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Experimental investigation and model development for effective viscosity of MgO–ethylene glycol nanofluids by using dimensional analysis, FCM-ANFIS and GA-PNN techniques☆

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ABSTRACT

Desirable effective viscosity behaviour is an essential transport property required for the effective utilisation of nanofluids in industrial systems as well as other applications. Viscosity influences significantly the pumping power and heat transfer effectiveness in a thermal system since Reynolds and Prandtl numbers are functions of viscosity. In this study, the optimum energy required for the preparation of MgO–ethylene glycol (MgO–EG) nanofluids was determined by varying the ultrasonication energy input into the preparation process. The uniformly dispersed nanofluids were characterised and the viscosity measurements were carried out as a function of temperature (20 to 70 °C), nanoparticle volume fraction (0 to 5%) and nanoparticle size (~21, ~105 and ~125 nm). Based on the experimental data, the effective viscosity of all the samples irrespective of nanoparticle size or volume fraction, decreases exponentially with increase in temperature and the trend is similar to that of the base fluid, but in different magnitude. Increasing the volume fraction of the MgO nanoparticles showed a corresponding increase in the effective viscosity of the nanofluid. It was also noticed that the samples containing 21 nm MgO showed higher effective viscosity compared to samples containing 105 and 125 nm MgO when the volume fraction is constant. The viscosity values in the present study quite differ from the values predicted by the existing prominent viscosity models as well as the existing models do not consider all the variables of present data (temperature, nanoparticle volume fraction and nanoparticle size). Therefore, new correlation is proposed using the method of dimensional analysis and considering essential factors, including nanoparticle size, volume fraction temperature, capping layer thickness, viscosity of the base fluid, the density of base fluid and the density of nanofluid as input parameters. Furthermore, genetic algorithm-polynomial neural network (GA-PNN) and fuzzy C-means clustering-based adaptive neuro-fuzzy inference system (FCM-ANFIS) were used to model the effective viscosity of the MgO–EG nanofluids considering the parameters mentioned above. The results of all the modelling techniques showed good agreement with the experimental data.

1. Introduction

In recent times, energy efficient systems have shared features which are portability, compactness and lightness in weight. These systems, such as mobile electronics, microelectromechanical systems (MEMs), nanoelectromechanical systems (NEMs) and power generating systems/devices are commonly used in major industries such as the electronics, energy, and transportation. Moreover, these systems are designed to perform more efficiently and have higher throughput than the previous systems which are massive, non-portable and heavy. The ratio of the increased throughput/efficiency to size is accompanied with thermal management challenges due to their high power density. The classic methods of improving heat transfer include an increase in heat transfer surface area (adding fins) and/or increasing convective heat transfer coefficient which they both have limitations. Other emerging methods such as geometric optimization of heat exchangers and the use of functionally graded materials, also have major setbacks. For instance, using extended surface increases the bulkiness of heat exchangers which contradicts the new design philosophy of attaining sustainable development and global energy sustainability. On the other hand, the use of functionally graded materials raises economic concerns because of the high price of functionally graded materials.

Nanofluid is a modified heat transfer fluid produced by homogenising nanoparticles in conventional heat transfer fluids such as water or ethylene glycol (EG). Research findings have shown that nanofluids have improved thermal properties such as thermal conductivity, heat capacity and convective heat transfer coefficient [1,2]. Heat transfer fluid that possesses higher thermal conductivity provides better heat removal capacity and also could support the reduction

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of the size and weight of heat exchanger in line with the global sustainable development and energy sustainability. Therefore, as the next-inline heat transfer fluid, nanofluid has received a considerable interest from the time when its thermal properties were first reported. Eastman et al. [3] investigated the thermal conductivity of Cu-EG nanofluids. They dispersed Cu nanoparticles having a mean diameter less than 10 nm in EG using a single-step procedure. Their results showed up to 40% enhancement in thermal conductivity of the Cu-EG nanofluid compared to the base fluid (EG) for a Cu volume fraction of 0.3% and thioglycolic acid was used as a pH modifier in order to improve the stability of the Cu-EG nanofluids. Kang et al. [4] showed that the enhancement obtainable from the dispersion of ultra-dispersed diamond nanoparticles (UDD) with 30–50 nm size in EG was up to 50% at 1% volume fraction. They also showed that for 8–15 nm silver (Ag) dispersed in water at 0.4% volume fraction, there was enhancement of 10% in thermal conductivity. Similar results for other types of nanofluids were reported by Murshed et al. [5] and Das et al. [6].

The presence of particles in a fluid medium creates increased resistance to flow of nanofluids due to intensified energy dissipation rate arising from the interactions between the particles and particle-fluid. Therefore, the problem of viscosity increase with an increase in the suspended volume fraction of nanoparticles is a major challenge that requires extensive investigations experimentally, besides, there exist the lack of models that can accurately predict the viscosity of nanofluids. If this problem is not properly understood and tackled, it may diminish the efficacy of nanofluids in practical applications [7]. In the past, the influence of nanoparticle dispersion on the viscosity of nanofluids has been investigated for some nanofluids as summarised below. Chandrasekar et al. [8] used microwave assisted technique to synthesise Al_2O_3 nanoparticles having an average particle size (APS) of 43 nm. They dispersed 0.33 to 5% volume fractions of the Al_2O_3 in deionised water (DI-water) and investigated their viscosity enhancement at room temperature. Their results showed a staggering viscosity increase of 136% at the suspension of 5% Al_2O_3. Fedele et al. [9] investigated the effective viscosity of DI-water based TiO_2 nanofluid with TiO_2% weight between 1 to 35 wt.% and temperature range of 10–70 °C. They also observed a very high viscosity increase of 243% at 35 wt.% of TiO_2 suspended.

