International Communications in Heat and Mass Transfer 73 (2016) 114–123

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Viscosity of nanofluids: A review of recent experimental studies☆

Kazem Bashirnezhad [a], Shahab Bazri [b], Mohammad Reza Safaei [b], Marjan Goodarzi [b], Mahidzal Dahari [c], Omid Mahian [b,*], Ahmet Selim Dalkılıça [d], Somchai Wongwises [e]

[a] *Department of Mechanical Engineering, Islamic Azad University, Mashhad Branch, Mashhad, Iran*
[b] *Young Researchers and Elite Club, Islamic Azad University, Mashhad Branch, Mashhad, Iran*
[c] *Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50630, Malaysia*
[d] *Heat and Thermodynamics Division, Department of Mechanical Engineering, Faculty of Mechanical Engineering, Yildiz Technical University (YTU), Yildiz, Besiktas, Istanbul 34349, Turkey*
[e] *Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok 10140, Thailand*

ARTICLE INFO

Available online 2 March 2016

Keywords:
Nanofluids
Viscosity
Experimental studies

ABSTRACT

During the past decade, nanotechnology with its rapid development has grabbed the attention of scientists, scholars, and engineers. Nanofluids are one of the surprising outcomes of this technology that could increase the efficiency of thermal systems remarkably. Nanofluids containing solid nanoparticles have a higher viscosity than common working fluids; hence, measuring the viscosity is necessary for designing thermal systems and estimating the required pumping power. In the current review study, an attempt has been made to cover the latest experimental studies performed on the viscosity of nanofluids. An experimental investigation is very vital for the analysis since the theoretical models usually underestimate the nanofluid viscosity. Through experiments, the real effects of volume fraction, temperature, particle size, and shape on the viscosity of nanofluids will be determined.

1. Introduction

The basic idea of particle-dispersed fluid can be traced back to Maxwell's study in 1873 [1]. Afterward, in 1904, he indicated that the molecule that has nano-scaled diameter could be considered as starting the striking technology of nano. From that time up to now, the rapid development of nanotechnology has been seen in all aspects [2,3]. Accordingly, nanofluid introduced as a new term, indeed, defined for the first time as liquids having nanometer-sized particles, emerged after Choi innovative work in 1995, which has been the pioneer one [2,4–7]. Before design a thermal system in which a nanofluid is the working fluid, it is necessary to know the thermophysical properties of nanofluid including thermal conductivity, viscosity, heat capacity, and density. Among the nanofluid properties, viscosity is an important property since it indicates the fluid's resistance. With increasing the viscosity, the required energy for pumping and mixing increases. Also, pumping power and pressure drop are two key factors that depend on viscosity [7]. Many parameters affect the nanofluid viscosity including preparation method, base fluid type, temperature, particle size and shape, volume concentration, acidity (pH value), shear rate, surfactants, and particle aggregation [2]. The aim of this paper is to review the latest experimental studies conducted on viscosity of nanofluids by considering the abovementioned parameters.

2. Nanofluid definition and applications

Nanofluids, as an innovative material, are solid–liquid mixtures in which the solid particles have usually a size more than 1 nm and less than 100 nm [8–9]. The particles could be metal particles such as Al, Cu, and Ni; oxides such as Al_2O_3, TiO_2, CuO, SiO_2, Fe_2O_3, and Fe_3O_4; and some other compound materials such as AlN, SiC, and graphene [2,10–11]. Nanofluids are new generation of heat transfer fluids with an anomalous behavior, which are taken from stably suspending colloidal nanoparticles in the original fluids (conventional heat transfer liquids). Nanofluids can be applied in various devices and systems such as cooling electronic components, transportation, industrial cooling, heating buildings, medical systems, reducing pollution, nuclear systems cooling, atomic engineering, space and defense, energy storage, solar absorption, friction reduction, magnetic sealing, antibacterial activity, nano-drug delivery, intensify micro reactors, microbial fuel cells, and so on [12–15].

☆ Communicated by Dr. W.J. Minkowycz.

* Corresponding author.
E-mail address: omid.mahian@mshdiau.ac.ir (O. Mahian).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.02.005
0735-1933/

Nomenclature

μ_r	Relative viscosity
μ_{eff}	Effective viscosity
μ_{bf}	Base fluid (liquid) viscosity
μ_{nf}	Nanofluid viscosity
ϕ	Volume fraction
ϕ_m	Maximum volume fraction
T	Temperature
$\dot{\gamma}$	Shear rate
r_a	Particle aggregate

3. Preparation and characterization

3.1. Preparation of nanofluids

There are some significant primary steps before using nanofluids in a specific application, first of all, is preparation step, and latter is the measurement of properties to estimate the well verification of nanofluids' performance. In other words, the method of nanofluids' preparation has a momentous effect on the properties. There are two fundamental methods for the fabrication of nanofluids: one-step method or chemical synthesis technique or single-step direct evaporation method in which particles are formed directly in the base liquid. Later is two-step method in which the nanoparticles are synthesized by different methods and then are dispersed into the base liquid. Two most imperative characteristics of the prepared nanofluid are (i) stable suspension without sedimentation during a long time and (ii) non-agglomeration [16–19].

