

Viscosity of nanofluids-A Review

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Abstract

In the present study a comprehensive review on rheological characteristics of nanofluids for their advanced heat transfer applications has been conducted and presented. The present article critically summarizes the recent research developments regarding the theoretical and experimental investigations about viscosity of different nanofluids. In addition, different reasonably attractive theoretical models and experimental correlations are explored and well discussed. Moreover, the current study analyzes several factors those strongly influencing viscosity of nanofluids include solid volume fraction, temperature, particle size, particle shape, different base fluids, surfactants addition, ultrasonication, nanoclustering and pH value. Important theoretical and experimental results from many researchers and predictions from a number of viscosity models are compared and discussed with appropriate justification. Most results reveal that the viscosity of nanofluid upsurges due to an increase in particle concentration while that belittles with diminishing temperature. Augmentation of nano-additives size leads to decreasing/increasing of nanofluid fluid viscosity. For the most nanofluids, Newtonian behavior is observed for low volume fractions, shear rates, concentrations and viscosity while non-Newtonian behavior is visualized for high volume fractions, shear rates, concentrations and viscosity. Nanofluids used carbon nanotubes are almost non-Newtonian in nature while nanofluids not involving carbon nanotubes are mostly Newtonian. Finally, the research challenges and needs in this important area of nanofluids are also highlighted.

Keywords: Nanofluids; Viscosity; Nanoparticle volume fraction; nanoclustering; Particle loading; Heat transfer.

1. Introduction

Nanofluids are a new generation of heat transfer fluids that have attracted researchers' attention from diversified fields due to their anomalous thermal behavior and tremendous potential in diversified aspects of engineering applications. The nanofluids are novel type of fluids in which nanoparticles [nano meter-sized particles (smaller than 100 nm)] such as copper (Cu), nickel (Ni), aluminium (Al), Silver (Ag), titanium oxide (TiO_2), aluminium oxide (Al_2O_3), copper oxide (CuO), iron oxide (Fe_3O_4), etc. are mixed with the base fluids/conventional fluids such as water, kerosene, ethylene glycol, light oil etc. through proper dilution and suspension. Simply, we may say that nanofluid is a suspension of solid nanoparticles (1-100 nm) in conventional fluids. It was Choi [1] who invented the nanofluid experimentally through proper suspension and dilution of nanoparticles with base fluids in 1995 at Argonne National Laboratory, USA.

From the research it is well known that micron-size particles mixed with base fluids to lead to poor stability and sedimentation of the micron-size particles, erosion, clogging of the channels, and the enhanced fluid pumping power in heat transfer systems. Such drawbacks impede the microfluids in heat transfer applications [2-3]. Later, nanofluids concept has emerged to overcome these experienced problems. Although dispersion of nano-size particles are expected to exhibit more stability, larger surface area to volume ratio and the higher surface energy of nano-size particles caused the aggregation and sedimentation of nanoparticles. Sustainment of the enhanced thermal conductivity of nanofluids is due to the dispersion stability. In order to enhance the stability of the colloidal suspensions, merely the synthesis of nanofluids by simply mixing of solid particles with the hosting fluid is not enough rather it involves different physical and chemical treatments for the purpose [4-8].

The study of heat transfer has become important industrially for determining the quality of final products with desired characteristics which greatly depends on the rate of heat transfer /rate of cooling between the fluid and solid surface. In view of diversified industrial usefulness, conventional fluids have received much attention by many vibrant researchers in the last quarter century. They do not have enough heat transfer capability. Such drawbacks of base fluids restrict their use as cooling agent in many heat flow devices include electronics devices, material processing, solar thermal collectors etc. Various methods of preparation, addition of surfactants for enhancement of stability and use of ultrasonication are used along with proper dilution and suspension that lead to the formation of nanofluids of enormous heat transfer capability. So, nanofluid is a fluid of remarkable thermo-physical properties, superior transport properties and significant enhancement in heat transfer capability. Because of high heat transfer capability, nanofluids lead to high performance with respect to improved efficiency, reduction in size and fabrication cost and better safety margin of heat transfer equipments/thermal systems. In view of high heat transfer capability of nanoparticles compared to conventional base fluids, nanofluids are served as better coolants in computers and nuclear reactors, cancer therapy, safer surgery, lubricants, heat exchangers, micro-channel heat sinks and several electronic devices for use in military sectors, vehicles and transformers, in designing the waste heat removal equipment, major manufacturing industries including materials and chemicals, oil and gas, food and drink, paper and printing, wound treatment, sterilized devices, gastric medications and great importance in the processes such as targeted drug release, asthma treatment, synergistic effects in immunology, elimination of tumors with hyperthermia etc. [9-15]. Therefore, the physical properties including thermal

conductivity and viscosity are essential parameters to investigate the great potential for heat transfer enhancement of flowing liquid. The knowledge of fluid flow properties, especially viscosity is a very important feature of any nanofluid since it is critically related to the pumping power needed for applications of nanofluids in the fluid flow system involved in heat exchangers.

Viscosity is one of the most important thermophysical properties of nanofluids have significant contribution to the determination of the fluid flow and heat transfer. The viscosity is one of the most important transport properties of nanofluids in the applications where nanofluids are expected to be used as a new class of heat transfer fluids such as heat exchangers or cooling systems [16-18]. The influence of viscosity on the velocity of the nanofluid will modify the temperature distribution and hence affects heat transfer characteristic of nanofluids. The viscosity of nanofluid essentially determines the flow resistance, pumping power and even the usability of nanofluids. The dimensionless numbers associated with heat transfer viz. Nusselt and Reynolds numbers are directly related to the viscosity of nanofluids [19-22]. Therefore, the viscosity should be determined by experimental or numerical means before design a heat transfer system with nanofluids as the working fluid.

Nanofluids are characterized by higher viscosity compared to their base fluids and it further upsurges with increasing concentration of nanoparticles [23]. The results regarding the viscosity of nanofluids cannot be predicted from the existing classical models. Further, it is fact that almost all recently proposed empirical correlations achieved by fitting their own experimental results are neither widely accepted nor suitable for other types of nanofluids [24-25]. An intensive study of literature reveals that there is scattering/disparities and inconsistency about the results of viscosity of nanofluids. The rationally behind such inconsistency and scattered results are due to several issues such as adopting different particle size, particle shape, pH of the suspension, purity of nanoparticles, temperature, different kinds of measuring equipment or geometry, considering change in shear rate, scale of agglomeration, and different dispersion and sample preparation methods [26-27].

In the past decades, the effects of influential pertinent physical parameters such as concentration of nanoparticles, temperature, base fluid types, dispersion, and particle size, type and shape on the viscosity of nanofluids have been studied for exploiting their potential in a wide range of applications [16]. In fact, the volume of studies carried on viscosity is much lower compared to the studies on thermal conductivity. However, regarding the cost-effectiveness parameter due to nanofluids usage studies on the viscosity have increased day by day in parallel with the studies on the thermal conductivity [20]. In some research, it is visualized that nanofluids even with high viscosity exhibit better heat transfer than the conventional heat transfer fluids used as base fluids. Prasher et al. [20] adopted a thermal and hydraulic analysis in their investigation and declared that the relative increase in the viscosity is around four times larger than the relative increase in thermal conductivity of nanofluids which are considered to be better than the base liquid in heat transfer applications. Such drawbacks that nanofluids exhibiting higher viscosity compared to their base fluids could be compensated satisfactorily through other significantly enhanced thermal properties like thermal conductivity, heat transfer coefficient, and critical boiling heat flux making them fluids of next-generation of coolants [15,20].

Motivated by above significant usefulness and relevant applications of nanofluids in diversified fields the main objective of the present study is to provide a comprehensive reviews on the latest developed classical and experimental viscosity models of nanofluids. The impact of several influential factors such as concentration of nanoparticles, temperature, base fluid types, dispersion, and particle size, type and shape on viscosity of each type of nanofluids that would be helpful updating the information for the researchers in this field has been explicitly reviewed. Important theoretical and experimental results from various research groups and predictions from many viscosity models are also compared and discussed. The novelty of the present study is to reveal the viscosity mechanisms responsible for the heat transfer coefficient behaviors. The present review article also reveals the issues that account for the existing scattering/disparities and inconsistency about the results of viscosity of nanofluids. At last, the present article focuses on the challenges and research needs in the indispensable areas of nanofluids.

2. Rheological Behavior of Nanofluids

An overview of the research conducted in the past decades reveals that Rheology of a nanofluid identifies its flow nature and affects the pressure drop in flow systems is perceived as its most significant outcome. Naturally, the rheological behavior of nanofluids can be obtained from the relationship between shear rate and shear stress or apparent viscosity. In fact, for Newtonian nature, the shear stress exhibits linear relation and the apparent viscosity remains constant with shear rate. On the other hand, fluids that show shear rate-dependent apparent viscosity or nonlinear relation between the shear rate and shear stress are non-Newtonian. Studies on Rheology of nanofluids convey that these fluids can have both Newtonian and non-Newtonian flow natures influenced by some factors and conditions [28-40]. Some of the factors include nanoparticle volume fraction, nanoparticle size, temperature, base fluid type, surfactants, pH, particle loading, aggregation, nanoclustering, use time, shear rate and stress. For instance, a nanofluid at a low concentration shows Newtonian behavior but at a higher concentration Rheology of a nanofluid is very significant as it identifies its flow nature and affects the pressure drop in flow systems. Thus it is cumbersome for precise determination of the rheological behavior of nanofluids that can be achieved from the relationship between shear rate and shear stress or apparent viscosity. Fig. 1 illustrates rheological behavior of different types of nanofluids showing a wide range of shear rate independent viscosity. Further, Fig. 2 shows shear rate-dependent apparent viscosity of various nanofluids confirming their non-Newtonian flow characteristics. Some of the important rheological outcomes from the literature are narrated in this section.

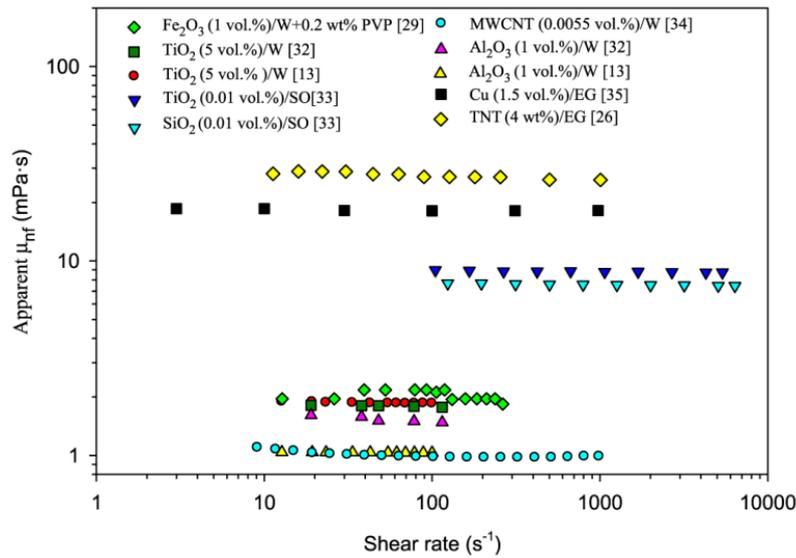


Fig. 1 Literature data on viscosity with shear rate of Newtonian nanofluids at room temperature (Murshed and Estellé [40]).

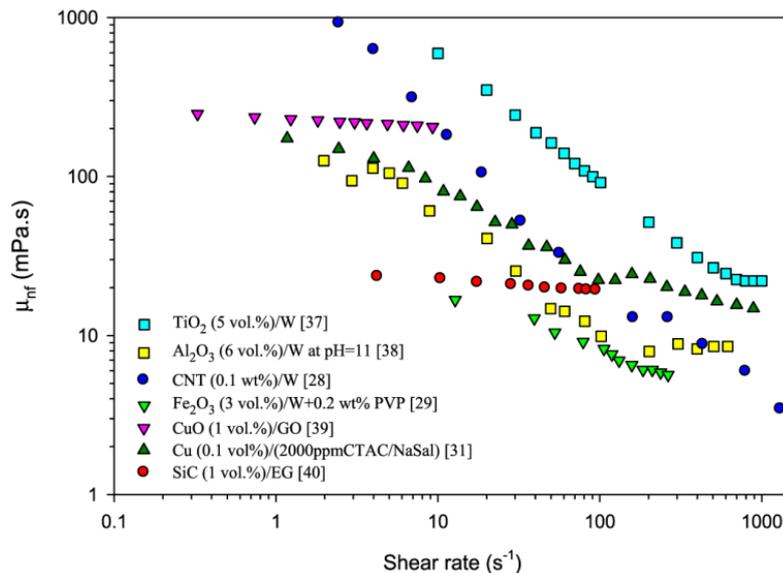


Fig. 2 Literature data on viscosity with shear rate of non-Newtonian nanofluids at room temperature (Murshed and Estellé [40]).

