

# Review on Nanofluid Theoretical Viscosity Models

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**Abstract** — Much interest is shown on nanofluid as nanofluid is suitable for cooling applications. The two important thermo physical properties of nanofluid such as thermal conductivity and viscosity play key role in practical heat transfer situations. The nanofluid viscosity is investigated by many investigators next to the thermal conductivity of nanofluid as the viscosity determines the pumping power. This review summarizes the nanofluids theoretical viscosity models proposed by different research groups. Though many viscosity models formulated of nanofluids, there is no universally accepted model and reliable mechanism for viscosity over the particles volume fraction. Therefore this review leads to further investigation on the hotly debated topic of viscosity of nanofluids.

**Key Words** — Brownian motion, Nanofluids, Nanofluid theoretical viscosity model, Particle volume fraction.

## I. INTRODUCTION

Nanofluid viscosity is an important parameter for practical applications since it directly affects the pressure drop in forced convection. Therefore, for enabling the usage of nanofluids in practical applications, the extent of viscosity increase of nanofluids with respect to pure fluids should be thoroughly investigated. Thus from application point of view, ideal nanofluid should not only possess high thermal conductivity but also should have low viscosity. At present, research on viscosity is limited when compared with the research related to the thermal conductivity of nanofluids. As conventional heat transfer fluids have already reached their thermal performance limitations, the need of developing novel heat transfer fluids becomes mandatory in order to meet out the high capacity existing cooling requirements. The novel fluid should have unique features comparing the conventional fluids, in particular the fluid which has higher thermal conductivity, consume comparatively less pumping power and improved thermal performances. Ref.[1] proposed a heat transfer fluids, called nanofluids, as a fluids with suspended discontinuous nanoparticles in the continuous base fluids and reported the nanofluids have superior thermal properties to the conventional fluids. It is known that nanofluid viscosity depends on many parameters such as; particle volume fraction, particle size, temperature, and extent of clustering. Increasing particle volume fraction increases viscosity and this was validated by many studies. Ref.[30], Ref.[17], Ref.[2]. and Ref.[3] revealed the relative viscosity increase over the particle volume fraction for nanofluids. They also reported the desirable

heat transfer increase may be offset by the undesirable increase in pressure drop.

## II. NANOFUIDS VISCOSITY MODEL

This section deals with the development of nanofluids viscosity model stating from the evolution and recent model proposed in open literature. In order to explain the effect of nanoparticle on viscosity, many theoretical models have been presented. Ref.[4] reported the nanofluids viscosity is as important as the thermal conductivity of nanofluids when nanofluids come into practical applications. The liquid layering, particle size, particle shape, particles interaction, and dispersion techniques are the depending factors for determining the nanofluids viscosity. Therefore comprehensive model is needed to apply the nanofluids effectively. Many investigators suggested the nanofluid has higher application potential in the field of heat transfer and revealed the application of nanofluid results pressure drop penalty while applying in the flow passage. Ref.[5] suggested a analytical model by incorporating the effect of temperature on the thermal conductivity enhancement. Ref.[6] reported that the temperature dependence is too weak and this model is not in agreement with the experimental data. Generally viscosity of fluid yields the pumping power and for a laminar flow in a circular tube, the heat transfer coefficient is directly proportional to the change in pressure drop.

### A. Classical Viscosity Model

There are two kinds of nanofluids viscosity model such as classical models and models derived from classical models. Ref.[7], Ref. [8], Ref. [9] and Ref. [10]. And Ref. [7] are the first who developed a nanofluid viscosity model. Therefore, those viscosity models were named as classical models. These models are based on the assumption of dilute, suspended, spherical particles and no interaction between the nanoparticles. It is found that this model is valid for relatively low particle volume concentration. Ref.[8] suggested a power law model for randomly mono-dispersed sphere by taking the maximum close packing of 0.64 and for intrinsic viscosity of 2-5. It reduces the Ref.[7] model when monomial expansion is performed and it also reduces model [10] model. Ref. [7] suggested a model by considering the maximum packing fraction.

