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On the evaluation of the viscosity of nanofluid systems: Modeling and data assessment

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ABSTRACT

Viscosity of nanofluids can significantly affect pumping power, pressure drop, workability of the nanofluid as well as its convective heat transfer coefficient. Experimental measurements of this property for different nanoparticles and base fluids at various temperatures is cumbersome and expensive. In this communication, a comprehensive review of the most important modeling works on viscosity of nanofluids including theoretical models, empirical correlations, and computer-aided models is conducted. Next, four multilayer perceptron (MLP) models optimized with Levenberg-Marquardt (LM), Bayesian Regularization (BR), Scaled conjugate gradient (SCG), and Resilient Backpropagation (RB), two radial basis function (RBF) neural network models optimized with Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), and one least square support vector machine (LSSVM) model optimized with coupled simulated annealing (CSA) were developed for the prediction of nanofluid viscosity based on 3144 data points. These data sets include 42 nanofluid systems under a wide range of operating conditions; including temperature from −35 to 80 °C, particle volume fraction from 0% to 10%, nanoparticle size from 4.6 to 190 nm, and viscosity of base fluid from 0.24 to 452.6 cP. Then, these seven models were combined in a single model using a committee machine intelligent system (CMIS). The proposed CMIS predicts all of the data with excellent accuracy with an average absolute relative error of less than 4%. Furthermore, the developed model was compared with five theoretical models and four empirical correlations through statistical and graphical error analyses. The results demonstrate that the proposed CMIS model significantly outperforms all of the existing models and correlations in terms of accuracy and range of validity. Finally, the quality of the experimental data was examined both graphically and statistically and the results suggested good reliability of the experimental data.

1. Introduction

Rapid advances in nanotechnology led to the invention of nanofluids in 1995 with a pioneering work by Choi [1] based on Maxwell's [2] study on colloidal suspensions. Nanofluids are colloidal dispersions of solid nanoparticles in a base fluid. The nanometer-sized particles can be metals (Ni, Cu, Al, Ag, Au, etc.), metal oxide (NiO_2, CuO, Al_2O_3, TiO_2, Fe_3O_4, Fe_2O_3, etc.), nonmetals (Si, Graphene, single and multi-wall carbon nanotube [SWCNT and MWCNT], etc.), and other particles ($CaCo_3$, SiC, SiO_2, AlN, Al_2Cu, Ag_2Al, etc.). Nanofluids can be water-based hydrosols or oil-based organosols, e.g. ethylene glycol (EG), engine oil, transformer oil, propylene glycol, etc. or mixture of two or more heat transfer fluids [3,4]. Hybrid nanofluids consist of either two or more type of nanoparticles dispersed in a base fluid or a suspension of hybrid (composite) nanoparticles in a base fluid [5–8]. Nanoparticles are very small in size (1–100 nm) and have very large specific surface area. Due to this unique characteristic, nanofluids display remarkable properties such as enhanced thermal conductivity, long-term stability, minimal clogging in flow passages, and homogeneity [9]. These properties of nanofluids make them extremely attractive for various applications; including heat transfer, pollution control, transportation, lubrication, solar energy, energy storage, nanodrug delivery, enhanced oil recovery, drilling fluids, reduction of fines migration, filtration loss control, wettability alteration and inhibition of asphaltene precipitation [10–32].

To select a nanofluid for any particular application, it is essential to determine its thermophysical properties including viscosity, thermal conductivity, density, and specific heat. Among the different properties of nanofluids, viscosity is very important since it describes the resistance of fluid to flow, and hence impacts many other phenomena;

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including heat and mass transfer within the fluid. For industrial applications, the viscosity of nanofluids can significantly influence pumping power, its workability, pressure drop, and the convective heat transfer coefficient [33,34]. Suspension of nanoparticles into the base fluid changes the dynamic viscosity. Over the past two decades, many investigations have been conducted to evaluate the viscosity of different types of nanofluids over wide range of experimental conditions; including temperature, concentration of nanoparticles, shear rate, nanoparticle size and shape, pH, and electrical conductivity. Moreover, many review articles by Mahbubul et al. [35], Sundar et al. [4], Meyer et al. [3], Azmi et al. [36], Raja et al. [37] and Basherizadeh et al. [38], Akilu et al. [8], Gupta et al. [39] have summarized the effect of these factors on nanofluids viscosity. Literature sources agree that the addition of nanoparticles into conventional base fluid increases the viscosity of the fluid with a monotonic increase in the viscosity with increasing particle concentration [40–51]. Moreover, the viscosity of nanofluids increases with decreasing temperature [10,33,50,52–55], although some studies report that the relative viscosity of nanofluids (viscosity of nanofluid over viscosity of its base fluid) is independent of temperature [41–43]. Similarly, most literature reported an increase in nanofluid viscosity with decreasing particle size [56–60] or a decrease in nanofluid viscosity with increase in particle size [40,61,62] with only few exceptions showing particle size-independent viscosity [43].

