A Review on Viscosity of Nanofluids

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Abstract: - *In this paper, we have discussed about the viscosity of nanofluids for enhancement in viscosity. There are two types of nanofluids discussed, one of the metallic and another of the non-metallic and researcher also findings the observations of the analyzed nanofluids. Different types of viscosity models are discussed. The effects of nanoparticles concentration and temperature on nanofluids viscosity have been clearly reviewed. The result shows that the effect of concentration and temperature on nanofluids viscosity, the nanofluids viscosity decreases with rising of temperature or increases with increment in nanoparticles concentration.*

Keywords- Nanofluids, Preparation of nanofluids, Viscosity models, Nanoparticles

I. Introduction

Nanofluid is a most important fluid for improving the heat transfer efficiency. The heat transfer efficiency can be improved by using of different types of technologies and different methods like use of vibration, extended surfaces and micro channels and some fluids are also improved the efficiency of heat transfer (EG, water and engine oil). Heat transfer is useful in many applications like vehicles, electronic equipments, chemical reactor, nuclear reactor, air conditioning systems, ventilating etc. In forced convective heat transfer system, the power consumption can reduce through a pump and increment in heat transfer efficiency [1]. In 1995, Choi [2] described a new heat transfer fluids and used these base fluids for improving the thermophysical properties. By suspension or dispersion of nanoparticles, we can achieve the highest thermal properties at smallest concentration. Common the heat transfer fluids are metallic like Al, Fe, Cu, Ag, Au and oxides like Al_2O_3, Fe_2O_3, ZnO, CuO, SiO_2, TiO_2 and polymeric particles. The issue of clogging can be solved by using nano-sized particles along with base fluids and dispersions of nanoparticles & these suspensions are called nanofluids. Nanofluids are used to improve the thermophysical properties and these thermophysical properties like viscosity, specific heat and thermal conductivity. Researchers gave less attention on the nanofluids viscosity (44%) as compared to the thermal conductivity (56%). Viscosity was found to be an important thermophysical property of nanofluids and it is mainly used in petroleum engineering and chemical engineering. The different parameter that affects the nanofluid viscosity are particle shape and size, preparation method of nanofluids, temperature, volume concentration, surfactants, base fluid, shear rate, particle aggregation and pH value. The rheological characteristics of nanofluids found that the all viscosities of nanofluids higher than their base fluids and increased with increasing nanoparticle concentrations. Mainly, an improved synthesis methodology is essential for making steady suspensions of particles in base fluids. Nanofluids properties are dependent on the stability of dispersion using different types of methods such as zeta potential, ultrasonication etc. [3-4]

II. Preparation of nanofluids

Mainly two methods are used for preparing the nanofluids and the methods are- One-step method and Two-step method:

One-step method: - In single step method, the particles are directly dispersed in base fluid, so it is called single step method. In single-step method, only used a single step, the nanoparticles dispersed into base fluid [5]. Nanofluid is formed by solidification of the nanoparticles in base fluid. In this method, some processes like storage, drying, dispersion and transportation are avoided, so that constancy of fluids is increased and the agglomeration of nanoparticles is minimized. This method is used to produce nanoparticles. The benefit of this method is reduces the aggregation effects, but it is only suitable for low vapour pressure fluids. Different types of techniques and methods used for preparation of nanofluids like liquid chemical method, physical vapour deposition, direct evaporation system etc. [6].

Two-step method: - This method is important method for preparation of nanofluids. In this method, first of all, being synthesis of particles and after that the nanoparticles dispersed into base fluid. Two-step method is useful for produced nanoparticles in large quantity. In this method, different method like mechanical, chemical and physical are used for preparing nanopowders and mixed with base fluids. For minimize the agglomeration [5] of nanoparticles, sonicators and vibrators are used for a better solution. This method is useful for oxide nanoparticles suspension. In this method, it is easy to produce the nanofluids and one can easily control the size distribution and particle concentration. Xuan and Li et al. [7] explained that the nanofluids (Cu/Water) used with volumetric concentration and used surfactant (sodium dodecyl benzoic sulphate). The result shows that the nanofluids heat transfer performance affects with surfactant.