Phuoc and Massoudi [29] investigated the effects of shear rates and concentration on viscosity of aqueous Fe_2O_3 nanofluids with two different dispersants namely Polyvinylpyrrolidone (PVP) and Polyethylene oxide (PEO). They found that Fe_2O_3 -water nanofluids with 0.2% PVP and having nanoparticle volume fraction less than 0.02 behaved as a Newtonian fluid while any further increase in nanoparticle concentration (beyond 2vol%) the nanofluid became non-Newtonian exhibiting shear-thinning behavior. Resiga et al. [36] analyzed rheological properties of highly concentrated transformer oil-based magnetic

nanofluids. The outcomes of their analysis are that the nanofluids become Newtonian at all concentrations except at the highest concentration of 20.8 vol%. Further, Chen et al. [41] carried out rheological behavior of titanate nanotubes (TNT)/EG-based nanofluids. They observed that at room temperature and low concentration nanofluids behave as Newtonian, while at higher temperature ($> 30\text{ }^{\circ}\text{C}$) and concentration ($> 2\text{ wt}\%$) nanofluids were highly shear thinning.

3. Experimental Studies on Viscosity Behavior of Nanofluids

In fact, the dimensionless number associated with heat transfer viz. Nusselt number and Reynolds number are directly related to the viscosity and flow velocity of nanofluids. Further, viscosity has great impact on the mass transfer process as it is related to the diffusion coefficient and transport resistance in both bulk and interfacial regions of nanofluids.

3.1 Ceramic nanofluids

Because the ceramic nanoparticles such as Al_2O_3 , CuO , TiO_2 , ZnO , SiC , SiO_2 etc. are chemically more stable in solutions due to their more resistance to oxidation [42], they are better preferred over metals for the synthesis of nanofluids. Furthermore, they have diminutive density and expected particle settling problem [16].

3.1.1 Aluminum Oxide (Al_2O_3) nanofluids

In view of best nanofluid-based coolant, the aluminum oxide (Al_2O_3) or alumina nanofluid is one of the promising demandable nanofluids which have attracted many researchers to carry out investigation on it. Most relevant studies of on the viscosity of nanofluids reveal that the viscosity augments with increasing particle concentration. Taking into consideration the Newtonian behavior of Al_2O_3 nanofluids with a particle diameter of 36 nm and a volume fraction of 1, 4, 9 and 12%, Das and Putra [8] declared that the relative viscosities were enhanced by 1.12, 1.6, 3 and 5.3%, respectively; and for particle diameter of 47 nm, and volume fractions of 2.1, 4.3, 8.5 and 12.2%, the relative viscosity upsurged by 1.1, 1.4, 2 and 3.1%. Chandrasekar et al. [9] studied the nanofluids viscosity for Al_2O_3 nanoparticles in water. They disclosed that the viscosity rises linearly by upgrading particle concentration up to the concentration of 2%.

There are numerous studies conducted on the effect of temperature on the viscosity of nanofluids. Prasher et al. [20] studied on the effect of temperature for Al_2O_3 -PG nanofluids for temperature range $30-60\text{ }^{\circ}\text{C}$. Meriläinen et al. [10], Kwek et al. [42] and Jarahnejad et al. [16] conducted the influence of temperature on viscosity of water-based aluminium oxide nanofluids at different temperature ranges $10-50\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$ and $20-50\text{ }^{\circ}\text{C}$ respectively. The above studies explored that the nanofluids viscosity is reduced by increasing the temperature. Tavman et al. [43] conducted experimental investigation of viscosity of suspensions containing nanosized Al_2O_3 particles and then they declared that the viscosity of nanofluid augments with increasing the number of nanoparticles and belittles with elevating the temperature.

Nguyen et al. [44] analyzed the effect of particle size on the Al_2O_3 -water nanofluid and showed that the effect of particle size is significant in high volume fractions. They found

that for volume concentrations less than 4%, the viscosity of Al_2O_3 -water nanofluid with a particle size of 36 nm and 47 nm is approximately identical. They declared that the viscosity of a nanoparticle with a size of 36 nm is 5% less than a particle with a size of 47 nm. They also declared that the effect of particle size is more for greater volume fractions (about 7% and 9%). Lu and Fan [45], numerically and experimentally examined the viscosity of Al_2O_3 -water nanofluid and Al_2O_3 -ethylene glycol in different sizes of nanoparticles, and observed that the viscosity of nanoparticles reduces with augmenting particle diameter. Wen et al. [46] found in examining the viscosity of Al_2O_3 -water and Al_2O_3 -ethylene glycol nanofluids that the nanofluids viscosity falls with rising particle diameter. Many researchers investigated the influence of particle size and concentration on the viscosity of Al_2O_3 nanofluids. They arrived at the conclusions that high viscosity increments (as high as 137%) were visualized with smaller particle size and higher concentrations.

On comparison of the results in Murshed et al. [12] with that in Prasher et al. [20], it revealed that the viscosity for water based nanofluids has more influence on nanoparticles than PG based Al_2O_3 nanofluids. Lower viscosity increment is achieved for 20:80% EG/W based Al_2O_3 nanofluids than that for 40:60% EG/W nanofluids (Sundar et al. [47]). In the study of LotfizadehDehkordi et al. [48] experimentally tested the viscosity of Al_2O_3 nanofluids at 0.01–1.0 vol% concentrations. Addition of SDBS surfactant (for stabilization) and sonication in the mixture of alumina nanoparticles with ethylene glycol-water (60:40 mass ratio) base fluid is a unique feature of their study. They observed from their investigation that enhancement of viscosity of nanofluid were 0–23% with particle concentrations of 0.01–1.0 vol%. Spherical and fibrous Al_2O_3 nanoparticles (5.5 vol%) were dispersed into ethylene glycol in a temperature range of 20–80 °C (Kim et al. [49]). With proper sonication for one hour they noticed that the increment of viscosity was higher with fibrous alumina nanofluid. But, at high temperature condition, fibrous nanofluids exhibited less viscosity increment than the spherical one. Duan [50] synthesized water-based Al_2O_3 nanofluids contained with 25 nm size Al_2O_3 nanoparticles at 1%, 2%, 3%, 4%, 5% particle volume concentrations and obtained the viscosities as 20% and 61% higher than the base fluid at 1 vol% and 5 vol%, respectively.

3.1.2 Titanium Oxide (TiO_2) nanofluids

Being environmental friendlier nanoparticles titanium dioxide (TiO_2) nanoparticles are characterized with high chemical and physical stability. TiO_2 nanoparticles are also considered as promising heat transfer medium due to their effective thermophysical properties. Usually, TiO_2 nanoparticles appear in three polymorphic phases such as rutile (tetragonal), anatase (tetragonal) and brookite (orthorhombic). Based on their commercial importance rutile and anatase are best suitable for the most researchers in their investigation of viscosity of nanofluids. TiO_2 nanofluids were synthesized by the two step method (Leena and Srinivasan [51]). In their synthesis, they dispersed distilled water at 0.04–0.2 wt% particle concentrations and sonicated the suspensions for duration of 3 h at 300°K. The resulting nanofluids were observed to be very stable for more than 6 hours. Hwang et al. [52] developed a well dispersed water-based TiO_2 nanofluid wherein they used a high shear

homogenizer to break particle aggregates and implemented electrostatic repulsion mechanism to stabilize nanoparticles for 1 month without any visual sedimentation. Kumar and Sonawane [53] synthesized aqueous and ethylene glycol-based TiO_2 nanofluids with varying duration of ultrasonication and proper dispersion.

The effect of temperature on viscosity of TiO_2 nanofluids is investigated by many researchers. The experimental results agree with the fact that viscosity of nanofluids decreases with the increase in temperature. However, the effectively viscosity ratios of nanofluids vary in different reports. Fedele et al. [54], Silambarasan et al. [55] and Jarahnejad et al. [16] declared that the absolute viscosity decreases with the growth of temperature, but the effectively viscosity ratio remain the same with temperature and it is independent of temperature. Teng et al. [56] found that the increment in viscosity of 0.5 wt% TiO_2 – water nanofluids is doubled when temperature increases from 10 to 40°C. However, some other results reveal that temperature effect on relative viscosity is different at different conditions. For instance, the outcome of Yapici et al. [57] conveyed us that temperature has a great effect on the effective viscosity ratio at low shear rate condition but has little effect at high shear rate condition. Das et al. [58] experimentally studied the thermophysical properties of TiO_2 nanofluids comprising broader particle concentration range of 0.1–2% vol% and at temperatures from 20 to 60°C. With the addition of surfactants like cetyl trimethyl ammonium bromide (CTAB), acetic acid (AA), oleic acid (OA) and sodium dodecyl sulfate (SDS) they found that the viscosity of the nanofluids increased with particle concentration and decreased with temperature. Azmi et al. [59] studied the heat transfer performance of water-ethylene glycol mixture-based TiO_2 nanofluids at temperature 30°C–60°C with proper dispersion and suspension at 0.5–1.5 vol%. The viscosity increments were in the range of 4.6–33.3%.

Arulprakasajothi et al. [60] synthesized water-based TiO_2 nanofluids with different volume concentrations of 0.1%, 0.25%, 0.5% and 0.75% with dispersion deionized water and ultrasonication. Interestingly, viscosity increments of the nanofluids with 0.1%, 0.25%, 0.5%, 0.75% volume concentrations were recorded as 3%, 4%, 6%, 8% and 13%, 13%, 14%, 15%, respectively for different volume concentrations of 0.1%, 0.25%, 0.5% and 0.75%. Sen et al. [61] developed a surface modification method to stabilize the colloidal suspensions of TiO_2 particles with particle concentration in the nanofluids as high as 50 wt%. This method is characterized by functionalization of TiO_2 nanoparticles by sulfonating the surface of the particles. They found that the viscosity increment was maximum at 50 wt% (= 21 vol%) sulfonated nanoparticles (TiO_2-S) loading as a 4-fold increment over that of the base fluid. However, the measured viscosity values of nanofluids with sulfonated nanoparticles (TiO_2-S) were much less than the previously published results.

Besides particle volume fraction and temperature, another factor such as base fluid can also affect the viscosity of TiO_2 nanofluids. Chen et al. [62] examined the viscosity of nanofluids with water and EG as base fluid and containing spherical (25nm) and rod-like (10×100) TiO_2 nanofluids, respectively. The results revealed that for both water and EG based TiO_2 nanofluids, the increment in viscosity by rod-like nanoparticles is much higher than that driven by spherical ones. Particularly, they showed that increment in viscosity of

TiO_2 water nanofluids is definitely higher than that with EG as base fluid. Chen et al. [63] showed that EG based TiO_2 nanofluid is a Newtonian fluid but the water based TiO_2 nanofluid showed non-Newtonian behavior.

3.1.3 Copper Oxide (CuO) nanofluids

Copper oxide is relevant due to its applications in the area of catalysis, superconductors and ceramics as an important inorganic material. It is fact that the nanoparticles of CuO exhibit superior catalytic activity, selectivity, peculiar physical and chemical properties than common copper oxide powder.