3.2. Characterization techniques

The methods for characterization of the structural properties of nanoparticles to estimate the chemical nature, size, and the morphology as well as the size of agglomerations are called characterization techniques. Here are all usable methods in most of the studies, including transmission electron microscopy (TEM) using wet-TEM technique to assess the dispersion state, x-ray diffraction (XRD), vibration sample magnetometer (VSM), energy-dispersive x-ray spectroscopy (EDX), thermal analysis TG-DTA, UV–Vis spectroscopy, Fourier transform infrared spectroscopy (FTIR), infrared absorption spectroscopy, scanning electron microscopy (SEM), and inductively coupled plasma–optical emission spectroscopy (ICP-OES) [6,17,20].

4. Predicted models and theories of nanofluids viscosity

There are some existing formulas and models to estimate the viscosity of nanofluids.

1- Einstein model (1906): The Einstein model [21–22] is the pioneer theory and mostly referred equation to predict the viscosity of nanofluids, which predicts and assumes only very low nanoparticle concentrations ($\varphi \leq 2\%$) and linearly viscous fluid having dilute, suspended, and spherical particles for. The model is stated as [23]:

$$\frac{\mu_{nf}}{\mu_{bf}} = [1 + 2.5\phi]. \tag{1}$$

In 1911, Einstein also presented a correlation of zero-shear viscosity [24].

2- Brinkman (1952) (by modifying Einstein Model): Brinkman [25] extended and modified the Einstein's model to volume concentration up to 4.0% to be useful for reasonable particle volume concentrations [23]:

$$\frac{\mu_{nf}}{\mu_{bf}} = \left[\frac{1}{(1-\phi)^{2.5}}\right]. \tag{2}$$

3- Krieger and Dougherty (K-D) (1959): Krieger [26] derived a semi-empirical relation for the shear viscosity that covered the full range of particle volume concentration, known as K-D model [27]:

$$\mu_{nf} = \mu_{bf}\left(1-\left(\frac{\phi}{\phi_m}\right)\right)^{-[\eta]\phi_m} \tag{3}$$

where φ_m is the maximum particle fraction, which varies from 0.495 to 0.54 under quiescent conditions and is approximately 0.605 at high shear rates.

4- Frankel (1967): In 1967, Franken and Acrivos [28] developed a mathematical expression [29]:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{9}{8}\left[\frac{\left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}}{\frac{(\phi_m-\phi)^{\frac{1}{3}}}{\phi_m^{\frac{1}{3}}}}\right]. \tag{4}$$

5- Nielsen (1970): Nielsen [30] proposed the power law model, in 1970, to determine the viscosity of nanofluids corresponding to the particle volume concentration more than 0.02, and here is the suggested mathematical equation [27,31]:

$$\mu_{nf} = (1 + 1.5\phi)e^{\frac{\phi}{(1-\phi_m)}}\mu_{nf}. \tag{5}$$

6- Lundgren (1972): Lundgresn [32] proposed the following formula to predict the suspension viscosity under the form of a Taylor series in terms of [29]:

$$\mu_{nf} = \mu_{bf}\left(1 + 2.5\phi + \frac{25}{4}\phi^2 + f\left(\phi^3\right)\right). \tag{6}$$

7- Batchelor (1977): Batchelor [33] considered the effect due to the Brownian motion of particles for an isotropic suspension of rigid and spherical particles [29]:

$$\frac{\mu_{nf}}{\mu_{bf}} = \left[1 + 2.5\phi + 6.5\phi^2\right]. \tag{7}$$

8- Graham (1981): Graham [34] developed a comprehensive outline of Frankel–Acrivos model by introducing particle radius and inter-particle spacing which has good agreement with Einstein's formula for small φ. The model is expressed as follows [29]:

$$\mu_{nf} = \mu_f\left(1 + 2.5\phi + 4.5\left[\frac{1}{\left(\frac{h}{d_p}\left(2+\frac{h}{d_p}\right)\right)\left(1+\frac{h}{d_p}\right)^2}\right]\right). \tag{8}$$

9- In 1981, Kitano et al. [35] proposed a simple correlation to predict the viscosity of a two-phase suspension [27]:

$$\mu_{nf} = \frac{\mu_f}{\left[1-\left(\frac{\phi}{\phi_m}\right)\right]^2}. \tag{9}$$

10- White (1991): Notice that all above correlations or models were developed only based on viscosity as a function of volume fraction; to clarify; there is no consideration of temperature dependence. However, viscosity has a strong function with the temperature; in