### B. Models Derived Based on Classical Models

Ref.[11] proposed a viscosity model based on the particle volume fraction for  $\text{Al}_2\text{O}_3$  /water nanofluids. They reported the effective viscosity increases when particle volume fraction is increased.

### C. Temperature Dependant Model

Ref. [12] developed a viscosity model for temperature dependant nanofluids in the range of particle volume fraction of 1% - 4%. They reported the Ref.[7], Ref.[10], Ref. [19] and Ref.[13] under estimates the nanofluids viscosity at these particle volume fraction. The model developed is valid for the nanofluids with a particle size of 36 nm. Experimental studies show that particle size is an important parameter that affects the viscosity of nanofluids. However, at present, it is difficult to obtain a consistent set of experimental data for nanofluids that covers a wide range of particle size and particle volume fraction. Ref.[14] gave a viscosity model by considering the volume fraction and maximum volume fraction of particle. Ref.[15] reported the nanofluids viscosity model based on the particle volume fraction and at room temperature. They suggested the nanofluids viscosity is temperature dependant and reported the viscosity decreases when the temperature increases.

### D. Based on kinetic theory

Ref. [16] developed an exponential model based on kinetic gas theories and correlated with the experimental data. This model considered the base fluid viscosity and particle volume fraction into account for determining viscosity. The particle size and interaction between the particles were not considered. Ward model was proposed by Chung-Lee Starling CLS by taking the exponent value as in [16] is two. This model gives good results for two-phase flow with particles larger than 100nm. But for smaller particles it gives wrong results with the deviation more than 100% in comparison with the experiments results. Ref. [16] presented an exponential model for hard and spherical particle volume fraction up to 35%. Ref.[17] suggested a model for  $\text{CuO}$  /water nanofluid and for a temperature range of 5-50°C. This shows the exponential decrease of viscosity when temperature is increased. Ref.[18] developed a model for varies particle volume fraction of  $\text{Al}_2\text{O}_3$  and at a temperature of -35°C to 50°C for 60:40 ethylene glycol: water as base fluids. It showed the exponential decreases of viscosity when temperature is raised.

### E. Based on inter particle spacing

Ref. [19] presented a generalized model by considering the particle radius and inter particles space for small particle volume fraction. This model agrees well with the Ref. [7] model for small particle volume fraction.

### F. Based on Liquid layering model

Ref. [20] by taking the liquid layering into account and named as Ref.[21]. Ref. [20] reported the deviation of results of Ward model and Renewed model [RW] is extremely high and RW model gives excellent results.

### G. Model Based on Mean Free Path

Ref. [22] developed a model based on the mean free path and materials characteristics. Ref. [23] suggested a viscosity model based on two contributions such as the effect electromagnetic aspects and the effect of mechanical –geometrical aspects. The first contribution accounts the interaction between two phases, composition and properties of liquid phases and also additives. The second contribution accounts specific surface area (SSA), density and apparent sphericity of the particle. This model shows good agreement with the model as in [7] and the results agree with the experimental results of Ref. [23] model. Ref. [24] suggested an exponential model based on the particle volume fraction for  $\text{TiO}_2$  / water nanofluids. Ref. [25] introduced the well known Einstein model for dilute suspension, small size spherical particles and for two phase mixture at low particle volume fraction. Ref.[26] developed a model based on the particle volume fraction. Ref. [27] developed a viscosity model by considering the particle volume fraction, suspension viscosity and base fluid viscosity into account to calculate the nanofluids viscosity. Ref.[13] proposed an equation in the form of a Taylor series by omitting higher order. This model reduces to that of Einstein classical model as in [7]. Ref. [28] proposed a model by extending model as in [7] with two corrections. This first correction is in view of particle size and the second one is structure of particles. This model reports the structure of particles affects the nanofluids viscosity and can be used for moderate particle volume fraction.

