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Investigation of Nanoparticles Morphology on Viscosity of Nanofluids and New Correlation for Prediction

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Abstract

This article presents an experimental investigation on effects of morphology of nanoparticles on the viscosity nanofluids (NFs). Water and ethylene glycol were used as base fluids. A two step method was used for preparation of NFs. SiO2 nanoparticles, CNT and graphene nano sheets were dispersed in the base fluids separately with the volume fraction ranging from 0.05% to 1.5%. Stability of the nanoparticles was established by adding adequate surfactant and sonication enough time. Then viscosity of the NFs was measured by Brookfield viscometer at fix ambient temperature. First, it has been concluded that, viscosity of NFs increases significantly with increasing of nanoparticle volume fraction. Then the results of theoretical models (Einstein, Brinkman, Batchelor and Wang) were compared with experimental data and the deviation of theme was calculated. In order to reduce of this deviation, a correlation was developed based on the geometry of nanoparticles. The modified models showed reasonably better agreement with the experimental results.

1. Introduction

Nanofluids (NFs), suspension of nanoparticles in water, ethylene glycol, oil and other basic fluids capable of providing a significant enhanced heat transfer behavior compared to conventional fluids. Many kinds of metal or metal oxide nanoparticles (Cu, CuO, Al2O3, TiO2, Fe3O4, SiO2, TiO2, ZnO) and nano carbon structures (SWNT, MWNT, Graphene, diamond) are used

as additives of NFs. Each of these nanoparticles has different morphology which shows the special behavior in fluid. There are also various potential advantages from NFs testing namely: superior long stability, thermal conductivity compared to micro suspensions, less pressure drop and erosion particularly in micro channels. Though, there are still major application prospects in advanced thermal applications, they remain in the early stages of development. In comparison with the works carried out on thermal conductivity of NFs, only a few studies have been reported on the rheological behavior of NFs. However, prior to use NFs for heat transfer, considerable knowledge about their thermo physical properties is required, mainly their thermal conductivity and viscosity. Therefore, viscosity is one of the necessary properties of NFs to determine the thermal behavior in order to use of it in industrial applications, such as cooling systems or exchangers as a new type of heat transfer fluids.

Specifying the viscosity of NFs is very important factor for determining pumping power as well as the heat transfer coefficient and also Prandtl and Reynolds numbers are functions of viscosity and influence of it [1]. The viscosity is the vital factor in dynamic behavior of NFs for heat transfer applications as the pressure drop. Viscosity determination of NFs is possible from both experimental and theoretical methods. A review of relevant experimental data about viscosity of NFs may be found in the measurement of CNT/water viscosity, prepared by using surfactant and acid oxidation [2], effect of metallic nanoparticles in viscosity of NFs and thermal conductivity [3,4]. the viscosities of diamond/EG, silver/water, and silica/water NFs was measured and founded the viscosity increment of 50%, 30% and 20% at volume concentrations of 1%, 2% and 3%, for the NFs respectively [5]. Viscosity of TiO2/water and Al2O3/water NFs was measured and reported a maximum increase of 80% at 4% and 5% volume fraction, respectively [6]. Similar increments in viscosity were reported earlier [3,4,7]. Rheological behavior of CuO/EG and water based nanofluid was presented over temperatures ranging of 35~50°C [1]. Prasher et al. founds a 30% increase in viscosity of propylene glycol at 3% volume fraction of alumina and relates this phenomenon to aggregation of the nanoparticles in base fluid with the size of the aggregates of around three times the size of the individual nanoparticles [8]. Nguyen et al. experimentally investigate the effect of particle volume fraction on the viscosity for an Al2O3/water and founds significant increase in viscosity with particle volume fraction [9]. Kwak and Kim established that huge thermal conductivity enhancements are accompanied by sharp viscosity increases at low volume fractions of nanoparticle, which is a reasonable result of aggregation effects [10].

There are discrepancies in the temperature dependency of viscosity of NFs. There are reports showing increase in viscosity with temperature [8,11-13] and decrease in viscosity with temperature [14] Apart from these, many results were reported temperature independency the viscosity of NFs [15,16]. In some studies, it has been reported that temperature had no effect on viscosity of NFs. For example at a fixed volume fraction of ZnO in EG, with increasing temperature, the viscosity of NFs does not significantly change but highest increase observed in viscosity of ZnO/EG is 30% at 5 vol % of ZnO. Complete study on the changes occurring in NFs with respect to the size distribution, Motion of nanoparticles and charge of particle surface during difference in temperature is required to recognize the temperature effects on viscosity of NFs. But generally temperature does not affect on morphology of nanoparticles.

