International Journal of Heat and Mass Transfer 127 (2018) 997–1012

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Review

A comprehensive review on rheological behavior of mono and hybrid nanofluids: Effective parameters and predictive correlations

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ARTICLE INFO

Article history:
Received 15 March 2018
Received in revised form 3 June 2018
Accepted 20 July 2018

Keywords:
Nanofluid
Enhanced heat transfer
Experimental
Rheological behavior
Mono and hybrid nano-additives

ABSTRACT

Nanoparticles are an evolution in improving heat transfer by fluids that have the good potential for heat transfer. Thus, in the last two decades, interest in researching them has increased dramatically. It has been proved that the thermophysical properties of nanofluids are different from those of common fluids. One of these properties is viscosity, which has a significant contribution to the calculation of the fluid heat transfer. In the present study, a brief introduction of nanofluid and its applications have been discussed in the first. Then, the classical equations suggested for predicting the viscosity of nanofluids and their accuracy have been reviewed. The role of effective parameters on the nanofluid viscosity has also been reported, indicating an increase in the viscosity of the common fluids by increasing the nano-additives volume fraction and reducing it with increasing temperature. For the effect of increasing nano-additives size, different results (decreasing or increasing) on fluid viscosity have been reported. The effect of changing the type of nano-additives has also been described for a variety of metal/metal oxides nanoparticles, and nanomaterial extracted from nature. In addition, nanofluids made with carbon nanotubes are described according to the high heat transfer coefficient. Finally, the introduction of hybrid nanofluid and their comparison with mono nanofluids has been explained by the conclusion that hybrid nanofluids can well cover nanofluid weaknesses and improve its strengths.

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.103
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Nomenclature

T	temperature (°C)
d	diameter
Subscripts	
nf	nanofluid
bf	base fluid
P	particle
eff	relative (nf/bf)
f	fluid
Greek letters	
γ	shear rate (1/s)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
τ	shear stress (Pa)
φ	volume concentration (%)

1. Introduction

In recent years, the advancement of nanofluids-related technologies has attracted the attention of many researchers. Researchers have focused to study in many scientific fields, including energy, air conditioning, electronics and microelectronics, transportation, new energies, medicine, as well as energy and fuel management with the help of nanofluids [1–10]. Most of this research has focused on the study of thermophysical properties of nanofluids and the application of dramatic changes in the properties. What is the basis of making this type of fluids is the application of the thermal conductivity of suspended solids in a fluid; and therefore, it is obvious that most research, since the construction of the first nanofluid, was on the changes in the thermodynamic properties, in particular the thermal conductivity [11–16]. On the other hand, the application of a nanofluid in a fluid flow system requires knowledge of fluid flow properties, especially its viscosity. Therefore, researchers began researching nanofluids viscosity to compute pumping power required for applications of nanofluids in the heat exchangers [17–21]. Although, compared with studies on thermal conductivity, the volume of studies conducted on viscosity has been much lower; but recently, with regard to the importance of the cost-effectiveness parameter of using nanofluids, studies on the viscosity have increased in parallel with the studies on the thermal conductivity [22–27].

Nanofluids usually increase the viscosity compared with the base fluids. This increase will be incremental by adding a volume percentage of nanoparticles. Existing classic relationships and models do not have the ability to describe or predict the nanofluids behavior. In other words, the most of proposed tentative relations to predict the viscosity of nanofluids are based on experimental and laboratory data of the same nanofluid and are not suitable for other types of nanofluids (Section 2.1). There are also numerous measurement disparities and inconsistencies between the experimental data on the viscosity of nanofluids [28–30]. Even for a type of nanofluid, the viscosity from the measurements of different researchers is significantly different with each other which will be discussed in the next sections. However, such inconsistency and disparity in the results can be due to different issues, for example, the application of different size and nanoparticles purity degree, applique measuring instruments or respective geometry, the range of shear rate, the scale of accumulation, disparity and preparation of samples, and materials. In addition, among the studies conducted, the effect of nanoparticle concentrations on the viscosity of nanofluids has been mostly investigated. In addition to the concentration of nanoparticles, the study of the effects of other factors such as temperature, base fluids, disparity, particle size, type and shape on viscosity is also important.

Despite the high viscosity, most nanofluids perform better for heat transfer from ordinary liquids used as the base fluid of the same nanofluid. Among the research on improving the heat transfer in heat exchangers, one of the low-cost and accessible ways is adding a material with a high thermal conductivity to the base fluid. In general, nanoparticles are from metals such as copper, aluminum, potassium, silicon and their oxides, as well as carbon nanotubes; and base fluids are also mainly from liquids with a relatively lower conductivity such as water, ethylene glycol (EG), motor oil. Nanoparticles are much more stable than larger particles, such as micro-particles, and have more contact surface. Also, due to the small size of the nanoparticles, the corrosion and pressure drop are greatly reduced, as well as the precipitation. Various methods have been studied for the preparation of nanofluids, but often one-step and two-step methods are used to produce nanofluids [31–35].

The following is a summary of the methods that are more widely used. One of the common methods for production of nanofluids is a two-step method. It is a physical method that involves the addition of solids in nanoscale to the base fluid. Due to the fact that today's industries produce enough nano-powder on a commercial scale, this method has grown widely. There are various methods for making nanoparticles, the most commonly used of which is the gas phase condensation method. In this method, nanoparticles or nanotubes are usually prepared in the form of dry powder using a Chemical Vapor Deposition (CVD) method. In the next step, the nanoparticle or nanotube is dispersed inside the fluid. For this, methods such as ultrasonic vibrations or surfactants are used to minimize nano-clustering and improve dispersion of nanoparticle. The two-step method is very suitable for some cases, such as metal oxide in deionized water, and has been less successful for nanofluids, including heavy metal nanoparticles. One of the advantages of nanofluids' production in a two-step process by Inert Gas Condensation (IGC) method, is to minimize the nano-clustering.

The one-step method generally has a chemical basis. One-step method has also been developed in parallel with the two-step method; for example, nanofluids containing metal nanoparticles are prepared using direct evaporation. In this method, the metal source is evaporated under vacuum conditions.

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