### H. Based on Brownian Motion

Ref. [29] formulated a model by considering the Brownian motion of the particles and reported this mode is applicable for  $\text{Al}_2\text{O}_3$ /water nanofluids. Ref. [30] reported the model as in [9], [8] are under predicted models for predicting the nanofluids viscosity. Ref. [41] tried to model the rheological properties of nanofluids and describe the importance in terms of designing new nanofluids. They adopted a Brownian dynamics simulation method to theoretical model for viscosity for  $\text{Al}_2\text{O}_3$  / water and EG based nanofluids and compared their model data with experimental data. Their simulation is in good agreement with the experimental results. Ref.[30] reasoned that the easily formed clustering and adsorption lead to the improved relative viscosity. They explained the size, shape, ionic strength of base fluids, surfactants, pH values , inter-particle potentials such as repulsive forces (electric double layer force ) and attractive force (vander walls force) may also play in altering the viscosity of nanofluids. Ref. [10] presented a viscosity model by extending Ref. [7] model by incorporating the effect of Brownian motion of nanoparticles. This model was derived by considering the isotropic suspension of rigid and spherical nanoparticles.

Table.1 shows the mathematical models proposed by different research groups.

Based on the review, nanofluid viscosity significantly increases when particle volume fraction is increased and nanofluid viscosity decreases when temperature increases.

The first effect is due to the direct impact of internal shear stress and the second one is due to weakening the inter-particle and intra-molecular adhesion forces. The mechanisms proposed are subject to the conditions such as lower/higher particle volume fraction, lower/higher temperature, spherical/non spherical shape, below/above critical size, pH value, base fluids etc. Therefore, the exact mechanism can not be conceived until the optimum level of particle volume fraction, optimum size for achieving the stability and low agglomeration of nanoparticles. Moreover the new nanofluid viscosity model is to derived based on the optimum particles loading and size in order to lower the viscosity. Because higher the particle loading results the more agglomeration and higher the particle size

results erosion and easy settling. At the same time lower the particle size leads to higher surface effect and easy agglomeration.

Experimental data for the effective viscosity of nanofluids are limited to certain nanofluids. Moreover the experimental data showed the trend that the effective viscosity is higher than the predicted viscosity. The successes of newly developed models are very limited. This may be due to the deviation of results between the macro scale measuring techniques and nano scale mechanism for enhanced viscosity. Therefore the comprehensive theoretical explanations of viscosity is needed to overcome the uncertainty. Table. A list out the mathematical models developed by several authors.

Table. A. Summary of Nanofluid Viscosity model proposed by several authors.

Model Name	Effective viscosity models / Equations	Remarks
<b>Classical models</b>		
Einstein, Ref. [7]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi$	Valid for spherical particles of low particle volume fraction $\phi \leq .02$ .
Krieger and Dougherty [K-D]model.Ref.[ 8]	$\frac{\mu_{nf}}{\mu_f} = \left[ 1 - \frac{\phi_p}{\phi_m} \right]^{-\eta\phi_m}$	Based on randomly mono-dispersed hard spheres. Valid for maximum close packed particles of 0.64.
Nielson,Ref.[9]	$\frac{\mu_{nf}}{\mu_f} = (1 + 1.5\phi_p) e^{\frac{\phi_p}{(1-\phi_m)}}$	Power law model and more appropriate for particle volume fraction more than 0.02.
Batchelor, Ref. [10]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 6.5\phi^2$	Considered the effect of Brownian motion .Extension of Einstein model
<b>Models formulated based on classical models</b>		
Eilers, Ref. [31]	$\frac{\mu_{eff}}{\mu_m} = 1 + 2.5\phi + [1.5625 + (2.5/\phi_{max})]\phi^2 + \dots$	Based on maximum particle volume fraction. Valid for spheres of 0.5236 <sub>max</sub> 0.7405
De Bruijn, Ref. [32]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 4.698\phi^2$	Valid for spherical shaped nanoparticles.
Vand, Ref. [33]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + 7.349\phi^2 + \dots$	Valid for spherical nanoparticles.
Saito, Ref. [34]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + 2.5\phi^2 + \dots$	Reported the viscosity depends on particles volume fraction.
Mooney, Ref. [35]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + [3.125 + (2.5/\phi_{max})]\phi^2$	Valid for spherical nanoparticles and for 0.5236 <sub>max</sub> 0.7405.