While the effect of morphology of nanoparticles in thermo physical properties of NFs have not well been investigated.

2. Nanofluids Viscosity Models

Even though many models have been developed to predict the NFs viscosity, all presented models can be classified into two general groups, as follows:

- Static models, which presume immobile nanoparticles in the host fluid in which conduction-based models predict the viscosity of NFs
- Dynamic models, which are based on the idea that nanoparticles have sideways, arbitrary movement in the fluid. The particle motion is believed to be responsible for energy transport directly through collision between nanoparticles or indirectly through micro liquid convection that enhances the thermal energy transfer.

On the other hand four groups of NFs were categorized for the rheological behavior as [15]:

(i) Dilute NFs ($\varphi<0.1\%$) whose viscosity fits Einstein model and there is no visible shear-thinning behavior. Applicable for spherical nanoparticles when there is no interaction between themes

(ii) Semi dilute NFs ($\varphi=0.1\sim5\%$) whose viscosity fits Brinkman equation and there is no visible shear-thinning behavior with aggregation of nanoparticles [17] Also when the particle concentration further increases to the maximum packing fraction, this model can be used to estimate the viscosity of NFs [18]

(iii) Semi concentrated NFs ($\varphi=5\sim10\%$) whose viscosity fits Batchelor model and there is visible shear-thinning behavior with aggregation of nanoparticles. Brownian motion of the nanoparticles and the interaction between them was taken into account in this model and it is an extension of the Einstein model.

(iv) Concentrated NFs ($\varphi>10\%$- out of the normal concentration range for NFs) with interpenetration of aggregation [14,19] whose viscosity fits Wang model which is an exponential model for $\varphi>35\%$

Based on these classifications, there are many theoretical models to calculate viscosity of NFs. A few of the commonly models are listed in Table 1.

Since most NFs are used in low concentrations the following models have considered for the viscosity usually mentioned in the literature for NFs, Brinkman is currently used in literature [20-22] and Batchelor's model given by [23]. It is noted that other classical models for calculating the viscosity of mixture also yield similar results [6] But these models have limitations in applications [8,24].

2.1. Proposed correlations

The morphology factor of nanoparticles is not considered by above theoretical models. Thus, these models do not distinguish particles with different geometries. While effect of fluid viscosity changed by changing the geometry of nano particles, Therefore impact of nanoparticles increases on the viscosity with increasing the dimension of nanoparticles. Also, it is related to diversity exposure of nanoparticles within fluid relative to each others. If the dimension of nanoparticles is more, then the number states of nanoparticles can be greater relative to each other. Consequently, their influence increases on the viscosity of the base fluid. Therefore, by considering morphology factor of nanoparticles in such models try to be effective them from geometry of nanoparticles and then increasing their accuracy of results. For this purpose first amount of effect of nanoparticle geometry on

Table 1. Most applicable theoretical models for viscosity of NFs

Model	Equation	Reformed Equation
Einstein	$\mu_{nf} = (1+2.5\varphi)\mu_f$	$\mu_{nf} = (1+2.5\phi)\mu_f$
Brinkman	$\mu_{nf} = \mu_f/(1-\varphi)^{2.5}$	$\mu_{nf} = \mu_f/(1-\phi)^{2.5}$
Batchelor	$\mu_{nf} = (1+2.5\varphi+6.2\varphi^2)\mu_f$	$\mu_{nf} = (1+2.5\phi+6.2\phi^2)\mu_f$
Wang	$\mu_{nf} = (1+7.3\varphi+123\varphi^2)\mu_f$	$\mu_{nf} = (1+7.3\phi+123\phi^2)\mu_f$

viscosity will considered proportional to the amount of nanoparticles in fluid. In this study, a geometric correlation of nanoparticles was added in common models as follows. The correlation was related to different shape of nanoparticles

$\phi = \varphi * (1 - \mathrm{D/L})$

Where the fraction D/L is morphology factor of nano particles which is a special value for particles with different geometries and the values are presented in table 2.

