



Experimental investigations into viscosity, pH and electrical conductivity of nanofluid prepared from palm kernel fibre and a mixture of water and ethylene glycol

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Abstract. Extensive research has been carried out on the synthesis and applications of nanofluid produced from metals, nonmetals and their oxides. However, little or no attention has been paid to bio-based nanoparticles. The need for the use of bio-based nanoparticles and bio-based nanofluids is imperative to mitigate over-dependence on toxic synthetic nanoparticles. This idea is also in line with renewable and sustainable developmental goals. Moreover, bio-based materials like palm kernel fibre (PKF) constitute environmental waste in some quarters and its conversion to useful products for engineering application will take a long time in solving environmental issues and health hazards. In this study, the top-down approach was used to synthesize nanoparticles from PKF using a ball-milling machine. The PKF nanoparticles with an average size of ~ 40 nm were dispersed in an ethylene glycol (EG)/water (50:50) base fluid up to 0.5% of the volume fraction. The viscosity, pH and electrical conductivity of PKF–water and EG (50:50) were studied for temperature ranging from 10 to 60°C. The results showed that the viscosity of the PKF-based nanofluid increases with an increase in volume fraction and decreases exponentially with an increase in the working temperature of the nanofluid. The pH and the electrical conductivity increased as the volume fraction of the PKF nanoparticle was increased from 0.1 to 0.5%. However, the pH decreased with an increase in the temperature while the electrical conductivity increased with an increase in the volume fraction. Since the notable theoretical models in the literature were unable to estimate the viscosity of the PKF–EG/water nanofluid, in the present case an empirical correlation based on dimensional analysis was proposed to estimate the viscosity of the PKF–EG/water nanofluids.

Keywords. Nanofluid; palm kernel nanofibre; viscosity; ethylene glycol; pH; electrical conductivity.

1. Introduction

The need for efficient heat transfer in thermal equipment is of paramount importance to increase effectiveness, productivity and the durability of equipment. Recent technological advances and the attendant miniaturization of devices have thermal management challenges accompanying them. These recent devices are designed for higher throughput and having higher processing capacities in compact spaces. Consequently, they are associated with a higher heat energy generation. Traditional methods of enhancing heat removal such as increasing the surface area will only make devices/equipment bigger and heavier than required. Therefore, nanofluid which is a novel heat-transfer fluid prepared by dispersing nanometre-sized solid particles in traditional heat-transfer fluids such as water or ethylene glycol (EG) to increase the heat-transfer performance has been proposed. For example, when 0.3 volume per cent of copper nanoparticles

was dispersed in EG, one can observe about 40% increase in thermal conductivity [1].

Although the colloidal suspension was first introduced in 1873 by Maxwell [2], in a bid to improve the heat-transfer characteristics of the conventional heat-transfer fluid, a breakthrough was not achieved until Choi's unique pioneering work on nanofluids in 1995 [3]. Due to very small size and large specific surface area of the nanoparticle, nanofluid has superior properties such as high-thermal conductivity, minimal clogging in flow passages, long-term stability and homogeneity compared to Maxwell's type of fluid [4]. The effective thermal conductivity of nanofluid is known to be a significant driver for efficient heat transfer and also, dependent on the amount of dispersed particles, material type, particle shape, size etc. On the other hand, the rheological characteristics of nanofluids dictate their efficient and optimal utilization of heat-transfer equipment that involves flow, such as in car radiators [5], heat pipes [6] and refrigeration and air-conditioning

systems. Nanofluids have shown higher thermal conductivity [4] and specific heat capacity [7,8] as a result of containing nanoparticles.

One of the many applications of nanoparticles and nanofluids in recent time is their usage in domestic solar still for water purification. Solar distillation using single-basin or other modified basin stills for water purification is one of the sustainable water purification methods for rural-arid domestic settlements. Different enhancing methods have been tried to increase distillate yield in single-basin solar stills. Some of these methods include the incorporation of steps, the corrugation of inner lining, the coupling of the external condenser, the addition of vacuum pump, coupling with flat-plate collectors and the addition of nanoparticles into the working fluid. Currently, synthetic nanoparticles such as Al_2O_3 , SiO_2 and CuO are being used to increase the yield of solar stills [9–11]. However, due to high cost, availability and their toxic effect during preparation and usage, it becomes imperative to explore the usability of a readily available, bio-friendly and low-cost agricultural material such as palm kernel fibre (PKF) nanoparticles. The use of this material will solve the problem of toxicity and also, will reduce the menace that the agricultural waste is hazardous to our environment.