Fullman, Ref.[22]	$\frac{\mu_{nf}}{\mu_f} = 1 + a \frac{1}{\lambda^n}$ , Where $\lambda = \frac{2}{3}d \frac{(1-\phi)}{\phi}$	Depends on the materials characteristics.
Simha, Ref. [36]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + [125/64\phi_{\max}] \phi^2$	Valid for spherical nanoparticles and for 0.5236 <sub>max</sub> 0.7405.
Brinkman, Ref. [28]	$\frac{\mu_{eff}}{\mu_f} = \frac{1}{(1-\phi)^{2.5}}$	Formulated by two corrections of Einstein's model.
Frankel and Acrivos, Ref. [14]	$\frac{\mu}{\mu_f} = \frac{9}{8} \left[ \frac{(\phi/\phi_m)^{1/3}}{1 - (\phi/\phi_m)^{1/3}} \right]$	Valid for spherical nanoparticles and for 0.5236 <sub>max</sub> 0.7405.
Lundgren, Ref. [13]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + \frac{25}{4}\phi^2 + 0(\phi^3)$	Formulated from the Taylor and Series. Reduction of Einstein model
Graham, Ref. [19]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 4.5 \left[ \frac{1}{\frac{h}{d_p} (2 + \frac{h}{d_p}) (1 + \frac{h}{d_p})^2} \right]$	Based on particle volume fraction and inter-particle spacing.
Kitano, Ref. [37]	$\frac{\mu_{nf}}{\mu_f} = \left[ 1 - \left( \frac{\phi}{\phi_m} \right) \right]^{-2}$	Based on maximum concentration of two phase mixture.
Pak and Cho, Ref. [15]	$\frac{\mu_{nf}}{\mu_f} = (1 + 39.11\phi + 533.9\phi^2)$	Developed by taking the room temperature as reference.
Chung-Lee Starling [CLS] model, Ref. [16]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + \left( \frac{35}{8} + \frac{5}{4}\beta \right) \alpha^2 + \left( \frac{105}{16} + \frac{35}{8}\beta + \frac{5}{12}\beta^2 \right) \alpha^3 + \dots$	Based on the kinetic gas theory. Considered the interaction between particles.
Bicerano, Ref. [27]	$\frac{\mu_{nf}}{\mu_f} = 1 + \eta\phi + k_H\phi^2 + \dots$	Considered the viscosity of base fluids and particles.
Wang, Ref. [26]	$\frac{\mu_{eff}}{\mu_f} = 1 + 7.3\phi + 123\phi^2$	Showed the particle volume fraction is the key factor for improved viscosity.
Drew and Passman, Ref. [25]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi$	Formulated for dilute suspension of small spherical particles of two phase mixtures.
Tseng and Li, Ref. [24]	$\frac{\mu_{nf}}{\mu_f} = 13.47e^{35.98\phi}$	Developed for TiO <sub>2</sub> /water nanofluids