III. Parameters affecting the viscosity of nanofluids

These parameters are affecting the nanofluids viscosity like temperature, volume concentration, shear rate, nanoparticles size and shape, pH value and electrical conductivity of suspension, base fluid. Namburu et al. [8] explained that the Newtonian behavior of nanofluid (CuO) and the result shows that the nanofluids viscosity decreases with rising of temperature and nanoparticles content also decrease. Zennifer et al. [9] expressed results that the nanofluids viscosity decreases with rising of temperature and the ratio of viscosity increased with temperature. Sundar et al. [10] studied that the weight % of nanoparticles effect the nanofluid viscosity and nanofluids viscosity increases with increment in particles concentration and shows improvement in viscosity. Suresh et al. [11] shows result that the nanofluids viscosity increases with increment in concentration of nanoparticles. Halelfadl et al. [12] expressed that the nanofluids (CNT) viscosity performed with particles loading.CNT nanofluids performed at high particle loadings as materials (shear-thinning) and the lower particle performed as Newtonian fluids. Kwak and Kim [13] investigated that the behavior of CuO nanoparticles with volume fraction and the CuO nanoparticles show generally in the structure of aggregates and show the behavior of shear-thinning for particle concentration higher than 0.1 vol%.

IV. Viscosity models for Nanofluids

Different researchers developed various models for determining the viscosity of particle suspensions. Classical and empirical models are discussed in literature.

Classical models:

Hatschek [14] developed a viscosity model for two phase systems at 40% concentration of solid particles,

$$\mu_{eff} = \mu_{f(1+4.5\varphi)} \qquad (1)$$

Similarly, Roscoe [15] proposed a viscosity model for high to low all concentrations and it is developed a model of viscosity,

$$\mu_{eff} = \mu_{f\left(1-\frac{\varphi}{\varphi_m}\right)} - 2.5 \qquad (2)$$

Brenner and Condiff [16] proposed a model in 1974, this model of viscosity developed for high shear rate & volume fraction up to $1/r^2$,

$$\mu_{eff} = \mu_{f(1+J\varphi)} \qquad (3)$$

Krieger and Dougherty [17] expressed a model of effective viscosity for suspensions & volumetric concentration of spherical particles,

$$\mu_{eff} = \mu_{f\left(1-\frac{\varphi}{\varphi_m}\right)} - [\mu]\varphi_m \qquad (4)$$

Empirical models:

Noni et al. [18] developed a modified model of viscosity for ceramic suspensions and this model depends upon volumetric concentration of solid particles,

$$\mu_{nf} = \mu_f\left(1 + b\left(\frac{\varphi}{1-\varphi_m}\right)^n\right) \qquad (5)$$

After that, Chandrasekar et al. [19] proposed the Noni et al.'s model at same specification,

$$\mu_{nf} = \mu_f \times 13.47e^{35.98\varphi} \qquad (6)$$

Frankel and Acrivo 0 proposed that the maximum volume concentration of particle with experimental value,

$$\mu_{nf} = \mu_{bf} \frac{9}{8} \left[\frac{\left(\frac{\varphi}{\varphi_m}\right)^{\frac{1}{3}}}{1-\left(\frac{\varphi}{\varphi_m}\right)^{\frac{1}{3}}} \right] \quad (7)$$

Chen et al. [21] proposed a model for spherical particles and modified the Krieger and Dougherty model,

$$\mu_{nf} = \mu_f \left(1 - \frac{\varphi}{0.605} \left(\frac{a_a}{a}\right)^{1.2}\right)^{-1.5125} \quad (8)$$

Chevalier et al. [22] also modified the Krieger and Dougherty model and expressed a model with their experimental results,

$$\mu_{nf} = \mu_f \left(1 - \frac{\varphi_a}{\varphi_m}\right)^{-2} \quad (9)$$

Williams et al. [23] expressed the two correlations with their results of viscosity of nanofluids for Al_2O_3/Water and ZrO_2/Water,

$$\mu_{nf} = \mu_f \times \exp\left[\frac{4.91\varphi}{0.2092-\varphi}\right] \quad (10)$$

V. Theoretical and experimental studies on viscosity of nanofluids

A literature survey of the studies performed by the researchers on nanofluids using theoretical and experimental studies of various metallic & non metallic nanofluids:-

