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Empirical and theoretical correlations on viscosity of nanofluids: A review

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ABSTRACT

In the past decade nanotechnology has developed in many directions. Nanofluid is a mixture of nanosized particles dispersed in fluids. Nanofluids are new generation heat transfer fluids used in heat exchangers for energy conservation. Viscosity is an important property particularly concerning fluids flowing in a tube in heat exchangers. In this regard, an attempt has been made to review the available empirical and theoretical correlations for the estimation of viscosity of nanofluids. The review also extended to preparation of nanofluids, nanoparticle volume concentration, nanofluid temperature, particle size and type of base fluid on viscosity of nanofluids. The available experimental results clearly indicate that with the dispersion of nanoparticles in the base fluid viscosity increases and it further increases with the increase in particle volume concentration. Viscosity of nanofluid decreases with increase of temperature.

Contents

1. Introduction

Conventional heat transfer fluids such as water, engine oil, transformer oil, ethylene glycol and propylene glycol play an important role in many industries such as power generation, chemical production, air-conditioning, transportation, microelectronics etc. Several heat transfer enhancement techniques are used to improve the heat transfer rate of such fluids. Those techniques are change of flow geometry and boundary conditions; improving thermophysical properties of fluids like increase of thermal conductivity is used. Thermal conductivity of solids is higher than fluids. Because of high thermal conductivity of solids, many studies

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have been conducted on the thermal behavior of solid particles dispersed in fluids. The existing classical models available in the literature for the estimation of thermal conductivity of solid–fluid mixtures are Maxwell's [1] and Hamilton–Crosser model [2], but there is no experimental evidence to prove these models.

Dispersion of ultrafine magnetic solid particles in the fluids was first introduced by Akoh et al. [3] who also estimated their magnetic properties. Later, Ahuja [4] measured the thermal conductivity and viscosity of 50 μm and 100 μm polystyrene spheres dispersed in aqueous sodium chloride and glycerin and obtained 3 times thermal conductivity enhancement compared to base fluid. Both the above mentioned researches considered microsize particles and also observed particle agglomeration in the base fluids. In a similar way researchers like Choi and Tran [5] and Choi et al. [6,7] at Argonne National Laboratory, USA, have developed advanced fluids for industrial applications, including district heating and cooling systems and they also found particle agglomeration in the base fluid. Masuda et al. [8] also used ultrafine particles of Al_2O_3, SiO_2 and TiO_2 dispersed in fluids for the estimation of thermal conductivity and viscosity and found better enhancement. Even though, they found better enhancement with dispersion of particles, they also observed particles agglomeration in the base fluid. The problem of particle agglomeration is solved by Choi [9] and his team by inventing nanometer sized solid particles in fluids called as 'nanofluid'. For the preparation of nanofluids, commonly used nanoparticles are metals (Al, Ag, Cu, Ni etc.), metal-oxides (Al_2O_3, CuO, Fe_2O_3, Fe_3O_4, SiO_2, TiO_2 etc.), some other compounds (Al_2Cu, Ag_2Cu, Ag_2Cu, Ag_2Al, AlN, SiC, graphene, carbon nanotubes etc.) and commonly used base fluids are water, ethylene glycol, propylene glycol, transformer oil, engine oil etc.

Many experimental investigations are available for thermal conductivity enhancement of nanofluids. Lee et al. [10] considered Al_2O_3 and CuO nanofluids and found better thermal conductivity enhancement compared to base fluid. Choi et al. [11] observed 160% thermal conductivity enhancement with CNTs dispersed in synthetic poly(α-olefin) oil at 1.0% volume concentration.

The thermal properties of nanofluids like thermal conductivity, viscosity, density and specific heat are very important, before introducing the nanofluids in devices like heat exchangers and condensers. Based on the solid–fluid homogeneous models, the properties like density and specific heat can be estimated. The other properties like thermal conductivity and viscosity can be estimated experimentally. For a nanofluid flowing in a tube or any equipment viscosity of the fluid plays an important role, because Reynolds number of the fluid depends on viscosity. Viscosity explains the internal resistance between the fluid layers. In the laminar flow or turbulent flow, the pressure drop of the fluid is directly proportional to the viscosity of fluid and it also influences the convective heat transfer coefficient. So, viscosity is also a very important property like thermal conductivity, whenever a system is involved in a fluid flow [12].