Table 2. Proposed Geometry factor of different nano particles

Dimension	Geometry	D/L	1-D/L
0D	spherical	0.21	0.79
1D	cylindrical	0.11	0.89
2D	sheet	0.01	0.99

3. Preparation of Nano Fluids

Since silica, CNT and graphene have 0D, 1D and 2D nano structures respectively. In thecurrent study, these three kinds of nanoparticles which have different geometry were dispersed in water and EG as base fluids separately. CNTs were synthesized by catalytic chemical vapor deposition (CCVD) method [25], graphene were synthesized by chemical vapor deposition (CVD) method [26] and silica nanospheres were synthesized by wet chemical methods [27]. Transmission electron microscope (TEM) was used to approximate the size and shape of the nanoparticles. This method is commonly used by a wide range of researchers [28,29]. Fig. 1 shows the TEM of the nanoparticles.

Fig. 1 shows that the SiO2 nanoparticles have spherical shape with the average diameter of 10 nm CNT have cylindrical structure with external diameter of less than 10 nm, and average length is about 10 micron and graphene have sheets structure with average size of 60 nm. In this experimental study, a two-step method was used to prepare water and EG based nanofluid containing the nanoparticles with different volume fraction at three ranges of 0.5, 1.0 and 1.5%. After adding the nanoparticles in to base fluids, the suspensions were subjected to ultrasonic vibrator for 45 min in order to reduce the particle agglomeration and get a uniform dispersion and a stable suspension. To prepare stable NFs, optimum concentration of SDBS was used, and this concentration was experimentally determined 1.5 times of that of the nanoparticles inside the NFs. A Specification of samples is given in Table 3.

4. Viscosity measurement

Kinematic viscosity of the NFs was measured using Brookfield viscometer. Fig. 2 illustrates the experimental set up for measuring viscosity. The set up consists of a temperature bath equipped with accuracy of 0.1% of range and 0.01% repeatability which meets ASTM D-445-04 standard. Two bubbles viscometer was used for black NFs.

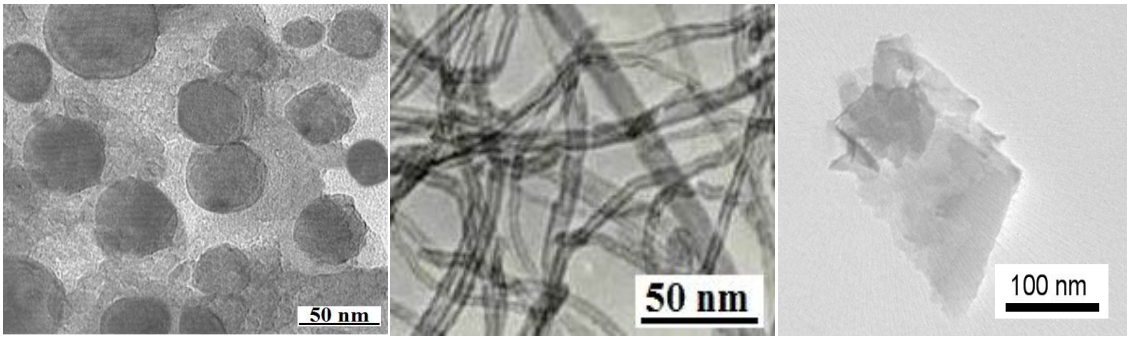

Fig. 1. TEM of a) SiO_2 b) CNT c) Graphene

Table 3. Name and Specification of Nanofluids

Dime.	Shape	NPs	Base fluid	Volume Fraction (%)	Sample Name
0D	Spherical	SiO_2	water	0.5	S/W-1
				1.0	S/W-2
				1.5	S/W-3
			EG	0.5	S/EG-1
				1.0	S/EG-2
				1.5	S/EG -3
1D	Cylindrical	CNT	water	0.5	CNT/W-1
				1.0	CNT/W-2
				1.5	CNT/W-3
			EG	0.5	CNT/EG-1
				1.0	CNT/EG-2
				1.5	CNT/EG-3
2D	Sheet	Graphene	water	0.5	G/W-1
				1.0	G/W-2
				1.5	G/W-3
			EG	0.5	G/EG-1
				1.0	G/EG-2
				1.5	G/EG-3

First the viscometer was calibrated with water and EG at ambient fix temperature. The results were repeated three times for each sample to assure its repeatability, and then the average was recorded. Dynamic viscosity was calculated by multiply kinematic viscosity in the density of NFs and the value was reported as viscosity of the NFs. Many models of viscosity have been used by the researchers to estimate the viscosity of NFs as a function of nanoparticle volume fraction. In this investigation, Einstein, Brinkman, Batchelor and Wang models have been used for comparing the predicted viscosity with the measured data. Fig. 3 shows the comparison between prediction of the models and the modified models with experimental data for viscosity of NFs.