Carbon nanotubes nanofluids

Kinloch et al. [24] explained that the rheological behavior of nanofluids (CNT/Water) and the nanofluids dispersion easily at all CNT volume concentration and show shear thinning behavior. The result shows that the nanofluids viscosity increase with increment in nanoparticles concentration. Yang et al. [25] investigated that the effects of nanofluids (MWCNT) loading, ultrasonication and surfactant on the viscosity of nanofluids. The results show that the surfactant (Polyisobutene succinimide) control the dispersant of nanofluids viscosity and the nanofluids viscosity increase with increases of MWCNT nanoparticle concentrations. Ko et al. [26] explained that the nanofluids (CNT) were prepared with addition methods & surfactant (SDS) used and measured the nanofluids viscosity (CNT). The result shows that the nanofluids (CNT) viscosity decrease with increases of shear rate and the nanofluids viscosity increase with increases of shear rate. Chen et al. [27] explained that the effect of nanoparticles concentration (0.4%) and temperature (55ºC) on viscosity nanofluids. The result shows that the viscosity of nanofluids increases with higher concentration (0.4%) of nanofluids & viscosity decrease with rising of temperature. Hung and Chou [28] explained that the effect of nanoparticles (MWCNT) concentration & chitosan dispersant on nanofluids viscosity. The result shows that the nanofluids viscosity increases with both nanoparticles (MWCNT) concentration and chitosan dispersant. The maximum enhancement in viscosity 233% at 1.5 wt %. Harish et al. [29] explained that the nanofluids (SWCNT) viscosity with surfactant (Sodium deoxycholate). The result shows that the nanofluids viscosity decrease with rising of temperature & the viscosity of nanofluids 30% increase with increases of SWCNT nanoparticles concentration. Vakili-Nezhaada and Dorany [30] explained that the nanofluids (SWCNT) viscosity measured at different temperatures (25ºC to 100 ºC). The enhancement in viscosity 33% at 0.2 wt% concentration.

Alumina nanofluids

Masuda et al. [31] explained that the nanofluids (Al_2O_3) viscosity measured and used volume concentration (4.3%) of nanoparticles. The result shows that the nanofluids viscosity increased 250% at 305 K of temperature. Similarly, Pak and Cho [32] show in their results the viscosity of nanofluids (Al_2O_3) increased 150% at 2.78 vol% of nanoparticles concentration. The maximum improvement in viscosity at 10 vol% of concentration. Wang et al. [33] explained that the viscosity of nanofluids measured of Al_2O_3/Water & ethylene glycol nanofluids and used volume concentration 5%. The result shows that the increment in viscosity 86% at 5 vol% nanoparticles concentration and also shows that 40% increment in viscosity of Al_2O_3/Water nanofluids at 3.5 vol% of nanoparticles concentration. Lee et al. [34] explained that the effect of temperature on nanofluids viscosity & used water based nanofluids (Al_2O_3) with low nanoparticles volume concentration (0.3%) and not used surfactant. The results show that the nanofluids viscosity decrease with increment in temperatures. Sharifpur et al. [35] explained that the viscosity of nanofluids measured with various sizes of nanoparticles (Al_2O_3). The result shows that the viscosity of nanofluids decrease with increment in temperatures and the nanofluids viscosity increase with increment in nanoparticles concentration.

Titania nanofluids

Masuda et al. [31] explained that the nanofluids (TiO_2) viscosity with nanoparticles size (27nm). The result shows that the increment in nanofluid viscosity 46% at 3.2 vol% at 32ºC of temperature. Similarly, Pak and Cho [32] investigated that the nanofluids (TiO_2) viscosity with nanoparticles size (27nm). The result shows that the increment in viscosity 36% at 3.16 vol% at room temperature. Turgut et al. [36] explained that the nanofluids (TiO_2) viscosity without using of any surfactant. The result shows that the increment in viscosity of 64% at 2 vol%. Similarly, Duangthongsuk and Wongwises [37] show their own results, the increment in viscosity 13% at same volume concentration (2%) and measured the viscosity of nanofluids. Yiamsawas et al. [38] investigated that the viscosity of EG/Water based nanofluids (TiO_2) measured. The result shows that the nanofluids viscosity increase with increment in nanoparticles concentration and found out a correlation with their experimental data. The maximum enhancement in viscosity 52% at 4% vol% & 23% enhancement at 1.8% of volume concentration. Duangthongsuk and Wongwises [37] explained that the effect of temperature on nanofluids (TiO_2) viscosity. The result shows that the nanofluids viscosity decrease with increment in nanoparticles concentration and the nanofluids viscosity increase with increasing at higher nanoparticles concentration. Bobbo et al. [39] investigated that the effect of temperature on nanofluids viscosity and nanofluids viscosity increase with temperature ranging from 10 to 20ºC.

ZnO nanofluids

Li et al. [40] explained that ZnO nanoparticles dispersed in EG and used surfactant (PVP) for rectangular and spherical shapes. The result shows that the nanofluids viscosity decreases with rising of temperature & shows the Newtonian behavior of nanofluids. Moosavi et al. [41] studied that the viscosity of EG based nanofluids (ZnO) and used Ammonium citrate surfactant. The result shows that the nanofluids viscosity increase with increment in nanoparticles concentration (0.2-0.6%) at 25ºC and the nanofluids viscosity decrease with rising of temperature from 25ºC to 50ºC. Suganthi and Rajan [42] explained that the nanofluids (ZnO) viscosity measured at volume fraction (0.25-2%) The result shows that the relative viscosity of nanofluids increase with rising of temperature from 35ºC to 55ºC. Heris et al. [43] studied that the properties of nanofluids (ZnO) and shows the effect of volume concentration (0.01-0.6) and temperature (0 to 60ºC) on the nanofluids viscosity. The result shows that the nanofluids viscosity decrease with rising of temperatures & the enhancement in viscosity with increases of nanoparticles concentration.