Experimental determination of nanofluid viscosity at different temperatures and particle sizes and concentrations is time consuming and expensive [63,64]. Subsequently, existing literature models can be used to estimate nanofluid viscosity. In general, nanofluid viscosity models can be classified into three major groups; namely theoretical models, empirical correlations, and numerical models [3]. In this study, almost all of the available experimental data, the most important theoretical models, empirical correlations, and computer-aided models pertaining to nanofluid viscosity systems are thoroughly reviewed. The performance of theoritical models and empirical correlations is gauged against the experimental data in order to evaluate their accuracy over a wide range of experimental conditions. In addition, the quality of the experimental data is gauged based on different statistical approaches.

1.1. Theoretical Models

Different theoretical models for estimating the viscosity of suspended particles into a fluid have been developed based on the fundamental work by Einstein [65]. According to Einstein model the viscosity of a nanofluid varies linearly with the volume fraction of the hard spheres [65]. It is applicable at infinite dilution ($\varphi < 2\%$) of uncharged hard spheres. The model is expressed as:

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi) \tag{1}$$

where μ_{nf} is the viscosity of nanofluid and μ_{bf} denotes the viscosity of the base fluid.

Brinkman [66] proposed modified Einstein's formula as shown in Eq. (2) below and extended the applicability of the model to $\varphi < 4\%$.

$$\mu_{nf} = \mu_{bf}(1 - \varphi)^{-2.5} \tag{2}$$

Considering Brownian motion of isotropic suspension of rigid spherical particles as well as the effect of the interaction between particles, Batchelor [67] developed the following model:

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi + 6.5\varphi^2) \tag{3}$$

Lundgren [68], based on Taylor series expansion of dilute concentrations of random bed of spheres, proposed a mathematical expression as follows:

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi + 6.25\varphi^2 + f(\varphi^3)) \tag{4}$$

Thomas and Muthukumar [69] considered three-body hydrodynamic effects and developed the following formula for predicting the viscosity of a suspension of spheres:

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi + 4.83\varphi^2 + 6.4\varphi^3) \tag{5}$$

In addition to the above equations, other theoretical models were developed over the years by Roscoe [70], Krieger and Dougherty [71], Graham [72], Saito [73], and Frankel and Acrivos [74]. Most of the abovementioned models are based on particle volume concentration and employed many simplifications in order to reach a presentable solution. Currently, there is no unified theoretical model able to estimate the viscosity of suspensions over the whole range of particle concentration, and major differences between experimental and predicted values are routinely reported [3].

1.2. Empirical models

With the advent of nanofluids, many empirical models in the form of simple mathematical correlations have been developed by fitting experimental data. Maiga et al. [75] used experimental data of Al_2O_3-water nanofluid to develop an empirical correlation applying the least-square curve fitting. Maiga et al.'s model is given in Eq. (6) as below:

$$\mu_{nf} = \mu_{bf}(1 + 7.23\varphi + 123\varphi^2) \tag{6}$$

Chen et al. [42], through investigating the viscosity of TiO_2-ethylene glycol nanofluid, developed the following correlation:

$$\mu_{nf} = \mu_{bf}(1 + 10.6\varphi + 10.6\varphi^2) \tag{7}$$

Sundar et al. [49] developed an empirical correlation for the prediction of Fe_3O_4-water nanofluid viscosity in the volume concentration ranging from 0.0% to 2.0% and temperature ranging from 20 °C to 60 °C. The developed correlation is expressed as:

$$\mu_{nf} = \mu_{bf}\left(1 + \frac{\varphi}{12.5}\right)^{6.356} \tag{8}$$

Meybodi et al. [76], by considering 701 viscosity data points for Al_2O_3, TiO_2, SiO_2 and CuO-water nanofluids, proposed a correlation as a function of nanoparticle size (S), volume fraction and temperature as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{(133.54064976 - 343.82413843 \times \exp(\varphi/S) + 290.11804759 \times (\exp(\varphi/S))^2 - 78.993120761 \times (\exp(\varphi/S))^3)}{\left(0.91161630781 + 32.33014233\frac{Ln(S)}{T} - 11.732514460\frac{(Ln(S))^2}{T}\right)} \tag{9}$$

There are also other empirical correlations available in the literature developed in the recent years based on experimental observations such as the correlations proposed by Nguyen et al. [61], Godson et al. [77], Garg et al. [78], Abu-Nada et al. [79], Hosseini et al. [80], Esfe et al. [81], Sekhar and Sharma [82] and Kole and Day [83]. Most of these empirical correlations have been developed based on experimentally measured data with limited experimental conditions (i.e. a few type of nanoparticles, confined range of particle concentration, temperature, and size). Some of these empirical correlations have been tested before and results showed that these models displayed high deviations from the experimental data [64,76,84,85]. Therefore, none of these models can be considered as a general model to predict viscosity of different types of nanofluids at various conditions.

1.3. Computer-aided models

By using the high computational power of the soft computing approach, several estimation methods have been developed in the recent years for estimation of thermophysical properties of nanofluids; including the viscosity of nanofluids. Karimi et al. [86] introduced an artificial