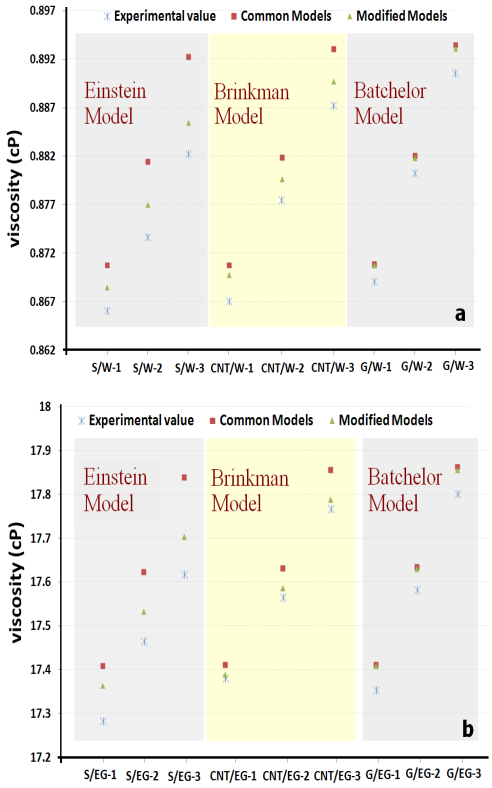

Fig. 3. Deviation of models and modified models with experimental viscosity of a) water base NF b) EG base NFs

Table 4. Summary of the samples viscosity value

Sample Name	Model	Experimental value	Error Model (%)	Error Modified Model (%)
S/W-1	Einstein	0.8661	0.54	0.28
S/W-2		0.8737	0.89	0.38
S/W-3		0.8823	1.13	0.36
S/EG-1		17.283	0.73	0.47
S/EG-2		17.465	0.92	0.40
S/EG-3		17.618	1.26	0.49
CNT/W-1	Brinkman	0.8671	0.43	0.31
CNT/W-2		0.8775	0.50	0.25
CNT/W-3		0.8873	0.66	0.27
CNT/EG-1		17.381	0.18	0.05
CNT/EG-2		17.565	0.38	0.13
CNT/EG-3		17.768	0.50	0.12
G/W-1	Batchelor	0.8691	0.21	0.19
G/W-2		0.8803	0.20	0.17
G/W-3		0.8906	0.32	0.28
G/EG-1		17.353	0.34	0.33
G/EG-2		17.582	0.30	0.28
G/EG-3		17.801	0.35	0.31
G/W-1	Wang	0.8691	2.87	2.83
G/W-2		0.8803	6.03	5.93
G/W-3		0.8906	9.81	9.65
G/EG-1		17.353	3.01	2.97
G/EG-2		17.582	6.14	6.05
G/EG-3		17.801	9.85	9.69

It can be seen that the predicted viscosity by the modified model is in excellent agreement with measured viscosity for all of studied nanoparticles and volume fractions. As can be seen in table 2, all of these theoretical correlations are unable to accurate predict viscosity of the samples in all considered volume fractions. Although, the results show that the viscosities of NFs agree well with the Modified Models. Einstein, Brinkman and Batchelor models predicted viscosity higher than actual values but Wang model has more error than other models to predict the viscosity of NFs. Also it is observed that with increasing aspect ratio of nanoparticles and changes in their geometry, the deviation of models increases than experimental data.

5. Conclusion

In this study, experimentally viscosity of water and EG based NFs was investigated. The NFs were containing nanoparticles with different geometry. First, SiO_2, CNT and Graphene nanoparticles were provided and dispersed in water and EG separately. After that, the various NFs with different concentrations from 0.05 to 1.5 vol % were prepared by ultrasonication. Viscosity of the NFs was measured by using Brookfield viscometer apparatuses with temperature bath in fix ambient temperatures for each sample.The results showed that the viscosity increases nonlinearly with the increase in nanoparticles concentration, and the maximum value of viscosity belonged to maximum volume fraction of Graphene in EG. Based on geometrical shape of nanoparticles, a new correlation for estimating the viscosity was proposed. The experimental data was in an excellent agreement with correlations, which have been presented in this investigation. The modified models can well predict viscosity of the NFs. It can be observed that the maximum

value of deviation is about 9.69% for 1.5 vol% of graphene nanoparticles in modified Wang equation which this value is 9.85% for Wang model.

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