SiC nanofluids

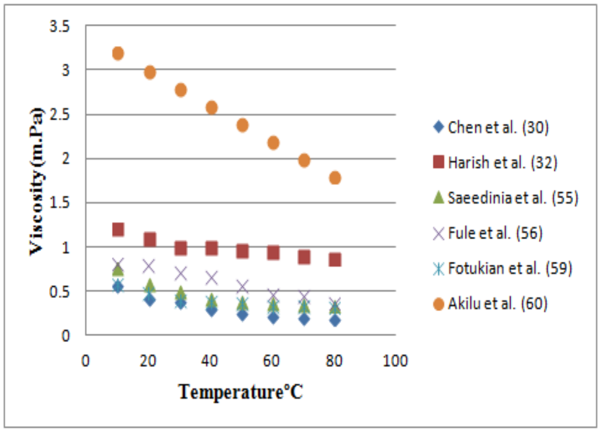
Singh et al. [44] studied that the viscosity measured of SiC nanofluids with size of 170 nm and not used any surfactant. The effect of temperature (15 to 55ºC) and volume concentration (1.8-7.4%) on nanofluids viscosity. The result shows that the nanofluids viscosity decrease with rising of temperatures and the enhancement in viscosity with increases of nanoparticles concentration. Lee et al. [45] explained that the viscosity of nanofluids (SiC) with 100 nm diameter with low concentrations of nanoparticle. Nikkam et al. [46] explained that the viscosity of nanofluids measured with 9% weight concentration at 20ºC of temperature and consider the nanoparticles structure (α-SiC and β–SiC). The result shows that the maximum increment in viscosity with β–SiC structure. Li et al. [47] investigated that the behavior of nanofluids (SiC/EG) and used nanoparticles concentration (0.2-1.0 vol %). The result shows that the viscosity of nanofluids decrease with rising of temperatures and the viscosity increase with increases of nanoparticles concentration.

Magnetic nanofluids

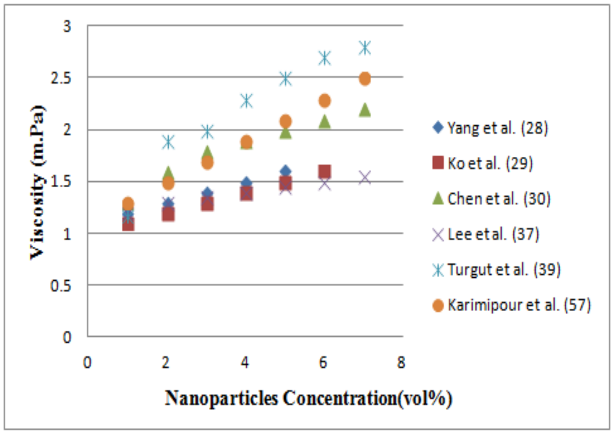
Hong et al. [48] explained that the effect of temperature on nanofluids (Fe_3O_4) viscosity. The result shows that the Fe_3O_4 nanofluids viscosity decreases with rising of temperatures. Phuoc and Massoudi [49] explained that the effect of concentration & shear rate on viscosity of Fe_3O_4 nanofluids and used PVP or PEO surfactants. The result shows that the nanofluids viscosity increases with increment in concentration and the maximum enhancement in viscosity 145% at 4 vol%. Resiga et al. [50] explained that the influence of nanoparticle clustering at high concentration of oil based nanofluids on rheological properties. Sunder et al. [51] explained that the effect of temperature on nanofluids viscosity of water based nanofluids Fe_3O_4. The result shows that viscosity of nanofluids increase with rising of temperature from 45 to 60ºC.