Namburu et al. [64] examined the viscosity of CuO (29nm) nanofluids with EG/Water(60:40) as base fluid. They carried out the measurements of the nanofluids in the range of loading from 0% to 6.12% and temperature from $-35^{\circ}C$ to $50^{\circ}C$. They found that the viscosity of nanofluids upsurge with particle loading enhancement and higher particle loading will yield more noticeable augmentation in viscosity. For instance, the viscosity of nanofluid with 3% loading is enhanced by 80%, but with 6.12% loading enhanced four times that of base fluid at $-35^{\circ}C$. Pastoriza-Gallego et al. [65] reported that increased viscosity is dependent on size and poly-dispersity of CuO with maximum relative viscosity=1.73 at 1.7vol% in the temperature range $10^{\circ}C$ to $50^{\circ}C$ for the viscosity of copper oxide nanofluids.

Prakash et al. [66] investigated that viscosity of the propylene glycol-based nanofluids was lower than ethylene glycol-HPLC water mixture (40/60 v/v ratio)-based CuO nanofluids. In their study, they stirred the suspensions for 2h and then added PVP and SLS surfactants and finally sonicated for 2 h to achieve stable solutions at $25^{\circ}C$. Table 1 conveys some reports based on the viscosity of CuO nanofluids.

Table 1 Some reports presented for the viscosity of copper oxide nanofluids.

Authors	Temperature □ & Concentration %	Rheology	Base fluid	Major outcomes with influence ranks
Naik et al [67]	-13 to 57 □ & 0.025 – 1.25 vol%	Newtonian	PG:Water (60:40)	Relative viscosity = 1.043 at 1.2 vol%
Kwak and kim [68]	25 □ & 0.01 – 10vol%	Newtonian (up to 0.1%) then shearthinning	EG:Water	Presence of aggregates, low shear viscosity increases with volume fraction
Pastoriza-Gallego et al. [65]	10-50 □ & 0.16 – 1.7%	-	Water	Increased viscosity is dependent on size and polydispersity of CuO , maximum relative viscosity = 1.73 at 1.7 vol% and 10 □
Namburu et al.[64]	-35 to 50 □ 0 – 6.12 vol%	Newtonian	EG:Water (60:40)	Higher relative viscosity of 4.5 at - 30□ and 6.12 vol%
Priya et al. [69]	25-55 □ & 0.004 – 0.16 vol%	-	Water	Maximum relative viscosity = 1.085 at 0.16 vol% and 55 □

Zennifer et al.[70]	25-140 □ & 0.25 – 1 vol%	Newtonian	EG:Water	Viscosity decrease with NP loading , relative viscosity = 0.87 at 1 vol%
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3.1.4 Zinc Oxide (ZnO) nanofluids

The ZnO nanoparticles are vital in view of its significant applications using their catalytic, electrical, photochemical, and optoelectronic properties. In addition, thermophysical properties of ZnO nanofluids were investigated by many researchers. Recently, investigations revealed that dispersion of ZnO nanoparticles in water without addition of surfactants was not easily carried out [71,72]. The reason behind such difficulties is that the isoelectric point of ZnO nanoparticles is around pH: 7 due to which the charges of ZnO nanoparticles in the suspension are insufficient to resist agglomeration without pH adjustment or surfactant addition (Suganthi and Rajan [71]). Further, the ZnO nanofluids become stable when the ZnO nanoparticles are dispersed into polar organic solvents such as ethylene glycol or propylene glycol by ultrasonic treatment (Witharana et al. [73]).

A mixture of ethylene glycol-water (50:50 vol%)-based ZnO nanofluids was synthesized by Cabaleiro et al. [74]. They implemented the sequential method of Suganthi and Rajan [71] for the synthesis of nanofluids where initially the ZnO nanoparticles were dispersed into ethylene glycol and sonicated in an ultrasonic bath of 90 W for 10 min. The suspension was then diluted by adding requisite amount of water for obtaining 1.0%, 2.5%, and 5% mass concentrations. This method prevents direct contact of ZnO nanoparticles with water. They sonicated the final dispersions at 20 kHz and maximum power of 130 W with optimum conditions 60min effective sonication at 120 W and ultrasound irradiation. An enhancement of viscosity was noticed with particle concentration.

Suganthi and Rajan [71] examined the influence of nanoparticles-liquid interactions on the viscosity of mixture of propylene glycol-water-based ZnO nanofluids. They added 2vol% of spherical ZnO nanofluids in the dispersion of propylene glycol-water (50–50 vol%) suspension which was treated by an ultrasonicator of 130W for 2h with no surfactant addition. The results of the work convey that the viscosity was reduced by 11.4% at 28 °C. Suganthi et al. [75] investigated the heat transfer performance of the mixture of propylene glycol-water-based ZnO nanofluids. They synthesized the suspension of ZnO propylene glycol with 4 vol% particle concentration. The suspension was diluted to 0.5 vol%, 1.0 vol%, 1.5 vol%, and 2.0 vol% concentrations by adding water and then sonicated using an ultrasonication probe. It was observed that 10% reduction in viscosity was obtained at 2 vol% particle concentration. In addition, higher solar heat absorption capability was visualized by the incorporation of ZnO nanoparticles attributing to reduced viscosity of propylene glycol-water-based ZnO nanofluids.

3.1.5 Silicon dioxide (SiO_2) nanofluids

Tavman and Turgut [76] examined the viscosity of water based nanofluids containing SiO_2 nanoparticles. They found that the effective viscosities become up due to the growth of particle loading and reduce with rise in temperature. They further added 1.85 vol.% SiO_2 nanoparticles and observed that viscosity of fluid was increased by 90%. Azmi et al. [59] disclosed in his study that viscosity ratio augmented from 1.05 to 1.49 due to increase in the

volume fraction from 0.5 to 4%. However, there is also a larger enhancement in viscosity of SiO_2 nanofluids in Masuda et al.'s report [77]. They also disclosed that the viscosity was increased up to three times of base water with addition of 2.4 vol. % SiO_2 nanoparticles.

Kulkarni et al. [78] developed EG/W (60: 40wt.%) based SiO_2 nanofluids and measured at different particle loadings (2% to 10%), sizes (20nm, 50nm and 100nm) and temperatures (-35 °C to 50 °C). They found that there is upgradation of viscosity of nanofluids with increase in particle content while it decreases as the particle size or temperature gets enhanced. The effect of particle loading, temperature and base fluid type on the viscosity of SiO_2 nanofluids was examined by Jamshidi et al. [79]. The outcome of their investigation is that the viscosity of SiO_2 nanofluids augmented with the particle loading and diminished with the growth in temperature. In fact, the viscosity of SiO_2 nanofluids with water as base fluid was higher than those with ethylene glycol or transformer oil. As a consequence, lower viscosity base fluid could lead to higher enhancement in viscosity of SiO_2 nanofluids.

3.1.6 Silicon Carbide (SiC) nanofluids

The measurement of the viscosity of SiC -water nanofluids by Yu et al. [80] revealed that the relative viscosity is about 1.8 to 2.0 times the viscosity of base water at 3.7 vol.% particle loading with temperature rise from 25 to 70 °C (viscosity increment is relatively low). A similar enhancement in the viscosity of SiC -water nanofluids was observed by Lee et al. [81]. In this case they found that the viscosity was doubled with the addition of 3 vol.% SiC nanoparticles. They also further found that the relative viscosity of SiC -water nanofluids at every concentration diminished with rise in temperature.

3.2 Magnetic nanofluids

The mixture of different magnetic nanoparticles such as metals (ferromagnetic materials) Co and Fe , metal oxides (ferrimagnetic materials) Fe_3O_4 , Fe_2O_3 , $CoFe_2O_4$ with several base fluids are referred as magnetic nanofluids [82-84]. Especially the magneto nanofluids are significant in applications like optical modulators, magneto-optical wavelength filters, tunable optical fibre filters and optical switches. Magnetic nanoparticles are especially useful in biomedicine, sink float separation, cancer therapy, aerospace etc. Specific biomedical applications involving nanofluids include hyperthermia, magnetic cell separation, drug delivery and contrast enhancement in magnetic resonance imaging [85-97]. Because the magnetic nanofluids can be controlled and manipulated by an external magnetic field, researchers consider such fluids as promising fluids in heat transfer applications [98-99]. Sundar et al. [47] examined the viscosity of nanofluids with water as base fluid and Fe_3O_4 as nanoparticles. Nanofluids were synthesized through proper dispersion, CTAB surfactant addition and sonication. They found the results later that for 0.2 vol% concentration, the viscosity upsurged by 106.3% at 20°C and 209% at 60°C.

3.3 Metallic nanofluids

Singh et al. [100] obtained the dispersion of Cu nanoparticles at different concentrations into synthetic oil. Well-Defined single crystal nanoparticles at 50–100 nm size range were developed after sonication of 4hrs at 120 °C. They found that the viscosity augmented with

the increase of particle loading. Diethylene glycol-based *Cu* nanofluids were prepared through the dispersion of diethylene glycol and *Cu* nanoparticles and proper sonication (Nikkam et al. [101]). The lower increments of viscosity of nanofluids were accomplished. Aqueous-based bimetallic *Cu/Pd* nanofluids with various molar ratios were developed by Jaiswal et al. [102]. Stable suspensions were achieved through PVP. They observed that addition of *Cu* nanoparticles led to small increments of viscosity of nanofluids. Because of high cost, few investigators have carried out their studies on gold and silver nanofluids. Chen and Wen [103] prepared an ultrasonic-aided single-step method for synthesizing gold nanofluids. The addition of a very low concentration of *Au* nanoparticles in water resulted in lower viscosity of nanofluids.

3.4 Diamond nanofluids

Diamond nanofluids have great advantages over other nanofluids due to the highest thermal conductivity of diamond (Diamond is characterized with strong carbon-carbon covalent bonding and low phonon scattering). For instance, thermal conductivity is typically over 2200 W/(mK) and as high as 3320 W/(mK) of isotropically pure monocrystalline synthetic diamond [104]. In order to suppress aggregation and improve the dispersion behavior of nanofluids, three different methods such as use of surfactants, pH control, and ultrasonic agitation have been implemented. To examine the nanoparticle shape and other significant characteristics transmission electron microscopy (TEM) has been usually applied before being the nanoparticles dispersed into the base fluid. In the analysis of diamond nanofluids, zeta potential is the best suitable method to evaluate nanofluid stability and dispersion. Sundar et al. [105] took nano diamond soot with strong sulfuric acid and nitric acid solution in their synthesis. The carbon impurities were removed by acid treatment and the nanodiamond particles were functionalized by forming carboxyl groups on the nanoparticle surfaces. The synthesized nanoparticles were dispersed into the base fluid of ethylene glycol water mixtures at varying mixing ratios. The suspensions were subject to sonication for 2h in an ultrasonic bath. Zeta potential was applied for the stability of the synthesized nanofluids. Their outcomes include that the viscosity values were also enhanced by 274%, 173% and 192%, respectively, at 1.0 vol% concentration and at 60^oC . The same acid treatment procedure was carried out on diamond nanoparticles by Sundar et al. [47]. In the synthesis procedure carboxylated nanodiamond particles were dispersed into distilled water at varying concentrations and then the solution was sonicated in an ultrasonic bath for 2 h. in view of long term stability along with good dispersion, zeta potential was adopted and the pH of the solution was adjusted by addition of *NaOH* . Under these conditions the viscosity was highly increased by 179%. Such very high viscosity increments implicate insufficient thermal properties of nanodiamond nanofluids. Kalidasan and Kanna [106] studied the natural convection on an open square cavity containing diagonally placed heaters and adiabatic square block and filled with hybrid nanofluid of nanodiamond - cobalt oxide/water. The influence of ash content on thermophysical properties of ethylene glycol based graphite/diamonds mixture nanofluids was analyzed by Yla et al. [107]. Further, Puzir et al. [108] explored the effect of silver ions electrolytically introduced into colloidal nanodiamond solution on its viscosity and thermal conductivity.