In this paper, the viscosity, pH and electrical conductivity of nanofluid prepared from PKF using a mixture of water and EG as the base fluid are investigated in a bid to study these thermophysical properties ahead of deploying the PKF nanoparticle in domestic solar stills for water purification. By the experiments herein conducted we will study the influence of volume fraction and temperature on the above-mentioned thermophysical properties.

2. Experimental

2.1 Preparation of PKF nanoparticles and characterization

A large amount of raw PKF (about 100 kg) waste was collected from a palm oil processing factory. PKF was washed with diluted sodium hydroxide (NaOH) to remove the residual palm oil from the fibre materials, and the resulting product was rinsed thoroughly with water and sun-dried. The sun-dried PKF was then oven-dried in a temperature range of 50–70°C for 24 h to ensure that the residual moisture was reasonably eliminated. This was monitored by constantly measuring the weight of the PKF and oven drying was stopped when the weight of the PKF became constant. The dried PKF was fed into a ball-milling machine and allowed to run continuously for 48 h. The PKF obtained after 48 h was reduced to ultrafine particles in the nanometre range as shown with scanning electron microscope (SEM) and transmission electron microscope (TEM) images in figure 1 a and b. The palm kernel nanoparticle was nearly spherical with an average size of 40 nm and a density of 1.565 g m^{-3} . The X-ray diffraction pattern of the PKF nanoparticles is shown in figure 1 c.