In recent years, lot of research progressed on the nanofluids related to thermal conductivity [13–22], forced convective heat transfer in a tube [23–32], forced convective heat transfer in a tube with inserts [33–41], natural heat transfer [42–44], mixed convection [45], boiling heat transfer [46–50], heat exchangers [51–55], solar flat plate collectors [56–58], car radiators [59], slip mechanism [60], electrical conductivity [61], cooling of electronic devices [62]. Some review papers [63–66] have emphasized on the thermal conductivity of nanofluids. Very few review papers are available on the viscosity of nanofluids [67].

During experimental investigations on viscosity of nanofluids, Pak and Cho [68] investigated the viscosity of TiO_2/water and Al_2O_3/water nanofluids and observed 3% and 200% enhancement respectively compared to base fluid. Masuda et al. [69] measured the viscosity of TiO_2 27 nm nanofluid and found 60% enhancement at 4.3% volume concentration compared to water. Bobbo et al. [70] investigated the viscosity of SWCNT/water and TiO_2/water nanofluids and found 12.9% and 6.8% enhancement at 1.0% volume concentration at 283 K respectively. Lee et al. [71] estimated the viscosity of Al_2O_3/water nanofluid and observed 2.9% enhancement at 0.3% volume concentration at a temperature of 21 °C. Wang et al. [72] estimated the viscosity of Al_2O_3 and CuO nanoparticles dispersed in water, vacuum pump fluid, engine oil and ethylene glycol and found 30% enhancement with Al_2O_3/water nanofluid at 3% volume concentration. They also reported that the enhancement of viscosity is similar in Al_2O_3/water nanofluid and Al_2O_3/ethylene glycol nanofluid. Chadwick et al. [73] studied the rheological behavior of titanium dioxide (uncoated anatase) in ethylene glycol and found viscosity enhancement with increase of particle volume concentration. Kwak and Kim [74] observed thermal conductivity and viscosity enhancement with CuO nanoparticles dispersed in ethylene glycol. Teipel and Forter-Barth [75] prepared paraffin oil and hydroxyl hydroxyterminated polybutadiene (HTPB) oil based aluminum nanofluid and observed that paraffin oil/aluminum suspensions exhibit non-Newtonian flow behavior over a wide range of concentrations, whereas the HTPB/aluminum suspensions exhibit Newtonian behavior up to 50% volume concentration. Katiyar et al. [76] prepared paraffin oil based Fe–Ni nanofluid and measured the viscosity in the 10% weight concentration. Prasher et al. [77] observed the viscosity enhancement for Al_2O_3/propylene glycol nanofluid; Chen et al. [78] found the viscosity enhancement for TiO_2/water, TiO_2/ethylene glycol nanofluid, TNT/water nanofluid and TNT/ethylene glycol nanofluids; Murshed et al. [79] observed the viscosity enhancement for ethylene glycol based TiO_2 and Al_2O_3 nanofluids.

The application of water based nanofluids is limited in subzero countries like Alaska, Canada, Northern Europe and Russia, because water can freeze at 0 °C. This can be overcome by adding small ratio of ethylene gylcol or propylene gylcol to water. By adding these fluids to water the freezing point of water can be reached to −35 °C. Kulkarni et al. [80] first time measured the convective heat transfer and viscosity of 60:40% ethylene glycol and water mixture based CuO, Al_2O_3 and SiO_2 nanofluids and also evaluated the performance of these nanofluids in the heating buildings in cold regions. Naik and Sundar [81] also prepared CuO nanofluids by considering 70:30% propylene gylcol/water mixture as a base fluid for the estimation of thermal conductivity and viscosity enhancement. Sundar et al. [82] prepared 50:50% ethylene glycol/water mixture based Al_2O_3 and CuO nanofluids for the estimation of thermophysical properties.

In the available literature most of the researchers have explained the viscosity of nanofluids with the effect of volume concentration and temperature. Some review papers discussed the viscosity of nanofluid but they mostly concentrated on the thermal conductivity of nanofluids. Review papers like Das et al. [83] have given the importance of nanofluid viscosity, Keblinski et al. [84], Daungthongsuk and Wongwises [85] mentioned the viscosity of nanofluid for convective heat transfer, Sridhar and Satapathy [86] have given the importance to viscosity of Al_2O_3 based nanofluids. The mentioned reviews are not sufficient for completely understanding the viscosity behavior of nanofluids. In this regard a complete study is required to cover all the aspects of viscosity of nanofluids.

In this regard, the present review paper focuses on viscosity of different kinds of nanofluids, with effects of base fluids, volume concentration, temperature, particle size, theoretical models and developed correlations.

Absolute viscosities of different commonly used fluids are summarized in Table 1. The available literature on viscosity of nanofluids with various parameters is shown in Table 2.