Augmentation in viscosity is the result due to addition of diamond nanoparticles to a base fluid. Such result is not desirable as it yields energy loss. This enhancement may be influenced by nanodiamond concentration and particle size. An enhancement of 20% in

viscosity at higher-concentration nanofluid samples was obtained by Ghazvini et al. [109]. Increasing density of a nanofluid did not yield significant increase in kinematic viscosity of the diamond nanofluid (Taha-Tijerina et al. [110]). However, up to a 12% increase in dynamic viscosity was obtained in a nanodiamond volume fraction of 0.03% at 100°C. Such increment was not a large rise compared to other studies, for instance the one by Gudson et al. [111] where more than a 30% rise in dynamic viscosity has been declared for silver nanofluids. Further, Tyler's work [112] reported 7, 76 and 140% increase in viscosity for concentrations of 1, 2 and 3 wt% using midel oil as the base fluid attributing to their large-sized nanoparticles (around 450 nm on average) compared to other nanodiamond fluids. Sundar et al. [47] found that the viscosity of the diamond nanofluids upsurges with more particle loading and belittles with rising temperature. The highest nanodiamond fluid viscosity rise was reported as 79% at 60°C. They compared their viscosity results with theoretical models for two-phase suspensions and validated the results. Generally, there is no consistency between viscosity increases in diamond nanofluids. The base fluid properties and, above all, interactions between the base fluid and diamond nanoparticles have the most influence on the viscosity.

When nanodiamond particles are added to dielectric fluids, such heat transfer nanofluids characterized by high thermal conductivity and minimal electrical conductivity can be appropriate for electronic cooling applications [113]. The thermal behavior of the cooling fluid in the fin-type heat sink of a central processing unit (CPU) in computers was modeled and compared it with experimental results (Naphon et al. [114]). Their results led to a non-uniform temperature distribution in the heat sink, which could be a problem for the electronic devices. However, those results can be guidelines for achieving a novel cooling system designed with enhanced thermal performance. Experimental examinations and simulations on diamond nanofluid thermal properties and heat transfer characteristics associated with cooling desktop PCs was carried out by Gunnasegaran et al. [115]. Three different nanoparticles including nanodiamond in transformer oil were examined by Choi et al. [116]. They considered them as a new type of coolant for automotive heat management. Ma et al. [117] reported that diamond nanofluid-based oscillating heat pipes can extract heat fluxes exceeding $10\text{MW}/\text{m}^2$ which they considered as the future generation of cooling devices in electric systems. Diamond nanofluids can be applied in wheel grinding and the associated tribological behavior in grinding of cast iron under wet and dry conditions (Shen et al. [118]). They used a minimum amount of lubrication for potential applications in engine operation and compared the results with those of water. They found that diamond nanofluid grinding could significantly reduce the grinding temperature and grinding forces, increase surface roughness, and prevent work piece burning compared to dry grinding.

3.5 Carbon nanotubes nanofluids

In 1991, Sumio Iijima [119] discovered carbon nanotubes. Because of excellent properties carbon nanotubes have been attracted by diversified sectors [120-122]. In the beginning, multi walled carbon nanotubes (MWCNTs) in carbon soot were produced by an arc discharge method (Iijima [123] in 1991. Two years later, he observed the single walled carbon nanotubes (SWCNTs). Dispersion of CNTs in the base fluid is challenging due to the tendency of nanotubes to agglomerate. Stable CNT nanofluids can be synthesized physically by ultrasonication, high shear mixing, ball milling, and/or chemically by functionalization through altering the surface chemistry of the nanotubes covalently, and the addition of

surfactants which adsorb onto the nanotubes surfaces non-covalently. Functionalization over the other surfactant free method provides good fluidity, long-term stability, significant heat transfer (Aravind et al. [124]). Functionalized CNTs are used as advanced heat transfer fluids in thermal energy/heat exchange engineering systems. They evaluated the viscosity of four groups of CNTs nanofluids at a very low volume fraction of 0.005% and 0.03% with water and EG as base fluids, respectively. The results conveyed that the relative viscosity of CNTs nanofluids is not sensitive to the base fluid type but influenced by the temperature since the relative viscosity at 70°C was higher than that at 30°C . A functionalization method to stabilize CNT nanofluids was developed by Esumi et al. [125]. In this method, 1 g CNT was dispersed and treated in a mixture of concentrated nitric acid and sulfuric acid (1:3 volume ratio) for 30 mins and refluxed at 140°C . Having washed with deionized water till $\text{pH} = 7$ nanotubes were dried at 100°C in vacuum and then 0.01 g of dried samples were suspended in 30 ml of different liquids. Ultrasonication was applied to the latest suspensions about 4hr. The resultant nanotubes were well dispersed into individual fibers in base fluids. This established method has been applied by many researchers in their experiments ([126-129]). The colloidal stability of functionalized MWCNT-based nanofluids was examined by Lamas et al. [130] where he suggested that functionalization of CNTs helps greatly in the formation of highly stable nanofluids. The thermophysical properties of water-based SWCNTs nanofluids with varying nanotubes concentrations in the range of 0.1–1 wt% and at a temperature range of $10\text{--}100^{\circ}\text{C}$ was studied by Xing et al. [131]. They declared from their study that viscosity and density of nanofluids incremented with the rise in nanotubes concentration. An increased viscosity of 35.9% at 1 wt% nanotubes loading at 60°C was reported. Ding et al. [28] used a variety of surfactants in stabilizing CNT-water nanofluids. Surfactants such as sodium laurate (SL), sodium dodecyl benzene sulfonated (SDBS) and Gum Arabic (GA) can stabilize CNTs in the suspension for over 1 month without any visual sedimentation. They reported linear shear thinning behavior of their nanofluids whereas their base showed nonlinear shear thinning nature. Sabiha et al. [132] prepared a water-based SWCNTs nanofluid with addition of SDS to stabilize the suspensions and with sonication for 1h. Increment of viscosity by 82.01% was the expected result. Singh et al. [133] investigated the viscosity of CNT-EG nanofluids. Before CNTs being dispersed into ethylene glycol and sonicated for 1.5 h, those were functionalized by acid treatment. The outcome of the study was that viscosity increased with CNT concentration but exponentially decayed with temperature.

Chen et al. [134] examined the viscosity of CNTs-water nanofluids and found that increment of temperature from 6 to 65°C can greatly reduce the viscosity of nanofluids but has little effect on the relative viscosity. With the addition of very slight amount of CNTs, such as 0.2vol.% can unexpectedly reduce the viscosity of base fluid. This implicates that the nanofluid has a lower viscosity compared to the base fluid. Phuoc et al. [135] found that the viscosity of water based nanofluids containing 0.5wt% CNTs were lower than distilled water. This is due to the lubricating effect of nanoparticles. Besides the particle loading and temperature effect, the shear rate effect is more extensively studied. CNTs nanofluids exhibit non-Newton behavior. Ko et al. [136] synthesized two types of water based CNTs nanofluids by acid treatment and by surfactant treatment, respectively. Their results showed that both kinds are non-Newton fluids and exhibit noticeable shear thinning behavior at all kind of concentrations. The viscosities of CNTs nanofluids prepared by both acid and surfactant treatment (TCNT) are lower than that of pristine CNTs nanofluids (PCNT). Further, the

viscosities of CNTs nanofluids developed by the acid treatment are obviously lower than the ones developed with surfactant. Garg et al. [137] measured the viscosity of CNTs nanofluids prepared by different period of ultrasonication. They disclosed that CNT nanofluids showed a typical non-Newtonian behavior in accordance with the Power Law viscosity model. The initial sonication will induce growth in viscosity of nanofluids. The rationale behind is that the clusters of CNT bundles by sonication improve the dispersion. However, the longer time sonication breaks the CNTs into shorter ones which in turn destroy the networking of CNTs and weaken the dispersion situation there by decreasing in viscosity. The impact of particle loading and temperature on the viscosity of CNT nanofluids was reported by Halefadi et al. [138]. The results revealed that the nanofluids exhibited Newtonian behavior at lower particle loading but a shear thinning behavior at higher loading. The viscosity greatly increases at high particle loading owing to the aggregates of CNTs. Temperature has impact on the absolute viscosity but has little effect on the relative viscosity of nanofluids at high shear rate. Many others [139-140] discussed in the related areas. Ding et al. [28] analyzed the viscosity of CNT water nanofluids under different particle loading, temperature and pH values. In their study, they observed that the viscosity of water-based nanofluids of multi-walled carbon nanotubes as a ratio of the shear rates in different volume fractions and temperatures. Their report reveals that at all shear rates, the viscosity of nanofluid enhances with rise in the volume fraction and reduces with incrementing the temperature. They also revealed the Newtonian behavior for a nanofluid without surfactant. With adding Arabic gum as a surfactant, they observed a thin shear behavior for lower shear rates and a thick shear behavior for shear rates over $200s^{-1}$. The experimental results focused in Fig.3 represents that the viscosity of CNT nanofluids upsurge with the rise of particle content and fall in temperature. It is also shown in Fig. 4 that how the viscosity varies with temperature for nanofluids made with water and ethylene glycol as base fluids and with multi walled carbon nanotubes as nanoparticles. A shear thinning behavior in nanofluids was noticed. Such characteristic is applied to tubular geometry because the lower viscosity and better lubrication appear at the wall region. They also showed that the viscosity of pure gum Arabic fluid is much lower than that of the CNT nanofluid. They also eliminated the doubt that the gum Arabic dispersant produce the shear thinning behavior since the viscosity of pure gum Arabic fluid is much lower than that of the CNT nanofluid (Fig.5).

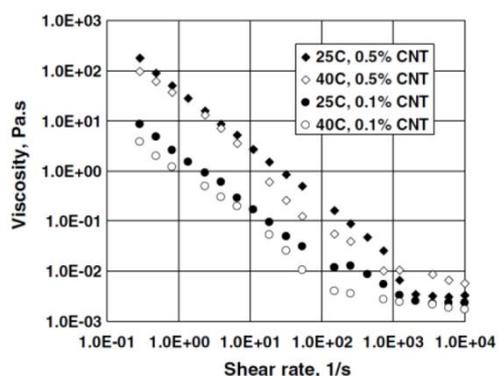


Fig. 3 Viscosity as a function of shear rate for CNT nanofluids (Ding et al. [28])

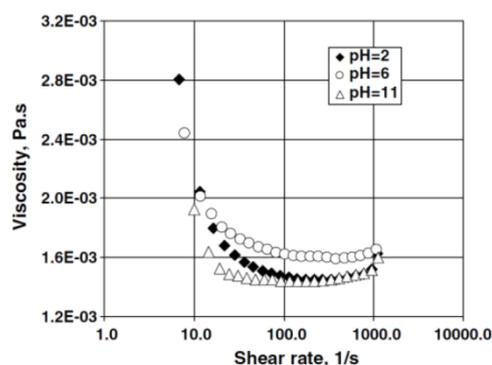


Fig. 5 Viscosity as a function of shear rate for gum Arabic solutions: 0.25% (Ding et al. [28])

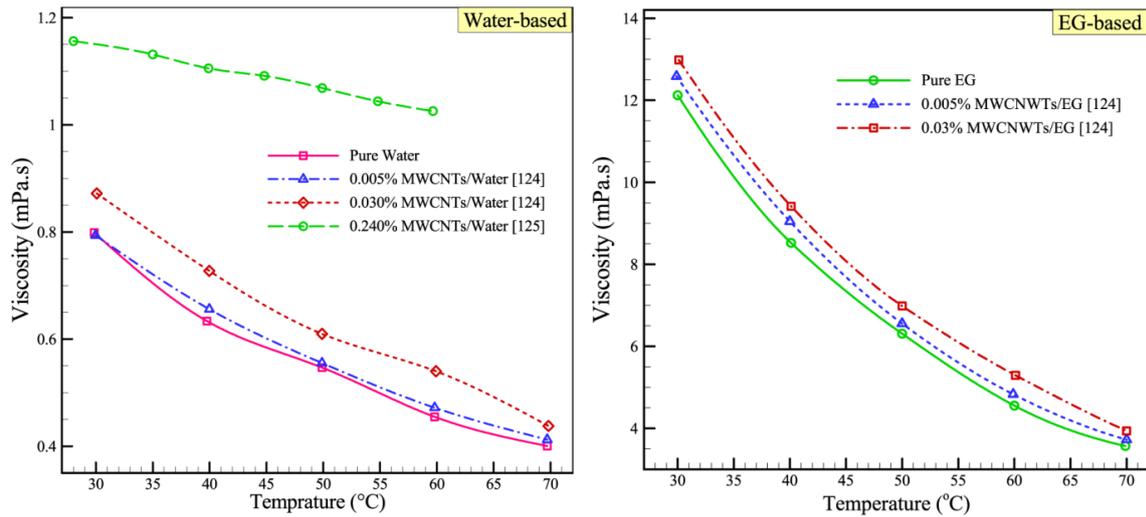


Fig. 4 Viscosity changes with temperature for Water-based and EG-based nanofluids containing MWCNTs (Khodadadi et al. [139])

In another study, Yang et al. [141] used polyisobutylene succinimide surfactant for the production of a nanofluid of multi-walled carbon nanotubes in oil. They also used the ultrasonic methods for homogenization and stabilization. They showed that this surfactant well controlled the viscosity of nanofluids, especially at low shear rates. The Newtonian behavior is observed for very low volume fractions of carbon nanotubes while the non-Newtonian behavior is observed at low shear rates. Kinloch et al. [142] studied the rheological behavior of water nanofluid-oxidized carbon nanotube. He observed a thin shear behavior for all nanofluids volume fractions. They also observed augmented viscosity by increasing the volume fraction. Vakili-Nezhaad and Dorany [143] determined the suspension of single-walled carbon nanotubes in lubricating oil at temperature ranging from 25^oC to 100^oC and obtained that increase of 33% viscosity of this nanofluid in a 0.2% volume fraction. Ruan and Jacobi [144] examined the rheological properties of nanofluid produced by considering multi-walled carbon nanotubes as nanoparticles and ethylene glycol with a volume fraction of 0.5 as base fluids with ultrasonic effects. They disclosed that at a constant shear rate, the viscosity initially increased and then decreased, with rising ultrasonic time. Table 2 conveys some studies conducted on nanofluids made with different carbon nanotubes.