To improve the viscosity of nanofluids, stability of nanoparticles in the base fluid must be ensured and there are about three effective methods that have been used viz.: (i) addition of surfactant, (ii) pH modification, and (iii) ultrasonic vibration. Timefeeva et al. [10] showed that modifying the pH of α-SiC/water nanofluid provided good stability for the 29 nm SiC nanoparticles in the base fluid and eventual reduction in the effective viscosity up to 34%. Zhao et al. [11] also observed that the viscosity of SiO_2-water nanofluid is significantly influenced by the pH value of the suspension. Li et al. [12] stabilised 25 nm Cu-water nanofluids using pH and/or sodium dodecylbenzensulfonate (SBDS) chemical surfactant. Although, they only measured thermal conductivity, the influence of surfactant was such that it reduced the nanoparticle agglomerate size when applied in right proportion [13]. Song and Youn [14] showed that poor dispersion can increase the effective viscosity of carbon nanotube (CNT)-epoxy nanocomposite and as a result, they used ultrasonic vibration to aid proper dispersion and minimise viscosity enhancement. Yang et al. [13] varied the energy of ultrasonication applied to the dispersion of multiwall carbon nanotubes (MWCNTs) in poly (α-oleifin) oil in order to obtain proper homogenisation of the MWCNTs at which point the viscosity was minimised.

A good nanofluid is supposed to have high thermal conductivity to be very efficient in thermal management (heat removal), and minimum viscosity in order to minimise pressure drop and pumping costs. Viscosity plays a major role in determining pumping power requirement of any heat exchanger, thus, precise knowledge of the nanofluids' viscosity behaviour is important [15]. Also, a key problem with nanofluid's research is the estimation of the effective viscosity of nanofluids. Einstein's model [16] showed that the viscosity of colloidal suspensions of spherical particles increases as the volume fraction of suspended particle increases, however the Einstein's model just involve the volume fraction and base fluid viscosity. Brinkman [17], Krieger and Dougherty [18] and Batchelor [19] all modified Einstein's model to show the effect of particle–particle interactions and concentrated volume fraction on the effective viscosity of suspension of solid spheres. However, the effect of size and temperature is not included in the abovementioned models. Therefore, these models have underperformed in most cases when used for predicting the viscosity of nanofluids [20].

Xie et al. [20] discovered that MgO–EG nanofluids formulated from 20 nm MgO have higher thermal conductivity and lower viscosity enhancements than those of ZnO–EG, SiO_2–EG, Al_2O_3–EG and TiO_2–EG all formulated from a similar particle size of their respective nanoparticles. Recently, Hemmat Esfe et al. [21] investigated the influence of different MgO nanoparticle sizes (20, 40, 50 and 60 nm), temperatures (25–55 °C) and volume fractions (0.25–5%) on the thermal conductivity of MgO–EG nanofluids and proposed a correlation for predicting the thermal conductivity of the nanofluids. To the best knowledge of the authors there is no study on the viscosity of ethylene glycol based nanofluids containing MgO, which proposes new correlations including particle size, temperature and volume fraction as parameters. In view of this, the viscosity of MgO–EG nanofluids is investigated experimentally considering various particle sizes, volume fractions and temperatures. The measured data are compared with the predictions of different prominent models existing in the literature which show no agreement. Therefore, an empirical-based correlation is developed using the method of dimensional analysis. Furthermore, fuzzy C-means clustering-based adaptive neuro-fuzzy inference system (FCM-ANFIS) and genetic algorithm-polynomial neural network (GA-PNN) modelling techniques [22] are applied for modelling and predicting the effective viscosity of MgO–EG nanofluids as a function of nanoparticle diameter, temperature and nanoparticle volume fraction.

2. Experimental

The two-step method was employed to prepare the MgO–EG nanofluid samples used in the present work. The nanoparticle APS is ~21, ~105 and ~125 nm, to be represented as MgO-I, MgO-II and MgO-III respectively. The transmission electron microscopy (TEM) image and particle size distribution (PSD) of the MgO nanoparticles are as shown in Fig. 1. Presented in Fig. 2 are the X-ray diffraction (XRD) and energy-dispersive spectroscopy (EDS) characterisations for the three nanoparticle samples. The EG used, was procured from Merck Millipore and has 99.5% purity, and viscosity of 16.9 mPa·s at 25 °C. No surfactant or pH modifier was added in the samples used for viscosity investigations since they were all stable.

To achieve good dispersions in the present study, the required optimum energy density (to form homogeneous nanofluids) was investigated by using a Hielscher UP200S ultrasonicator. The energy densities of 2.183×10^6 kJ/m^3 to 13.092×10^6 kJ/m^3 were applied to the samples and the nanofluid consistency was monitored by viscosity measurements. This is a well-known procedure, to use rheology to characterise the state of dispersion of nanostructures in base fluids [14]. Programmable constant temperature thermal bath (LAUDA ECO RE1225) was used to vary the temperature of the samples within the experimental range (20 to 70 °C). The viscosity of the samples was measured with a vibro-viscometer (SV-10, A&D, Japan) with 5.0% uncertainty at full range. The viscometer was calibrated using pure EG at 25 °C and benchmark test were carried out between 20 and 70 °C. The result of the benchmark test as presented in Fig. 3 shows good agreement with values reported by Xie et al. [20] and Pastoriza-Gallego et al. [23] within the present experimental uncertainty. A more detailed step-by-step experimental procedure can be found in Adio et al. [24].