CuO nanofluids

Saeedinia et al. [52] explained that the behavior of rheological properties and used CuO-oil based nanofluid with nanoparticles concentration (0.2-2 vol %). The results show that the nanofluid (CuO) viscosity increase with increment in nanoparticles concentration (0.2-2%) & the maximum enhancement in viscosity 12.7% at 2 wt% of nanofluid. Fule et al. [53] explained that the CuO-Water based nanofluids used with volume fraction (0 to 0.5%) and prepared by two step method. The result shows that the heat transfer rate of nanofluid increases with increment in concentration. The heat transfer coefficient increases 37.3% at 0.5 vol%. Karimipour et al. [54] explained that the influence of temperature on nanofluids viscosity and temperature range lies between 40˚C to 70˚C with nanoparticles concentration (2.5%). The result shows that the nanofluids viscosity increases with increment in nanoparticles concentration (2.5%) and viscosity decreases with the rising of temperature. The experimentally result shows that the enhancement in viscosity 25% at 2.5 wt%. Aguila et al. [55] explained that the effect of volume concentration and temperature on the viscosity and used concentrations (2.5%, 5.0%, and 10.0%). The results show that the viscosity increase with increases of nanoparticle concentrations (2.5%, 5.0%, and 10.0%) and decreases with rising of temperature and 60% enhancement in viscosity with the increases of nanoparticle concentrations. Fotukian et al. [56] explained that the heat transfer rate with CuO-Water based nanofluids flowing through a tube and used volume concentration (3%). The result shows that the heat transfer rate increased 25% with increment in concentration (3%) and the viscosity of nanofluid decreases with rising of temperature and the enhancement in viscosity approximately 23% at 3% of concentration. Akilu et al. [57] explained that the various parameters used for characterization & measure of viscosity. The result shows that the viscosity increases by nearly 80% at 2.0% volume concentration. Viscosity increases with increment in concentration and decreases with rising of temperature. Kannadasan et al. [58] explained that the difference of pressure drop and heat transfer characteristics of nanofluid & used volume concentrations (0.1%, 0.2%). The result shows that the nanofluid friction factor increases with increment in nanoparticle concentrations & the enhancement in viscosity of nanofluid (Cuo-Water) at 0.1% of 36% and 0.2% of 45%.



(a)



(b)

Fig. 1 (a,b) Viscosity decreases with rising of temperature and increases with increment in concentrations

VI. Conclusions:-

With increasing in the nanoparticles concentration, the viscosities of nanofluids increased. On the nanofluids viscosity, a mixed effect of temperature is confirmed by literature. Some studies reported negative effect of temperature on nanofluids viscosity and some found positive effect of temperature on nanofluids viscosity. For application at high temperature environment with increment in temperature, decrement in viscosity of nanofluids is desirable. Classical and empirical viscosity models have also been compared by the experimental results in the literature. Empirical models were based on the experimental data and not right for prediction of nanofluids viscosity also classical models were found unable to do same. The nanofluids viscosity decrease with rising of temperature and viscosity increase with increases of nanoparticles concentration.

Table 1. Literature data related with viscosity of nanofluids

Author	Nanofluid	Base Fluid	Surfactant	Particles concentration	Temp.(°C)	Observations
Yang et al. [25]	MWCNT	Oil	PIBSI	-	-	Viscosity increase with increases of concentration
Chen et al. [37]	MWCNT	Water	Surface treated	0.4	55	Viscosity increases with concentration (0.4%)
Hung and Chou [28]	MWCNT	Water	Chitosan	1.5	-	Max. enhancement in viscosity 233% at 1.5 wt %
Masuda et al. [31]	Al_2O_3	Water	-	4.3	32	Increased 250% at 305 K of temperature
Pak and Cho [32]	TiO_2	Water	-	3.16	-	Increment in viscosity 36% at 3.16 vol% at room temp.
Wang et al. [33]	Al_2O_3	EG/Water	-	5	-	Increment in viscosity 86% at 5 vol% nanoparticles
Li et al. [40]	ZnO	EG	PVP	1.75–10.5	15-55	Viscosity decreases with rising of

						temperature
Moosavi et al. [41]	ZnO	EG	AC	0.6-1	25-50	Viscosity increase with concentration (0.2-0.6%)
Suganthi and Rajan [42]	ZnO	Water	SHMP	0.25-2	25-55	Viscosity increase with temp. from 35ºC to 55ºC
Singh et al. [44]	SiC	Water	Not used	1.8-7.4	15-55	Enhancement in viscosity with concentration
Aguila et al. [55]	CuO	Water	-	2.5-10	30-55	60% enhancement in viscosity at 2.5 vol%
Fotukian et al. [56]	CuO	Water	-	3.0	-	23% enhancement in viscosity at 3 vol%
Akilu et al. [57]	CuO	EG	-	2.0	41	80% enhancement in viscosity at 2.0 vol%

Nomenclature

φ = Nanoparticle volume fraction μ_{eff} = Effective Viscosity h = Internal particle spacing

μ = Viscosity (Pa s) a = Radius of the particle bf = Base fluid

nf = Nanofluid $\varphi_{m=}$ Maximum packing fraction

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