Table 2 Some studies on nanofluids made with carbon nanotubes.

Authors	CNTs/base fluid	Rheology	Key results/remarks with influence ranks
Yang et al. [145]	MWCNTs/Oil	Newtonian and shear thinning	At $\phi = 0.34\text{vol}\%$ $\tau = 10\text{Pa}$: $\mu_{eff} = 1570$ $\tau = 50\text{Pa}$: $\mu_{eff} = 30.20$
Garg et al.[146]	MWCNTs/Water	Non-Newtonian shear thinning	A number of mechanisms related to boundary layer thickness ,micro-convective effects,particle rearrangement, effect due to viscosity
Chen et al.[41,128]	MWCNTs/Water	-	At $\phi < 0.4\text{vol}\%$ $T < 55^\circ$: $\mu_{eff} < 1$ (decreasing) $T=55^\circ$: $\mu_{eff} > 1$ (increasing)

Xie and Chen [147]	MWCNTs/Silicon oil	Newtonian	At $\varphi = 0.54wt\%$: $\mu_{eff} < 1$ (decreasing)
Phuoc et al.[135]	MWCNTs/Water	Non-Newtonian	At $\varphi = 0.5 wt\%$: $\mu_{eff} = 0.8$ (decreasing)
Harish et al.[148]	SWCNTs/Water	-	At $\varphi = 0.3vol\%$: $\mu_{eff} = 1.3$
Estelle et al.[149]	MWCNTs/Water	Newtonian and shear thinning	At $\varphi = 0.55vol\%$ $\mu_{eff} = 5.2$ wit \square SDBS $\mu_{eff} = 1.5$ wit \square lignin
Sadri et al.[150]	MWCNTs/Water	Newtonian and shear thinning	Nanofluids viscosity increased up to 7 min of sonication and then decreased with more rise in sonication time
Maillaud et al.[151]	CNTs/Water	Shear thinning	Nanofluids viscosity augmented with TX100 and CNT loading

3.6 Other nanofluids

Fe_2O_3 nanofluids

There are some factors including particle loading, temperature, surfactant, shear rate and shear time have impacts on viscosity of Fe_2O_3 nanofluids. Abareishi et al. [152] synthesized $\alpha - Fe_2O_3 -$ glycerol nanofluids and revealed that the viscosity shows an ascending trend with increase of particle volume fraction and belittles with the growth of temperature. The magnetic $\alpha - Fe_2O_3 -$ glycerol nanofluids exhibit non-Newtonian behavior where the shear viscosity is greatly affected by temperature. As a unique property, they found that the relative viscosity is lower than the prediction of conventional models. The viscosity of ammonia water based Fe_2O_3 nanofluids with SDBS as dispersant was studied by Yang et al. [145]. They observed that the effect of surfactant on the viscosity is greater in comparison to Fe_2O_3 nanoparticles at low concentrations. They also observed that the viscosity will decrease due to the addition of very little amount of Fe_2O_3 nanoparticles in ammonia water with higher concentration of SDBS. The root cause behind this decrement in viscosity is that the adsorption of SDBS on the particle surface will reduce the “free surfactant” in the fluid. Pastoriza-Gallego et al. [65] analyzed the viscosity of EG based Fe_2O_3 nanofluid at room temperature. In their investigation, the nanoparticles are composed of hematite of hexagonal scalenohedral-shaped ones. According to their declaration for a given shear rate, $Fe_2O_3 - EG$ nanofluids showed non-Newtonian behavior and the shear thinning effect is related to the time until arrives at a final status of exhibiting viscoelasticity.

$Al_2O_3 -$ Isopropanol nanofluid

Initially, the original dried out nanoparticles were characterized by SEM (scanning electron microscopy), TEM (transmission electron microscopy) and EDS (electron diffraction spectra). Here, nanoparticles are close to spherical in shape. The TEM images were used to measure the size of dry nanoparticles and reported that the log-normal distribution for dry

nanoparticles corresponds to 8 nm. Further, distribution of nanoparticles size in solution obtained by DLS is also lognormal, but its peak corresponds to 70 nm (mean size is 75 nm). Moreover, the mean size of nanoparticles obtained by ST (spectral turbidimetry) method [153–155] was 82 nm. The viscosity of nanofluids obtained from theory is in good agreement with obtained experimental results at low concentrations of nanoparticles (up to 0.992 mass %). However, at the higher concentrations of nanoparticles in the solution the deviations are quite big (up to 0.53 m Pa s) [Fig. 6].

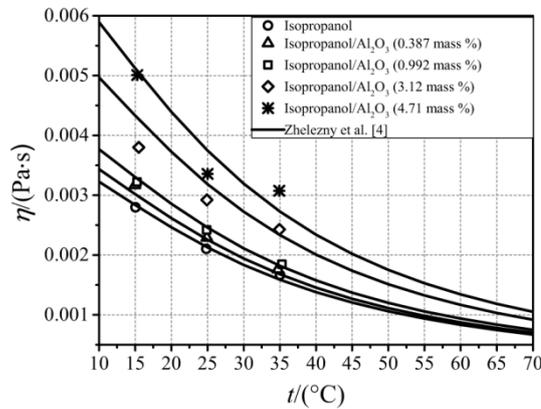
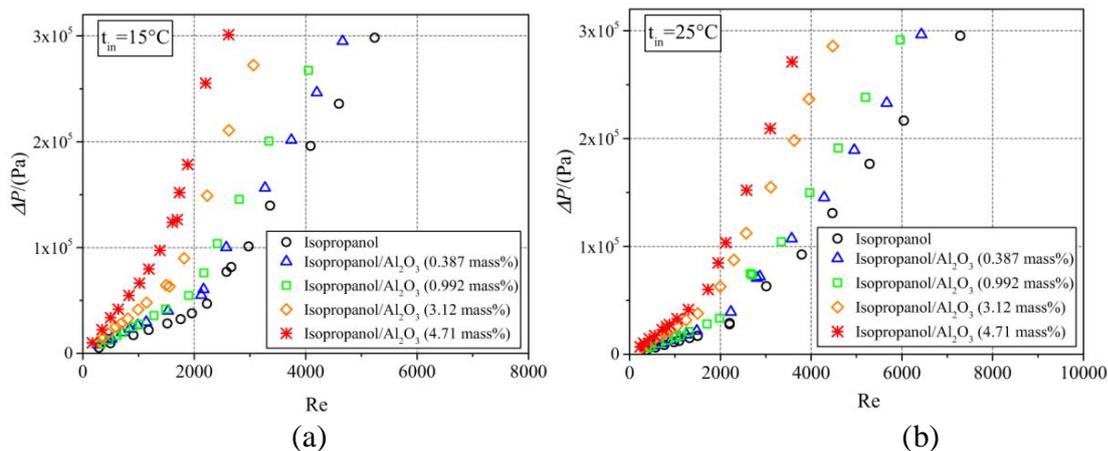


Fig. 6 Viscosity as a function of the temperature and mass fraction of nanoparticles

The experimental study on the viscosity of nanofluids revealed that at 4.71 mass% of nanoparticles the temperature dependence of the viscosity is non-linear. It is important to mention here that the non-linear temperature dependence of viscosity was previously found in Murshed et al. [33] and indicate structural changes in isopropanol/ Al_2O_3 nanofluid at the certain concentrations and temperatures. Moreover, the temperature dependence of the viscosity at 4.71 mass% shows a non linear behavior. Furthermore, isopropanol/ Al_2O_3 nanofluids obey Newton’s law of viscosity (Newtonian liquid) within the entire range of parameters and with addition of Al_2O_3 nanoparticles to isopropanol increase the viscosity. As far as the hydrodynamic behavior of the nanofluid is concerned, the higher viscosity of the nanofluid, due to the enhancement of the nanoparticles mass fraction, leads to a rise in pressure drop, both in laminar and turbulent regimes [Fig. 7].



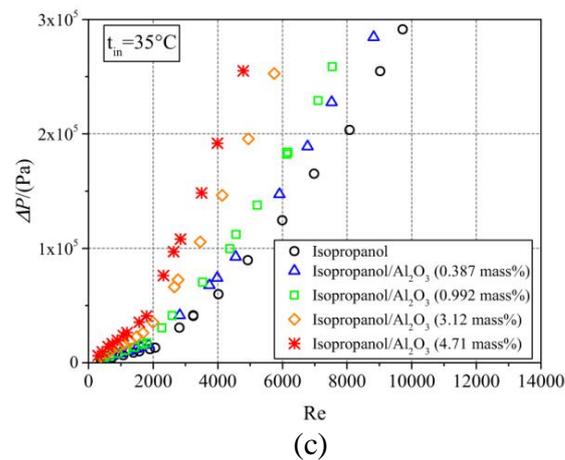


Fig. 7 Pressure drop as function of Re number and mass fraction of nanoparticles for: (a) $t_{in} = 15^{\circ}C$ (b) $t_{in} = 25^{\circ}C$ (c) $t_{in} = 35^{\circ}C$ (Nikulin et al. [156])

$CaCO_3$ nanofluid

The $CaCO_3$ –water nanofluids possessing $CaCO_3$ nanoparticles of sizes 20 to 50 nm was synthesized by Zhu et al. [157]. A relatively modest growth in viscosity of nanofluids about 70% at 4 vol.% particle loading was their result.

$MgAl_2O_4$ nanofluid

Zyla et al. [158] studied on the viscosity of diethylene glycol based $MgAl_2O_4$ nanofluids at different shear rates at a very high pressure of 7.5 MPa. They found the Newtonian behavior of the nanofluid where the viscosities at such high pressure are higher than that at atmospheric pressure. They also found that the viscosity of this kind of nanofluid is not influenced by the electric field.

$FeC - H_2O$ nanofluid

Huminic et al. [159] investigated the impact of viscosity on a rare kind of nanofluid viz. FeC –water nanofluids. Their results showed that the viscosity is increased by 20% due to the addition of 1% nanoparticle in water. The summary of experimental data on viscosity of nanofluids from different investigations conducted by some researchers is enlisted in Table-3.

Table 3 Summary of experimental data on viscosity of nanofluids in different investigations.