Maiga, Ref. [11]	$\frac{\mu_{nf}}{\mu_f} = 123\phi^2 + 7.3\phi + 1$	Derived for Al <sub>2</sub> O <sub>3</sub> /water nanofluids.
White, Ref. [38]	$\ln \frac{\mu_{nf}}{\mu_f} = a + b\left(\frac{T_o}{T}\right) + c\left(\frac{T_o}{T}\right)^2$	Temperature dependant viscosity of Al <sub>2</sub> O <sub>3</sub> nanofluids.
Koo and Kleinstreuer, Ref. [39]	$\mu_{Brownian} = 5 \times 10^4 \beta \rho_m \phi_p \sqrt{\frac{K_B T}{2 \rho_p r_p}} [(-134.63 + 1722.3\phi_p) + (0.4705 - 6.04\phi_p)T]$	Additional viscosity due to Brownian motion. Valid for CuO nanofluids.
Kulkarni, Ref. [17]	$\ln(\mu_{nf}) = -(2.8751 + 53.548\phi - 107.12\phi^2) + (1078.3 + 15857\phi + 20587\phi^2)(1/T)$	Temperature dependent model and valid for 5°C-50°C.
Nguyen, Ref. [12]	$\frac{\mu_{nf}}{\mu_f} = (2.1275 - 0.0215T + 0.00027T^2)$	Temperature dependent nanofluids viscosity model and valid for 1%-4%.
Ward (CLS)[16]	$\frac{\mu_{nf}}{\mu_f} = 1 + \eta\phi + (\eta\phi)^2 + (\eta\phi)^3$	An exponential model for up to 35% of spherical particles.
Chen. Ref. [40]	$\frac{k_{nf}}{k_f} = \left[ 1 - \left( \frac{\phi}{a_a} \right)^{1.2} \right]^{-[\eta]\phi_m}$	Considered the radii of aggregates. Modified Krieger-Dougherty model.
Jurij Avsec, Ref. [20]	$\frac{\mu_{nf}}{\mu_f} = 1 + \eta\phi_e + (\eta\phi_e)^2 + (\eta\phi_e)^3$	An exponent model and valid for 35% of volume fraction.
Namburu, Ref. [18]	$\text{Log} \mu_{nf} = A e^{BT}$	Temperature dependent model. Valid for 1-10% of Al <sub>2</sub> O <sub>3</sub> nanofluids and -35°C to 50°C.
Masoumi Ref. [29]	$\frac{\mu_{eff}}{\mu_f} = 1 + \frac{\rho_N V_B d_N^2}{72C\delta\mu_f}$	Based on the Brownian motion of particles and valid for Al <sub>2</sub> O <sub>3</sub> /water nanofluids.
Chandrasekar, Ref. [23]	$\frac{\mu_{nf}}{\mu_f} = 1 + b \left( \frac{\phi}{1-\phi} \right)^n$	Contribution of Electromagnetic aspects and mechanical – geometrical aspects taken into account.

**Notation:**  $\phi_e$  –effective volume fraction,  $\phi$  -volume fraction,  $\eta$  -intrinsic viscosity,  $\mu$  - dynamic viscosity,  $\beta$  -ratio of nanolayer thickness to the original particle radius,  $r_p$  - radius of particle in m,  $c_p$  –specific heat in kJ/kgK,  $h$  -liquid layer thickness in m,  $T$  –temperature,  $h$  -inter particle spacing in K,  $K_B$  –Boltzmann constant,  $\rho$  -density,  $d$  -diameter of particle,  $\beta$  -exponent,  $\phi_e$  –effective volume fraction. Subscripts and Superscripts: p-particle, f, b, m -base fluid, eff- effective, nf- nanofluids, A,C, a, b, c, n –constants.



### III. CONCLUSION

From this literature review, viscosity of nanofluid depends on many parameters such as base fluids, nanoparticle volume fraction, particle size, particle shape, temperature, surface charge, pH value, base fluid, particle material, Brownian motion of nanoparticles, effect of clustering, nanolayer and dispersion techniques. However no theoretical formula is currently available to predict the nanofluid viscosity with good accuracy. The validated experiments result show that the nanofluid viscosity did not have good agreement with the theoretical models. The main deviation between the theoretical model and experimental results may be the effect of Brownian motion, assumptions made while deriving the models, different size and shape, type of dispersion, modeling approach, and dispersion techniques. The tabulated viscosity models in this review can be generally applied for determining the viscosity of nanofluids. The criteria, validity with experimental results and limitations of nanofluid are still under suspension. It is seen in the literature that there is no report on the optimum level of nanoparticles to be dispersed in the base fluids for attaining better stability and less tendency to agglomerate. Moreover there is no report on the critical size to attain stability and less agglomeration. Further work is needed to optimize the particle size and particle volume fraction for formulating the new model for different particle materials for attaining optimum nanofluid viscosity. Recent investigation of nanofluid application in heat exchanger reported the pumping power penalty is undesirable when particle loading is more than the optimum. They suggested the increased viscosity is the reason for higher pumping power. Therefore alternate way is urgently needed to meet this problem so as to replace conventional coolants by nanofluids.

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