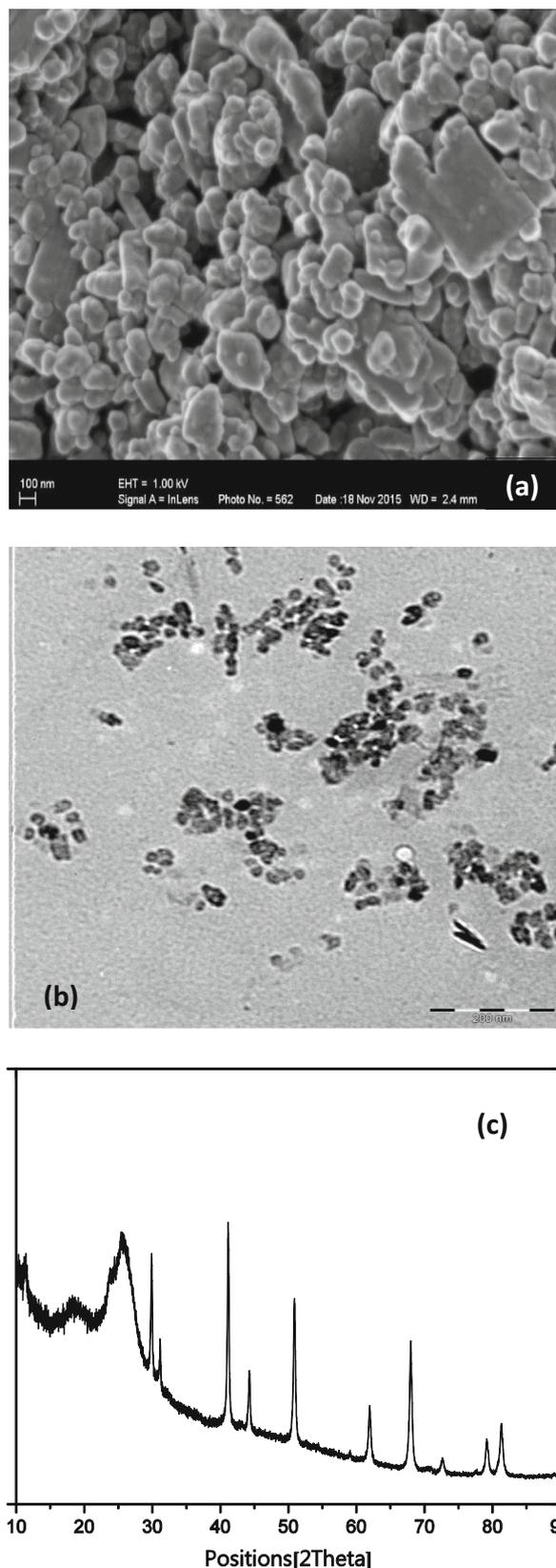


Figure 1. Microscopic images of the PKF nanoparticles: (a) SEM image of the PKF nanoparticles, (b) TEM image of the PKF nanoparticles and (c) X-ray diffraction pattern of PKF nanoparticles.



Figure 2. Nanofluid samples of PKF–water and EG (50:50).

2.2 Nanofluid preparation and thermophysical measurements

A ‘two-step’ method was used in the preparation of nanofluid from PKF since it is the only feasible method out of the two common methods in use. A known mass of the PKF nanoparticles corresponding to a predetermined volume concentration was measured and mixed with a binary mixture of EG and deionized water in a ratio of 50:50. The mixture was sonicated continuously using a 24-kHz Q700 Qsonica ultrasonicator with a 12 mm sonotrode. This ensured a good dispersion of the PKF in the base fluid, and there was no visual sedimentation or separation 24 h after preparation as shown in figure 2.

During the process of dispersion, the nanofluid sample was kept in a programmable temperature bath (LAUDA ECO RE1225 Silver temperature bath) and the temperature was maintained at $15 \pm 0.1^\circ\text{C}$. The viscosity was measured using a SV-10 vibro-viscometer; the pH was measured using a Jenway pH metre (model 3510) and the electrical conductivity was measured using a EUTECH CON700 conductivity metre. The details of each measurement and the calibration of the devices used are given elsewhere in previous publications [12,13].

3. Experimental results and discussion

3.1 Influence of temperature on the viscosity of PKF–water/EG nanofluids

After performing the benchmark experiments, confirming that the obtained readings were correct, viscosity measurements of fluid samples with different volume concentrations were carried out with varying temperature between 10 and 60°C .

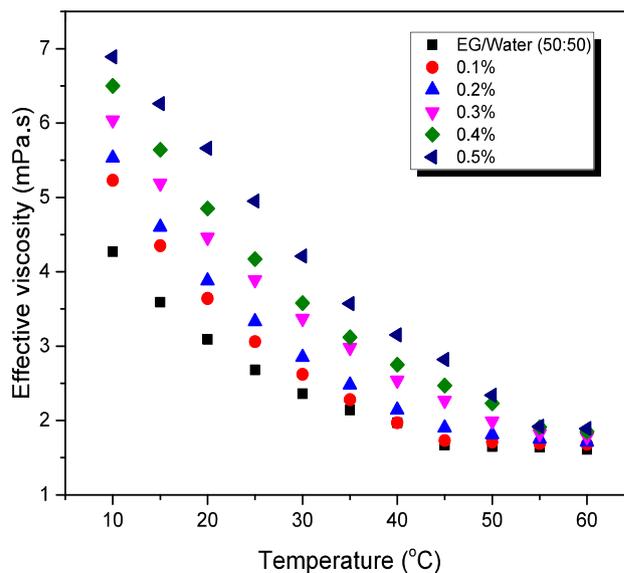


Figure 3. Effect of temperature on the viscosity of PKF–water/EG (50:50) nanofluids at various volume fractions.

Previously, Namburu *et al* [14] had shown that dispersing CuO nanoparticles up to 6.12% in the binary mixture of EG–water (60:40) gives a Newtonian behaviour. Kulkarni *et al* [15] also showed that dispersing CuO up to 15% volume fraction at temperature between 5 and 50°C behaves as a Newtonian fluid similar to Kole and Dey [16].