Authors	Nanofluid Type	Size (nm)	Volume fraction (%)	Temperature(C)	Viscosity ratio (μ_{nf} / μ_{bf})
Chandrasekar et al. [9]	Al ₂ O ₃ /water	43	0.33-5	Room	1-2.36827
Wang et al. [160]	Al ₂ O ₃ /water	28	5-6.17	Room	1.855-1.765
Pak and Cho [32]	Al ₂ O ₃ /water	13	1.3-2.78	Room	1.615-2.59
Nguyen et al. [161]	Al ₂ O ₃ /water	36-47	0-13	Room	4.315-5.44
	Al ₂ O ₃ /water	47	1	20-43-71	1.128-
	Al ₂ O ₃ /water	36	1	20-43-71	1.035-
	Al ₂ O ₃ /water	47	9	20-45-54	1.129
	Al ₂ O ₃ /water	36	9	20-58	1.223-1.066-1.145-4.446-3.550-3.801-5.311-4.368
Kole and Dey[39]	Al ₂ O ₃ -Car coolant	< 50	0.1-1.5	10	1-2.096
	Al ₂ O ₃ -Car coolant	< 50	0.1-1.5	30	1.033-
	Al ₂ O ₃ -Car coolant	< 50	0.1-1.5	45	2.352-1.030-2.459
Murshed et al. [12]	Al ₂ O ₃ -DIW	80	1-5	Room	1.03597-1.82734
Prasher et al. [20]	Al ₂ O ₃ -PG	27-50	0.5	30	1.070-
	Al ₂ O ₃ -PG	27-50	2	30	1.053
	Al ₂ O ₃ -PG	27-40-	3	30	1.236-
	Al ₂ O ₃ -PG	50	3	40	1.153
	Al ₂ O ₃ -PG	27-40-	3	50	1.277-
	Al ₂ O ₃ -PG	50	3	60	1.363-
		27-40-			1.218
		50			1.291-
		27-40-			1.376-
		50			1.231-1.306-1.349-1.246-1.306-1.349-

					1.267
Schmidt et al. [163]	Al ₂ O ₃ -decane	40	0-1	Room	1-1.086
	Al ₂ O ₃ -PAO	40	0-1	Room	1-1.073
Anoop et al. [162]	Al ₂ O ₃ -water	95	0-7	20	1-1.772
	Al ₂ O ₃ -water	100	0-7	20	1-1.572
	Al ₂ O ₃ -EG	100	0-7	20	1-1.298
	CuO-EG	152	0-7	20	1-1.321
Nguyen et al. [44]	CuO-water	29	1	20-67	1.188-
	CuO-water	29	4	20-63	1.112
	CuO-water	29	7	20-57	2.147-
	CuO-water	29	9	20-45-51	1.840 4.409- 3.566 9.776- 6.939- 7.284
Namburu et al. [64]	CuO-ethylene	29	1	-35- -30-50	1.145-
	CuO-ethylene	29	2	-35- -30-50	1.230-
	CuO-ethylene	29	3	-35- -20-50	1.102
	CuO-ethylene	29	4	-35- -30-50	1.675-
	CuO-ethylene	29	5	-35- -30-50	1.780-
	CuO-ethylene	29	6.12	-35-50	1.399 1.802- 1.950- 1.613 2.396- 2.523- 1.929 3.117- 3.286- 2.375 4.537- 3.032
Kwak and Kim [68]	CuO-ethylene	10-30	0.001-1	Room	1-1.04855
He et al. [164]	TiO ₂ -Water	20	0.125-1	Room	1.11-2.41
He and Zheng [165]	TiO ₂ -BaCl ₂ /water	-	0.167- 1.13	Room	1.029- 1.319
Ling et al. [166]	TiO ₂ -Water	35	0-0.225	Room	1.072
Chen et al. [167]	TiO ₂ -EG	10×100	1.8	Room	1.72
	TiO ₂ -water	10×100	0.1-0.6	Room	1.01-1.82
	TiO ₂ -EG	25	0.25-1.2	Room	1.03-1.11
	TiO ₂ -Water	25	0.1-1.86	Room	1.005-1.23
Mahbubul et al. [17]	TiO ₂ -R123	21	0.5-2	Room	1.013-1.052

Yiamsawas et al. [168]	TiO ₂ -EG/Water(20/80wt%)	21	1-4	Room	1.136-1.60
Arulprakasajothi et al. [60]	TiO ₂ -Water	32	0.1-0.75	Room	1.005-1.021
Chen et al. [134]	CNTs-DW	15-30	0.2	6-65	0.930-
	CNTs-DW	15-30	0.4	6-65	1.706
	CNTs-DW	15-30	0.6	6-60	0.951-
	CNTs-DW	15-30	0.8	6-65	1.407
	CNTs-DW	15-30	1	10-60	1.045-1.334
Lee et al. [81]	SiC/DIW	≤100	0.001	30-70	1.1763-1
	SiC/DIW	≤100	0.1	30-70	1.285-
	SiC/DIW	≤100	1	30-70	1.077
	SiC/DIW	≤100	2	30-70	1.458-
	SiC/DIW	≤100	3	30-70	1.512
	SiC/DIW	≤100	0-3	30	1.938-
	SiC/DIW	≤100			1.621
Yu et al. [80]	SiC-Water	170	3.7	25-70	2.024-1.761
Masuda et al. [77]	SiO ₂ -water	12	2.4	12	1-2.018
Tavman and Turgut [76]	SiO ₂ -water	12	1.85	20-50	1.7
Azmi et al. [59]	SiO ₂ -water	50	4	30	3
Tseng and Chen [169]	Nickel-Terpineol	-300	3-10	25	1.9
Zhu et al. [157]	CaCO ₃ -water	20-50	0-4	Room	1.49
Huminic et al. [159]	FeC-water	7-14	1	15-70	4.396-474.725
					1-1.692
					1.275-1.203

4. Role of Models on the Viscosity of Nanofluids

4.1 Theoretical Models

In the past decades, many theoretical models on viscosity of nanofluids have been developed by researchers. The most classic and pioneer model was developed by Einstein [170]. This model can be used in low concentrations of below 2 vol.% because the model

considered the hard sphere particles and non-interaction among them. The Einstein model reads

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\phi \quad (1)$$

where μ_{nf} is the dynamic viscosity of the nanofluid, μ_{bf} is the dynamic viscosity of base fluids and ϕ is the nanoparticle volume fraction.

After Einstein's precious gift to the society, many researchers have been succeeded in accomplishing new eye-catching models in amending or upgrading it. Brinkman [171] extended the Einstein model considering a little higher volume fraction of 4% and provided his model as:

$$\mu = \frac{\mu_f}{(1-\phi)^{2.5}} \quad (2)$$

Further, de Bruijn [172] also extended Einstein model to a higher concentration as follows:

$$\mu = \mu_f (1 - 2.5\phi + 1.55\phi^2) \quad (3)$$

Batchelor [173] introduced the effect of Brownian motion and interactions of hard spherical particles and developed a correlation as:

$$\mu = \mu_f (1 + 2.5\phi + 6.5\phi^2) \quad (4)$$

Considering the effect of Brownian motion and mutual forces in suspension Vand [174] proposed two equations to determine the viscosity of suspension as:

$$\left. \begin{aligned} \log\left(\frac{\mu}{\mu_f}\right) &= \frac{2.5\phi + 2.5\phi^2}{1 - 0.609\phi} \\ \mu &= \mu_f (1 + 2.5\phi + 7.34\phi^2) \end{aligned} \right\} \quad (5)$$

Lundgren [175] developed a formula based on the Taylor series expansion as:

$$\mu = \mu_f (1 + 2.5\phi + 6.5\phi^2 + O(\phi^3)) \quad (6)$$

In a study Guo et al. [176] declared that small particle size will induce higher viscosity in nanofluids, and they upgraded Batchelor's correlation associated with particle size effect and then developed his own correlation as follows:

$$\mu = \mu_f (1 + 2.5\phi + 6.5\phi^2)(1 + 350\phi/d) \quad (7)$$

where d is the particle radius.

Considering the particle radius and inter-particle distance, Graham [177] developed a correlation similar to Einstein model as:

$$\left. \begin{aligned} \mu &= \mu_f \left[(1 + 2.5\phi) + \frac{4.5}{(l/d)(2+l/d)(1+l/d)^2} \right] \\ \mu &= \mu_f (1 + 2.5\phi + 6.5\phi^2)(1 + 350\phi/d) \end{aligned} \right\} \quad (8)$$

where d is the particle radius and l is the inter-particle distance.

Considering higher volume concentrations, Thomas et al. [178] developed correlation as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 2.5\phi + 10.5\phi^2 + 0.00273e^{166\phi}) \quad (9)$$

Krieger and Dougherty [179] presented a correlation where they have adopted the difference of viscosity in different shear rate. The resulting model is as follows:

$$\mu_{nf} = \mu_f \left(1 - \frac{\phi}{\phi_m}\right)^{[\eta]\phi_m} \quad (10)$$

Where ϕ_m is the maximum particle volume concentration, which is between 0.495 to 0.54 for static fluid and 0.605 for high shear rates. $[\eta]$ is the intrinsic viscosity, whose typical value for mono disperse suspensions of hard spheres is 2.5.

Chen et al. [63] modified Krieger and Dougherty model by taking into consideration the packing volume fraction of an imaginary sphere possessing clusters based on fractal theory. Their modified form of correlation is

$$\mu_{nf} = \mu_f \left(1 - \frac{\phi_{cl}}{\phi_m}\right)^{[\eta]\phi_m} \quad (11)$$

where ϕ_{cl} is the volume fraction of clusters.

Jeffrey and Acrivos [180] developed another model for the viscosity of non-dilute suspensions of rod-like particles in extensional flow. The model is as follows:

$$\mu_{eff} = \mu_f \left\{ 3 + \frac{4}{3} \left(\frac{\phi r^2}{\ln\left(\frac{\pi}{\phi}\right)} \right) \right\} \quad (12)$$

This formula reveals that even though ϕ is small, the factor r^2 causes substantial increase in relative viscosity $\left(\frac{\mu_{eff}}{\mu_f}\right)$ over the Newtonian value of 3.

Taking interfacial layers surrounding the clusters into consideration, Selvakumar and Dhinakaran [181] upgraded Chen et al's model and developed the new model as

$$\mu_{nf} = \mu_f \left(1 - \frac{\phi_{ecl}}{\phi_m}\right)^{[\eta]\phi_m} \quad (13)$$

$$\phi_{ecl} = \phi_{cl} (1 + \beta)^3 \quad (14)$$

where ϕ_{ecl} is the effective volume fraction of the cluster with interfacial layers. β is the ratio of interfacial layer thickness to the average cluster radius.

In order to establish a relationship between viscosity with the volume concentration and the maximum particle volume concentration, Franken and Acrivos [182] proposed a model as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{9 \left(\frac{\phi}{\phi_m} \right)^{\frac{1}{3}}}{8 \left[1 - \left(\frac{\phi}{\phi_m} \right)^{\frac{1}{3}} \right]} \quad (15)$$

A model meant for calculating the viscosity of suspension with a solid-liquid mixture was developed by Kitano et al. [183]:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{\left[1 - \left(\frac{\phi}{\phi_m} \right) \right]^2} \quad (16)$$

The power law model to determine the viscosity of nanofluids at higher volume fraction more than 2% was developed by Nielsen [184]. The model is as follows:

$$\mu_{nf} = \mu_f (1 + 1.5\phi) e^{\frac{\phi_m}{1-\phi_m}} \quad (17)$$

It is important to mention here that the above concentration. However, the viscosity of nanofluids can also be influenced by other important factors such as temperature and density of particles. In view of this some authors taking such aspects into consideration developed some new models.

Masoumi et al. [185] considered the effect of density of nanoparticles, Brownian motion, temperature and diameter of nanoparticles and developed their model accordingly as

$$\mu_{nf} = \mu_f + \frac{\rho_p V_B d}{72cl} \quad (18)$$

where ρ_p is the density of nanoparticle, $V_B = \frac{1}{d} \sqrt{\frac{18k_B T}{\pi \rho_p d}}$ is the Brownian velocity, k_B is the

Boltzmann's constant, $l = \left(\frac{\pi}{6\phi} d \right)^{\frac{1}{3}}$ is the distance between the centers of the nanoparticles from each other. In the above equation c is the correction factor which is a function of nanoparticle diameter and temperature as

$$c = (c_1\phi + c_2)d + (c_3\phi + c_4) \quad (19)$$

Here the constant values $c_1 = -1.133e^{-6}$, $c_2 = -2.771e^{-6}$, $c_3 = -9e^{-8}$, $c_4 = 3.93e^{-7}$ have been extracted by curve fitting of experimental data.

