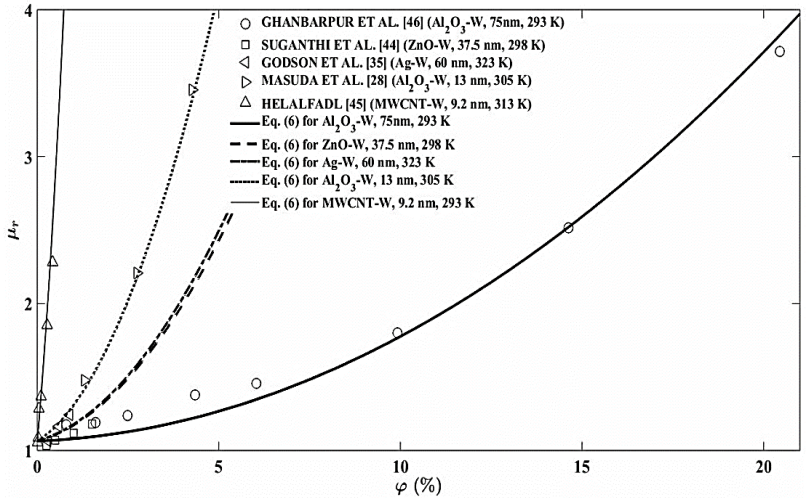

Figure 4. Comparison between the predicted values of μ_r generated using Equation (6) and the values obtained by the experimental data of W based nanofluids

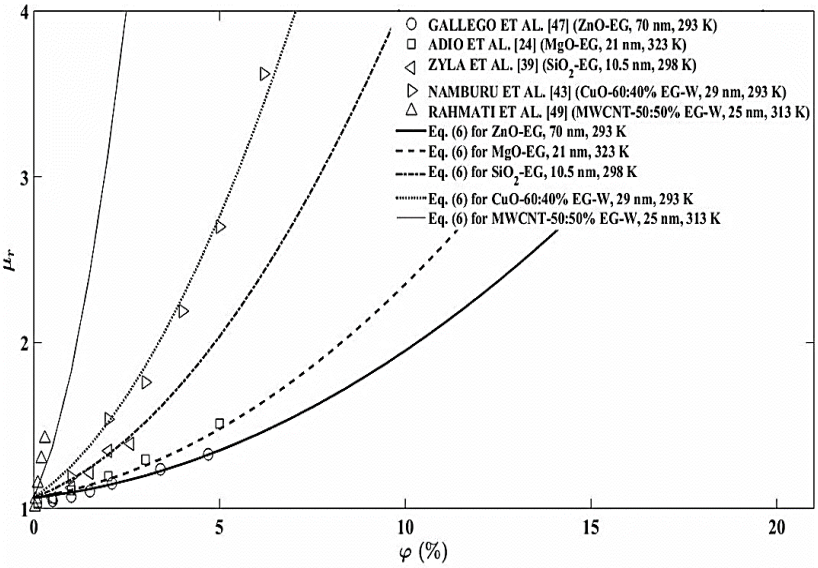

Figure 5. Comparison between the predicted values of μ_r generated using Equation (6) and the values obtained by the experimental data of EG / EG-W based nanofluids

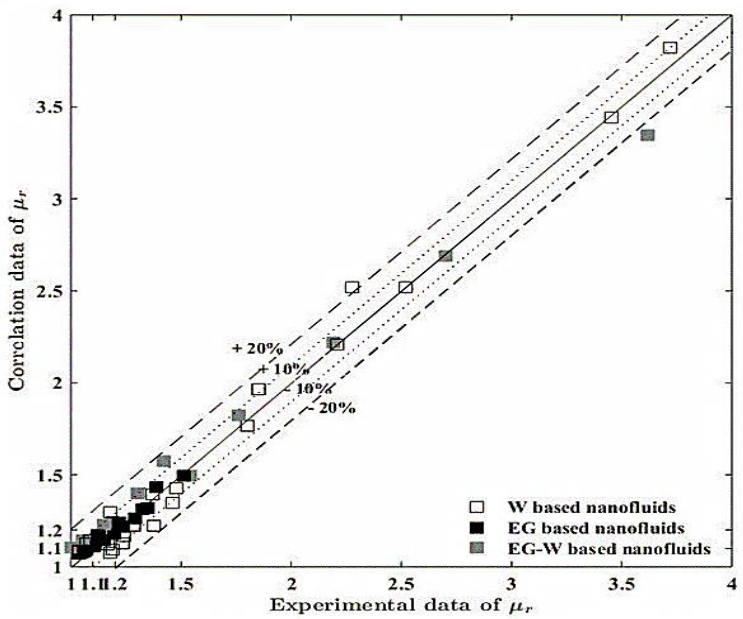

Figure 6. Comparison between the estimated values of μ_r calculated using Equation (6) and the measured values of μ_r for W, EG / EG-W based nanofluids

4. Conclusions

In this paper, k_r and μ_r of nanofluids are estimated by using the correlations with various dimensionless parameters related to the Brownian motion and properties of base fluids and nanoparticles as an extension study of [53]. The following results are achieved:

- Since k_r and μ_r of nanofluids depend on many factors, increasing number of parameters instead of using only φ and extending range of parameters in the correlations enhance accuracy of the results.
- Experimental results show that k_r generally increases when decreasing d_p and increasing k_p, T, and φ while μ_r generally increases when increasing φ and decreasing d_p and T. The suggested correlations suit this general trend.
- Adding $1/\psi$ in Equations (2) and (7) helps to improve the estimation of k_r and μ_r of nanofluids with cylindrical shape nanoparticles.
- The dimensionless parameters including particles Brownian motion and thermophysical properties of base fluids contribute to estimating k_r and μ_r of nanofluids for different weight ratios of EG-W mixtures.
- Owing to improving the correctness of predicting k_r and μ_r of nanofluids with spherical and cylindrical nanoparticles by using new dimensionless parameters,

Equations (1) and (6) will be useful tool in designing the nanofluids for various industrial applications.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

All authors conceived the study and developed the methodology. M. Kaplan performed the computations and wrote the manuscript. M. Özdinç Çarpınlıoğlu contributed to the final version of the manuscript.

Nomenclature

c_p	: Specific heat, J/kg K
d	: Nanoparticle diameter, nm
h	: Capping layer thickness, Nm
k	: Thermal conductivity, W/m K
k_b	: Boltzmann constant, 1.3806 x 10^{-23} J/K
T	: Temperature, K
Pr	: Prandtl number
Re	: Reynolds number
u_{Br}	: Brownian velocity (m/s)
β	: Empirical constant
Δ	: Correlation term
η	: Empirical constant
μ	: Dynamic viscosity, Pas
ρ	: Density (g/cm^3)
φ	: Volume fraction (%)
ψ	: Particle sphericity
bf	: Base fluid
p	: Particle
r	: Relative
ref	: Reference
AIN	: Aluminium nitride
CNT	: Carbon nanotubes
EG	: Ethylene glycol
MWCNT	: Multiwalled carbon nanotubes
W	: Water

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