Figure 3 shows the influence of temperature on the effective viscosity of the PKF–water/EG nanofluid. The trend is similar to that available in the open literature [12–14,17]. The viscosity of the nanofluid reduces exponentially with an increase in the working temperature. In this work, the trends describing the change in viscosity with temperature are similar for all volume fractions. In figure 3, the data points for the viscosity of the pure base fluid are provided for comparison, and it can be noticed that the difference between the viscosity of the base fluids and the nanofluids reduced as the temperature increased. This is largely due to the temperature influence, as the temperature increased the cohesive bonding that exists between the molecules of the fluid is weakened. Thus, the fluidity of the nanofluids drastically increased.

3.2 Influence of volume fraction increment of the viscosity of PKF–water/EG nanofluid

The graph shown in figure 4 is the relative viscosity against the volume fraction, and it represents the behaviour of the PKF–water/EG nanofluid to increase in the PKF volume fraction. The viscosity increases with an increase in the volume fraction with the highest value of 6.89 mPa s recorded at a volume fraction of 0.5% and 10°C . In figure 4, the relative viscosity enhancement of 1.60 times more than the base fluid is observed. Similar trends were observed by Kole

and Dey [16,18] using Al_2O_3 dispersed in engine coolants (polyethylene glycol (PG)–water; 50:50 and EG–water 70:30). In their work, the viscosity also increases with an increase in volume concentration. A similar result was presented by Syam Sundar *et al* [19] on Fe_3O_4 and different EG–water binary mixtures. The binary mixtures used by them were 60:40, 40:60 and 20:80% EG–water mixtures with respective viscosity enhancements at 1% volume fraction and 50°C as 2.94, 1.61 and 1.42 times the value obtained for the respective base fluids.

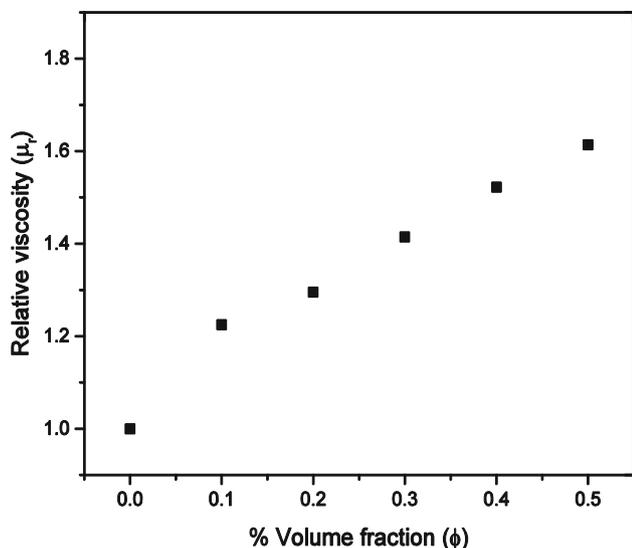


Figure 4. Relative viscosity of PKF–water/EG (50:50) nanofluids at various volume fractions and 10°C working temperature.

3.3 Effect of temperature and volume fraction on the electrical conductivity of PKF–water/EG nanofluid

The effect of temperature on the electrical conductivity of the PKF–water/EG-based nanofluid was investigated at various volume fractions, and the result is shown in figure 5a. The electrical conductivity of the base fluid was between 6.93 and 10.30 $\mu S\ cm^{-1}$ when the temperature was increased from 10 to 60°C. This represents a 48.63% increment at the temperature of 60°C. Deionized water is a polar liquid in the binary mixture (water and EG), which tends to dominate the ionization process that occurs in the suspension.

The addition of PKF nanoparticles into the base fluid showed an increment in the value of the suspension and increasing the temperature also gave a corresponding increase in the electrical conductivity values. As the volume fraction was changed from 0.1 to 0.5%, there is an appreciable enhancement in the electrical conductivity as shown in figure 5b. The enhancement due to the volume fraction increase is higher than the temperature increase. For instance, ~55% enhancement in electrical conductivity was observed at 0.1% volume fraction and between 10 and 60°C. However, at 10°C increasing the volume fraction from 0.1 to 0.5% gave 910.10% enhancement in electrical conductivity. According to Sarojini *et al* [20], the polarization of the nanoparticles when dispersed in a polar base fluid (such as water or base fluid containing water) is extant and leads to the formation of surface charges which causes the enhancement in the effective electrical conductivity observed.