Table 4 incorporates the main proposed models regarding the viscosity of nanofluids.

Table 4 General theoretical model for nanofluids viscosity as a function of volume fraction

Reference	Formula
Einstein [170]	$\mu_{eff} = (1 + 2.5\phi_p)$
Brinkman [171]	$\mu_{eff} = \frac{1}{(1-\phi_p)^{2/5}} = (1 + 2.5\phi_p + 4.375\phi_p^2 + \dots)$

Lundgren [175]	$\mu_{eff} = \frac{1}{1-2.5\phi_p} = (1 + 2.5\phi_p + 6.25\phi_p^2 + \dots)$
Batchelor [173]	$\mu_{eff} = (1 + \pi\phi_p + k_H\phi_p^2) = (1 + 2.5\phi_p + 6.2\phi_p^2)$
Frankel and Acrivos [182]	$\mu_{eff} = \left(\frac{9}{8} \frac{\left(\frac{\phi_p}{\phi_{pmax}}\right)^{1/3}}{1 - \left(\frac{\phi_p}{\phi_{pmax}}\right)^{1/3}} \right)$
Graham [177]	$\mu_{eff} = (1 + 2.5\phi_p) + \left[\frac{4.5}{\left(\frac{h}{r_p}\right) \cdot \left(2 + \frac{h}{r_p}\right)^2} \right]$
Mooney [186]	$\mu_{eff} = \exp\left(\frac{2.5\phi_p}{1 - k\phi_p}\right) = \left\{ 1 + \frac{2}{5\phi_p} + \left[\frac{3}{125} + \left(\frac{2}{5k}\right)\phi_p^2 + \dots \right] \right\} \rightarrow 1.35$ $< k < 1.91$
Eilers [187]	$\mu_{eff} = \mu_f \left[1 + \frac{1.25\phi_p}{\frac{1-\phi_p}{0.78}} \right] = (1 + 2.5\phi_p + 4.75\phi_p^2 + \dots)$
Saito [188]	$\mu_{eff} = \mu_f \left[1 + \frac{1.25\phi_p}{1-\phi_p} \phi_p \right] = (1 + 2.5\phi_p + 2.5\phi_p^2 + \dots)$

Many others [189-192] worked in the related areas. Fig.8 illustrates some analytical models which are compared with some new experimental works in terms of viscosity estimation.

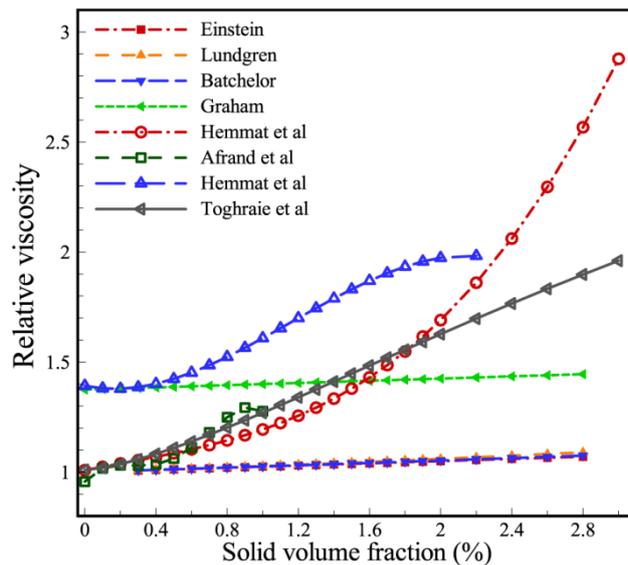


Fig. 8 Comparison of theoretical models with experimental results for the viscosity estimation of nanofluids (Khodadadi et al. [139]).

From Fig. 8 it is evident that the results of the theory relations are far from experimental facts and, except for very low volume fractions, are unable to estimate the nanofluids' viscosity and for which further research is needed.

4.2 Experimental Correlations

Nevertheless, many models have been proposed for determining the viscosity of nanofluids the most practicable method is still experimental mean due to the wide range of variations in different samples. The dynamic viscosity of Al_2O_3 – water nanofluid depends upon the temperature and volume fraction (Nguyen et al. [161]). They observed the effects in the temperature range between $22^{\circ}C$ and $75^{\circ}C$ and a volume fraction of 1–9.4%. The correlation that was proposed for aluminum oxide particles with diameters of 47 and 36 nm is as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = 0.094e^{14.83\phi} \quad (20)$$

Further, they proposed the following two equations considering the effect of temperature for volume fractions of 1 and 4% of aluminum oxide particles, respectively:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.125 - 0.0007T \quad (21)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = 2.1275 - 0.0215T + 0.002T^2 \quad (22)$$

Where T is the fluid temperature in ($^{\circ}C$)

The above correlations are unable to estimate the viscosity of nanofluids over a wide range of volume fractions. Maiga et al. [193] used curve-fit on the empirical data of Wang et al. [160], and developed the model:

$$\mu_{eff} = 1 + 7.3 + 123\phi^2 \quad (23)$$

The viscosity of suspended copper nanoparticles at a temperature range of $5-50^{\circ}C$ can be calculated by a new correlation (Kulkarni et al. [78]):

$$\ln\left(\frac{\mu_{nf}}{\mu_{bf}}\right) = A\left(\frac{1}{T}\right) - B \quad (24)$$

The rheological properties of a suspended blend of copper oxide nanoparticles in a mixture of water and ethylene glycol (60:40 wt%) was experimentally examined by Namburu et al. [64]. They determined viscosity in the volume fractions range between 0 and 6.12% and temperatures between $35^{\circ}C$ and $50^{\circ}C$. Based on their results, they developed an experimental model that relates the viscosity with temperature and the nanoparticle volume fraction and the temperature as follows:

$$\ln\left(\frac{\mu_{nf}}{\mu_{bf}}\right) = Ae^{-BT} \quad (25)$$

where μ_{nf} is the viscosity of copper oxide nanofluid in terms of centi-Poise (cP), T is the temperature in Kelvin, the constants A and B are functions of nanoparticle volume fraction:

$$\left. \begin{aligned} A &= 1.8375\phi^2 - 29.643\phi + 165.56 \\ B &= 4 \times 10^{-6}\phi^2 - 0.001\phi + 0.0186 \end{aligned} \right\} \quad (26)$$

In the above relation, μ varies from 0 to 6.12%. They declared that the nanofluid exhibits Newtonian behavior in their study.

Kao et al. [194] investigated experimentally the behavior of aluminum oxide nanoparticle in a mixture of ethylene glycol-water. They found that nanofluids exhibits non-Newtonian Behavior at temperatures ranging from $-35^{\circ}C$ to $0^{\circ}C$ while they show Newtonian behavior at temperatures ranging from $0^{\circ}C$ to $90^{\circ}C$. In their study they considered the diameter of nanoparticles as 53 nm and the volume fractions ranged from 1 to 10%. According to the experimental results, they obtained a correlation for the estimation of viscosity as follows:

$$\left(\frac{\mu_{nf}}{\mu_{bf}} \right) = A e^{\left(\frac{B+C\phi}{T} \right)} \quad (27)$$

The values for A, B, and C are $A=1.2200 \times 10^{-6}$ (low temperature region), $A=2.3920 \times 10^{-6}$ (high temperature region), $B=4285$ (low temperature region), $B=2903$ (high temperature region) and $C=0.1448$ (low temperature region), $C=0.1265$ (high temperature region).

Vajjha [22] obtained a more complete model for nanoparticles of aluminum oxide and copper oxide in a mixture of water and ethylene glycol (60:40 wt%):

$$\left(\frac{\mu_{nf}}{\mu_{bf}} \right) = A e^{B\phi} \quad (28)$$

where the constants A and B at temperatures ranged from $20^{\circ}C$ to $90^{\circ}C$ for aluminum oxide nanoparticles, are: $A = 0.983$, $B = 12.959$ and for copper oxide nanoparticles: $A = 0.9197$, $B=22.8539$. Table 5 incorporates the experimental correlations developed by many researchers.

Table 5 Summary of experimental correlations conducted in the viscosity field

Reference	Correlations	Nanofluids
Nguyen [161]	$\frac{\mu_{nf}}{\mu_{bf}} = 0.904e^{14.83\phi}$ $\frac{\mu_{nf}}{\mu_{bf}} = [1 + 2.5\phi + 150\phi^2]$ $\frac{\mu_{nf}}{\mu_{bf}} = 1.125 - 0.0007T$ $\frac{\mu_{nf}}{\mu_{bf}} = 2.1275 - 0.0215T + 0.002T^2$	Aluminum oxide/ Water (47nm) Aluminum oxide/ Water(36nm) Aluminum oxide/ Water (1% vol) Aluminum oxide/ Water (4% vol)
Maiga [193]	$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 7.3\phi + 123\phi^2)$	Aluminum oxide- Water or EG
Kulkarni [78]	$\ln\left(\frac{\mu_{nf}}{\mu_{bf}}\right) = A\left(\frac{1}{T}\right) - B$	Cu/Water
Namburu [64]	$\log\left(\frac{\mu_{nf}}{\mu_{bf}}\right) = (165.56 - 29.643\phi + 1.8375\phi^2) * \exp[(0.0186 - 0.001\phi + 4 * 10^{-6}\phi^2)T]$	Copper oxide/Water: EG (60:40)

Vajjha [22]	$\frac{\mu_{nf}}{\mu_{bf}} = Ae^{-BT}$	Aluminum oxide/copper oxide Water: EG (60:40)
Abu-Nada [195]	$\mu_{nf} = -0.155 - \frac{19.582}{T} + 0.794\varphi + \frac{2094.47}{T^2} - 0.192\varphi^2 - 8.11\frac{\varphi}{T}$ $- \frac{27463.863}{T^3} + 0.0127\varphi^3 + 1.6044\frac{\varphi^2}{T}$ $+ 2.1754\frac{\varphi}{T^2}$	Aluminum oxide/ Water
Duangthongsuk and Wongwises [196]	$\frac{\mu_{nf}}{\mu_{bf}} = a + b\varphi + c\varphi^2$	Titanium de oxide Water

5. Parameters Influencing the Viscosity of Nanofluids

This section reveals information how different effective parameters such as surfactants addition, the temperature, nanoparticle volume fraction, base fluid type, pH value, production technique, etc. influence the viscosity of diversified nanofluids (contributing major role in enhancing the heat transfer of nanofluids).

5.1 Surfactants addition

Stability of nanofluids is greatly influenced by the nature of the base fluid and nanoparticles. For instance, water as a base fluid is polar while oil non-polar. Also, oxide nanoparticles are hydrophilic whereas CNTs are hydrophobic in nature. Thus, the addition of surfactants can be regarded as most appropriate method to upgrade dispersion of nanoparticles in the base fluids like dispersion of CNTs in water or oxide particles in the oil. Surfactants act as a bridge to attach nanoparticles to the base fluids in order to avert particles aggregation (lowers the viscosity). Surfactants are the products used in the chemical industries, detergents, pharmaceuticals, drilling mud's etc. These are widely used for developing even dispersion of nanoparticles in the base fluid. Surfactants are oil soluble as well as water soluble. Therefore, the selection of surfactant depends on the nature of the base fluid. Surfactants can be negatively charged (anionic), positively charged (cationic), neutral (non-ionic) or both negatively and positively charged (amphoteric) based on the charge on its head group. Mainly, the nanoparticles' surface charge and the base fluid considered determine the surfactant to be selected. This is because the use of surfactants may be unfavorable for the applications at elevated temperatures [197–198].

5.2 Particle volume concentration

Most of the experimental studies on nanofluids deal with the effect of particle volume concentration on viscosity. Many researchers agreed with the consensus that the increase in the particle concentration upsurges the viscosity [199] and belittles the stability. Therefore, researchers carried out studies on nanofluids by keeping the particle concentration at a limit usually below 10 wt%. The behavior of copper oxide-ethylene glycol, aluminum oxide-ethylene glycol and aluminum oxide-water nanofluids was analyzed by Anoop et al. [162]. They studied the variation of viscosity at temperature ranging from 20°C to 50°C and volume fraction of 0.5, 1, 2, 4 and 6%, and observed that increasing particle concentration

escalates the viscosity of the fluid. Behi and Mirmohammadi [200] reported that augmented nanoparticle volume fraction from 0.6 to 0.8, a 1.7% enhances the viscosity. Kole and Dey [39] observed in their study that viscosity as a function of volume fraction. In Fig. 9 variations in viscosity with respect to the volume fraction are presented for some nanofluids.