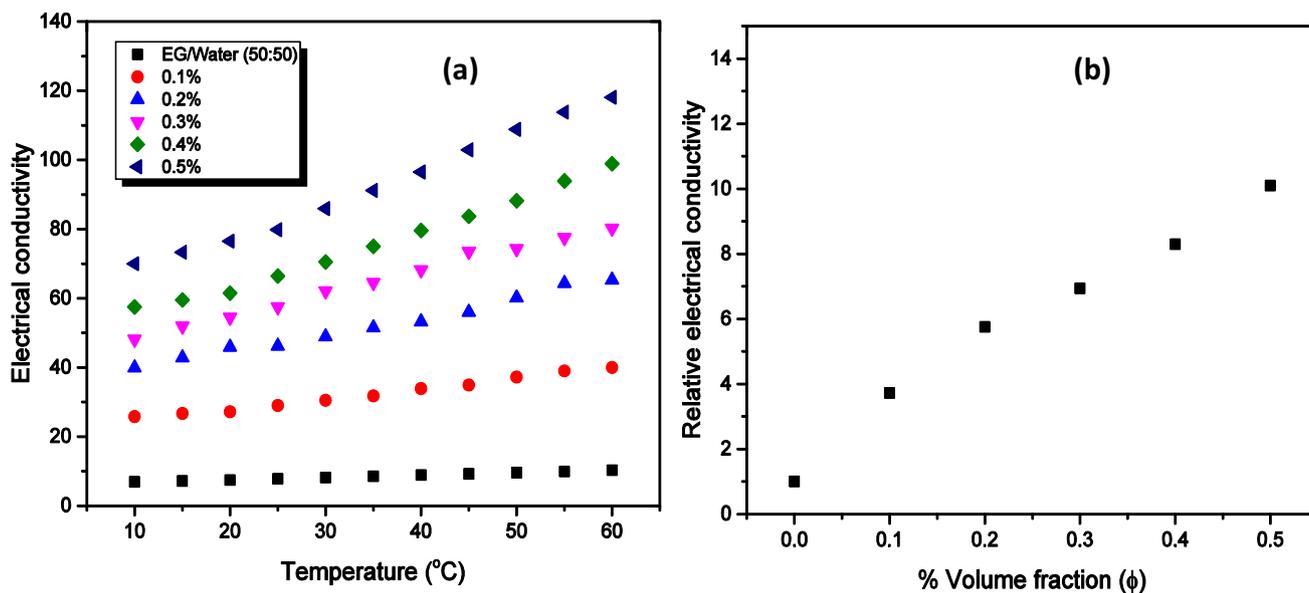


Figure 5. Effect of temperature and volume fraction on the electrical conductivity of PKF–water/EG (50:50) nanofluids: (a) influence of temperature at various volume fractions and (b) influence of volume fraction on the relative electrical conductivity at 10°C.

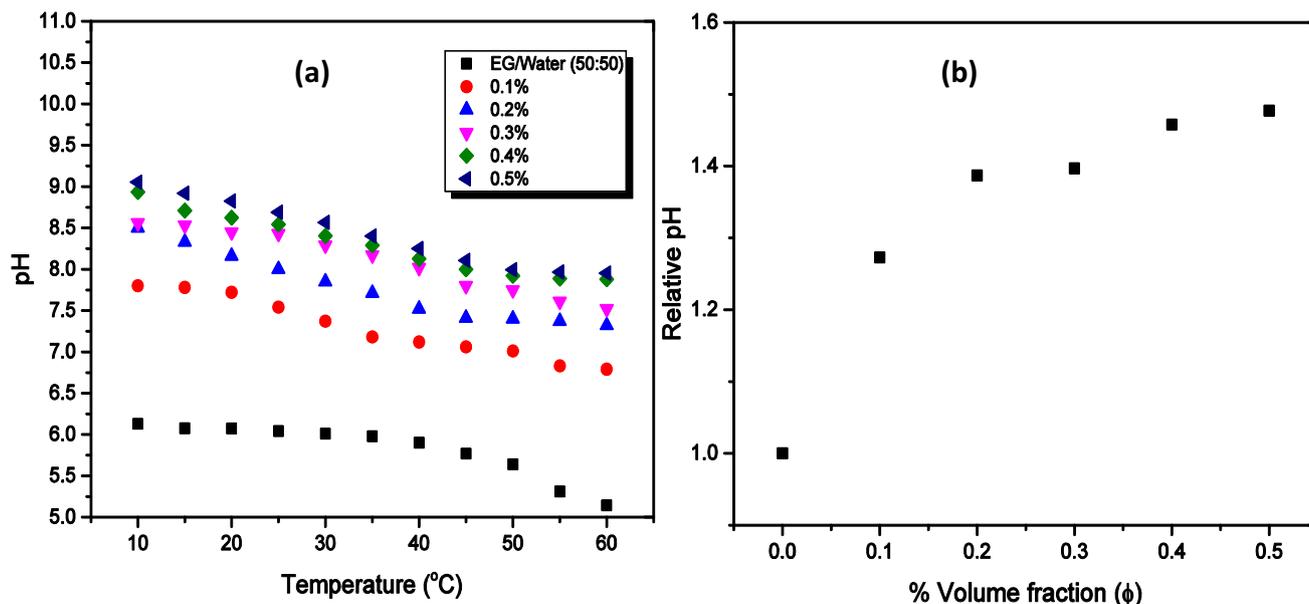


Figure 6. Influence of temperature on the pH of PKF–water/EG (50:50) nanofluids: (a) influence of temperature at various volume fractions and (b) influence of volume fraction on the relative pH at 10°C.

3.4 Effect of temperature and volume fraction on pH

Figure 6a shows the influence of temperature on the pH values of the PKF–water/EG nanofluid for various volume fractions. The pH of the base fluid is in the mild acidic range and varies between 5.1 and 6.1. The pH of the base fluid reduced with an increase in temperature in a similar manner reported by Konakanchi *et al* [21] on the pH of PG–water, 60:40 base fluid. Although the addition of PKF nanoparticles to the base fluid gave a higher pH value compared to the base fluid, increasing the temperature from 10 to 60°C showed a continual decrease in the pH value. The temperature increase influences the pH of any solution due to the dissociation of the weak acids’ and bases’ groups and splitting of water component into H⁺ and OH[−] [22]. In figure 6b, the relative pH of the nanofluid increased as the volume fraction is increased up to a point corresponding to where counterion condensation effects set in at 0.3%. At this point, the rate of increase of pH reduced as the volume fraction increased. A similar phenomenon of counterion condensation relating to electrical conductivity and pH of nanofluids was observed previously by Adio *et al* [22].

4. Theoretical models

There are not much established theoretical models that may be applicable for the prediction of the effective viscosity of nanofluids. The few available models are derived from the well-known Einstein model [23]. Although nanofluid is a two-phase fluid, most of its thermophysical properties defied the already established features in solid–liquid

mixtures such as microfluids. Therefore, the applicability of the classical theoretical models to predict nanofluids’ thermo-physical properties remains tentative and uncertain. Below are some of the widely used classical models for nanofluids.

The established work of Einstein [23] on the dilute suspensions of uncharged hard spheres was the pioneering theoretical study on the viscosity of suspensions which proposed the model in equation (1). Einstein’s work is applicable for very dilute volume fractions, $\phi \leq 2\%$.

$$\mu_{\text{eff}} = \mu_o(1 + [\eta]\phi) \quad (1)$$

where μ_{eff} is the effective viscosity of the suspension, μ_o the viscosity of the base fluid and $[\eta]$ the intrinsic viscosity taken as 2.5. Brinkman [24] extended Einstein’s formula for use with a moderate particle concentration as

$$\mu_{\text{eff}} = \mu_o(1 - \phi)^{-2.5} . \quad (2)$$

Also, Batchelor [25] while extending Einstein’s work considered the effect of interparticle interactions on the viscosity of suspension to obtain the model given in equation (3). The model is expected to be stable for the prediction of the viscosity of suspensions having volume fraction, $\phi \leq 4\%$. In the limit of very low-volume fraction, this model approaches equation (1), that is at low particle volume fraction, the assumption of the noninteraction of particles, as assumed by Einstein [23], is also inherently considered:

$$\mu_{\text{eff}} = \mu_o(1 + [\eta]\phi + k_H([\eta]\phi)^2) \quad (3)$$

where k_H is Huggin’s coefficient, also known as the interaction parameter. This coefficient accounts for interparticle interaction. Krieger and Dougherty [26] proposed a semi-empirical model for shear viscosity covering the full-range of particle volume fractions, and it is expressed as

$$\mu_{\text{eff}} = \mu_o \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m} \tag{4}$$

where ϕ_m is the maximum volume fraction that allows fluid flow to occur still, and the intrinsic viscosity $[\eta]$ was taken as 2.5 for monodispersed suspensions of hard spheres.

Largely, the inconsistencies in the reports of the viscosity of nanofluids have been mostly attributed to agglomeration of the nanoparticles in a suspension. Therefore, Chen *et al* [27] considered agglomeration of the nanoparticles and modified the work of Krieger and Dougherty [26] to arrive at equation (5). They considered the agglomerates as spherical and of different sizes. Based on the maximum packing fraction of agglomerates and the fractal index of the agglomerates, which is an indication of the degree of variation in the

packing fraction from the centre of the agglomerates to the outer edge.

$$\mu_{\text{eff}} = \mu_o \left(1 - \frac{\phi_a}{\phi_m}\right)^{-[\eta]\phi_m} \tag{5}$$

ϕ_a is the agglomerate volume fraction which is given by $\phi_a = \phi/\phi_{ma}$, where ϕ_{ma} is the packing fraction of the agglomerates. Considering the fractal index of the agglomerate, D , ϕ_a can be expressed as $\phi_a = \phi(a_a/a)^{3-D}$, where a_a/a is the ratio of the effective radii of aggregates and the primary nanoparticles. Namburu *et al* [28] proposed empirical viscosity correlation considering the temperature and nanoparticle volume fraction, and is given as

$$\log \mu_{\text{eff}} = Ae^{-BT} \tag{6}$$

where the empirical constants A and B are polynomial functions of the nanoparticle volume fraction.

In this paper, the experimental volume fraction is within the stability region of Einstein’s equation (i.e., $\phi < 2\%$) and other

Table 1. Correlation coefficients for equation (8).

Coefficient	Equation (8)
a_1	42.2527
a_2	3313.4286
a_3	3455.6426
α	0.9770
β	0.9796

Table 2. Statistics on the accuracy of model in equation (8).

Statistical parameters	Equation (8)
R^2	0.9419
SSE	0.1672
MSE	0.0033
RMSE	0.0578

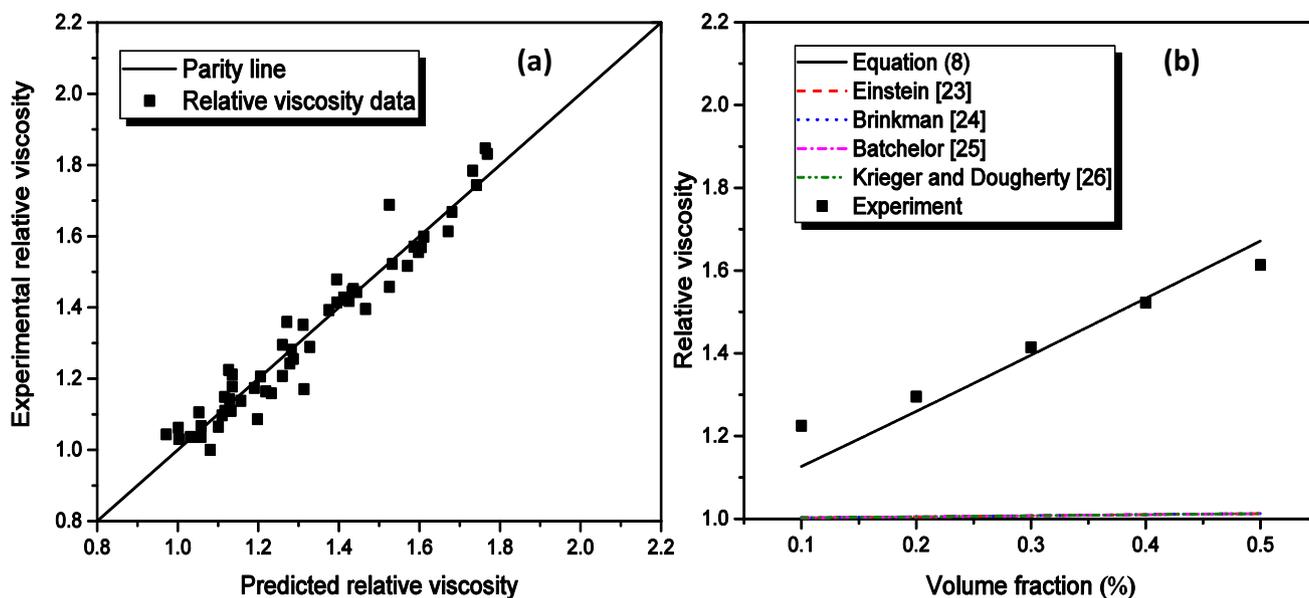


Figure 7. Model performance in predicting the viscosity of PKF-EG/water nanofluids: (a) parity plot between the experimental data and the model (equation (8))-predicted relative viscosity and (b) comparison between the present model and some prominent viscosity models.

prominent classical models. However, when these models were used to predict the present experiment, they underestimated the experimental data, and this will be shown in what follows. By using the methods of dimensional analysis, the experimental data have been accurately predicted. Based on the methodology employed by Adio *et al* [29], the nondimensional parameters for the PKF-based nanofluids are presented in equation (7). The function f in equation (7) is obtained using nonlinear regression and presented in equation (8):

$$\pi_1 = \frac{\mu_{\text{eff}}}{\mu_o} = f\left(\pi_2 = \frac{T}{T_0}, \pi_3 = \phi\right), \quad (7)$$

$$\frac{\mu_{\text{eff}}}{\mu_o} = 1 + a_1\phi + a_2\phi^\alpha \left(\frac{T}{T_0}\right) + a_3\left(\phi\frac{T}{T_0}\right)^\beta \quad (8)$$

where a_i , α and β are correlation coefficients presented in table 1.

The parity plot between the experimental data and the predicted results of equation (8) shows good agreement as shown in figure 7a. Table 2 shows the statistics of the accuracy of the correlations. Figure 7b shows the comparison between the prominent classical models used for nanofluid viscosity prediction and the proposed model (equation (8)) on their performance in estimating the present experimental data. From figure 7b it is evident that the proposed model gave a better estimation compared to the classical models. Equation (8) considered both particle volume fraction and temperature while the classical model only considered the volume fraction.

5. Conclusion

In this paper, a top-bottom approach was used to produce nanoparticles from a PKF biomass material using a ball-milling machine at room temperature. The PKF nanoparticles had an average size of 40 nm and were dispersed in an EG/water (50:50) mixture to produce a nanofluid with the volume fraction ranging from 0.1 to 0.5%. No surfactant was added to the sample before, during and after the preparation. The thermophysical properties such as viscosity, electrical conductivity and pH response to volume fraction were studied for a temperature range of 10–60°C. The values obtained from some of the notable classical models were different from the data in the present experiments.

The viscosity of the nanofluid increased with an increase in volume fraction and reduced exponentially with an increase in temperature. The pH and electrical conductivity increased with increasing volume fraction of the PKF nanoparticles. The pH of nanofluid reduced with an increase in temperature while the electrical conductivity increased with temperature increase. The notable theoretical models used in predicting nanofluid viscosity were unable to estimate the

viscosity of the PKF–EG/water nanofluid in the present case. Therefore, an empirical correlation based on dimensional analysis was proposed to estimate the viscosity of the PKF–water/EG nanofluids.

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