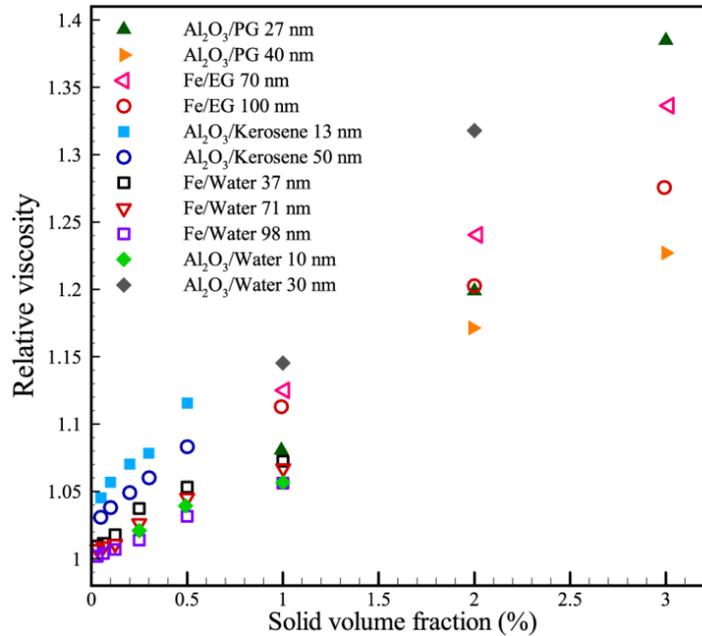


Fig. 9 Relative viscosity variations with respect to the volume fraction for some nanofluids (Khodadadi et al. [139])

It is universally concluded that the enhancement in volume fraction leads to augmentation in viscosity. It is remarkable that the dimensionless relative viscosity has been adopted in Fig. 9. The most appropriate models considering the effect of particle volume fraction are enlisted in Table 6.

Table 6 Summary of viscosity models for given types of nanofluids in different researches

Authors	Nanofluids	Volume fraction range(%)	Expressions of viscosity models
Namburu et al.[64]	Al ₂ O ₃ -EG/W	1.0-10	$\log(\mu_{nf}) = Ae^{-BT}$
Buongiorno[201]	Al ₂ O ₃ -water	0-10	$\mu_{nf}/\mu_{bf} = 1 + 39.11\phi + 533.9\phi^2$
Nguyen et al.[161]	Al ₂ O ₃ -water	1-4	$\mu_{nf}/\mu_{bf} = 1.125 - 0.0007T$
Maiga et al.[193]	Al ₂ O ₃ -water	0.0-6.0	$\mu_{nf}/\mu_{bf} = 1 + 7.3\phi + 123\phi^2$
Rea et al.[202]	Al ₂ O ₃ -water	0.0-6.0	$\mu_{nf}/\mu_{bf} = e^{(4.91\phi/0.2092-\phi)}$
Naik and sundar[203]	CuO- EG/W	0.0-1.2	$\mu_{nf}/\mu_{bf} = 3.444(T_{max}/T_{min})^{0.514} \phi^{0.1829}$
Kole and Dey[39]	Al ₂ O ₃ -car engine coolant	0.1-3.5	$\log(\mu_{nf}) = Ae^{-BT}$ $A = -225.245\phi^2 + 18.404\phi + 1.749$ $B = 575.835\phi^3 - 32.101\phi^2 + 0.148\phi + 0.01$

Kulkarni et al.[78]	CuO-water	1.0-6.12	$\log(\mu_{nf}) = A(1/T) - B$
Nguyen et al.[161]	CuO-water	1.0-13.0	$\mu_{nf}/\mu_{bf} = 1.475 - 0.319\varphi + 0.051\varphi^2 + 0.009\varphi^3$
Nguyen et al.[161]	CuO-water	1-4	$\mu_{nf}/\mu_{bf} = 2.1272 - 0.0215T + 0.0002T^2$
Sundar et al.[204]	Fe ₃ O ₄ - EG/W (EG:W=2:8or4:6)	0.0-1.0	$\mu_{nf}/\mu_{bf} = (1 + \varphi)^{0.68}$
Sundar et al. [204]	Fe ₃ O ₄ -EG/W (EG:W=2:8 or 4:6)	0.0-1.0	$\frac{\mu_{nf}}{\mu_{bf}} = (1 + \varphi)^{1.205}$
Brenner and Condiff [205]	CNT-Water	-	$\frac{\mu_{nf}}{\mu_{bf}} = (1 + n\mu)$
Boboo et al. [206]	MWCNT-Water	0.0-1.0	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + a\varphi + b\varphi^2$
Vakili-Nezhaad et al. [207]	SWCNT-lubricant	0.01-0.2	$\frac{\mu_{nf}}{\mu_{bf}} = 0.2T^2 - 30.3T + 1048$
Yu et al.[80]	SiC-water	0.0-3.7	$\frac{\mu_{nf}}{\mu_{bf}} = 0.00496e^{\left(\frac{17366}{T}\right)}$
Sharma et al. [208]	SiC-Water	-	$\frac{\mu_{nf}}{\mu_{bf}} = 1.4(1 + \varphi/100)^{11.3}(1 + T_{nf}/70)^{-0.038} + (1 + \frac{d_p}{170})^{-0.061}$
Namburu et al. [64]	SiO ₂ -EG/W	2.0-10.0	$\text{Log}(\mu_{nf}) = Ae^{-BT}$ A=0.1193 $\varphi^3 - 1.9289\varphi^2 - 2.245\varphi + 167.17$ B=(-7*10 ⁻⁶) $\varphi^2 - 0.0004\varphi + 0.0192$
Tseng and Lin[37]	TiO ₂ -water	0.05-0.12	$\frac{\mu_{nf}}{\mu_{bf}} = 13.47e^{35.98\varphi}$
Duangthongsuk and Wongwises [196]	TiO ₂ -water	0.2-2.0	$\frac{\mu_{nf}}{\mu_{bf}} = a + b\varphi + c\varphi^2$
Buongiorno [201]	TiO ₂ -water	0-10	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 5.45\varphi + 108.2\varphi^2$

5.3 Particle size

The general trend of theoretical as well as experimental results shows the viscosity greatly depends on the particle size in the sense that viscosity of nanofluids increases with increasing particle diameter. The effects of the changes in the size of particles on the relative viscosity of the water-based and ethylene glycol-based nanofluids are shown in Fig. 10 and 11, respectively.

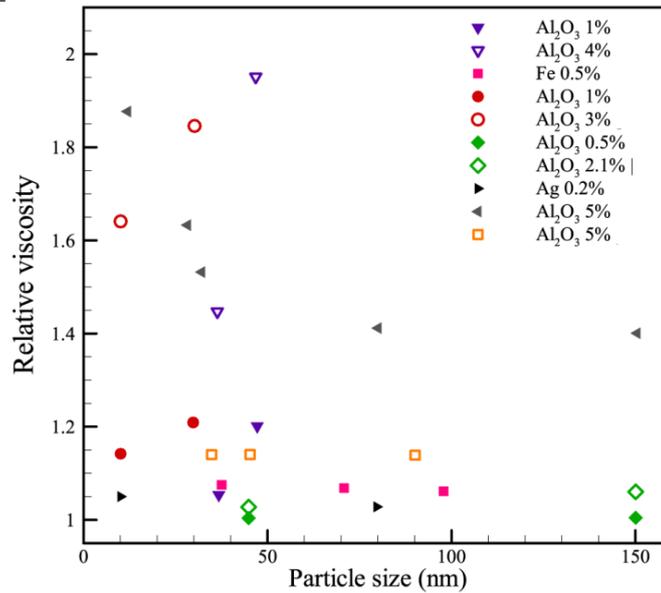


Fig. 10 The effect of changes in the size of particles on the relative viscosity of water-based nanofluids (Khodadadi et al. [139]).

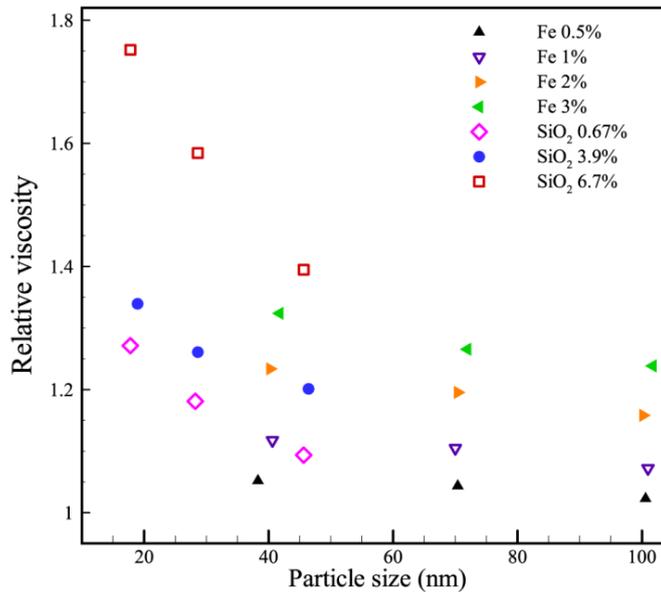


Fig. 11 The effect of changes in the size of particles on the relative viscosity of ethylene glycol-based nanofluids (Khodadadi et al. [139]).

He et al. [209] reported the viscosity of titanium oxide-water nanofluid for different concentrations in different sizes of nanoparticles (95, 145, and 210 nm). Although they achieved a contradictory result, such as the result achieved by Lu and Fan [210], they numerically and experimentally examined the viscosity of aluminum oxide-water and aluminum oxide-ethylene glycol in different sizes of nanoparticles, and found that the viscosity of nanoparticles reduces due to increase in particle diameter. From Table 5, it is

inferred that Nguyen et al. [161] proposed some correlations for predicting the viscosity of Al_2O_3 –water nanofluid as separated functions of the temperature and volume fraction for different nanoparticles' diameters. However, their correlation could not comply with the effects of temperature and nanoparticles volume fraction simultaneously. Abu-Nada [195] used experimental data reported in Nguyen et al. [161] and proposed a new correlation on the viscosity of Al_2O_3 –water nanofluid as a function of temperature and nanoparticles volume fraction as follows:

$$\begin{aligned} \mu_{nf} = & -0.155 - \frac{19.582}{T} + 0.794\phi + \frac{2094.47}{T^2} - 0.192\phi^2 - 8.11\frac{\phi}{T} \\ & - \frac{27463.863}{T^3} + 0.0127\phi^3 + 1.6044\frac{\phi^2}{T} + 2.1754\frac{\phi}{T^2} \end{aligned} \quad (28)$$

Later, Khanafar and Vafai [211] established a general correlation for viscosity in the Al_2O_3 –water nanofluid, as a function of the volume fraction, nanoparticle diameter and temperature:

$$\begin{aligned} \mu_{eff} = & -0.4491 + \frac{28.837}{T} + 0.574\phi_p - 0.1634\phi_p^2 + 23.053\frac{\phi_p^2}{T^2} \\ & + 0.0132\phi_p^3 - 2354.735\frac{\phi_p}{T^3} + 23.498\frac{\phi_p^2}{d_p^2} - 3.0185\frac{\phi_p^3}{d_p^2} \end{aligned} \quad (29)$$

$$1\% \leq \phi_p \leq 9\%, \quad 20 \leq T(^{\circ}C) \leq 70, \quad 13nm \leq d_p \leq 131nm$$

Wen et al. [212] concluded that the nanofluids viscosity decreases with increasing particle diameter, by analyzing the viscosity of aluminum oxide-water and aluminum oxide-ethylene glycol nanofluids. Usually, particles with two different morphologies such as spherical and cylindrical are commonly used in nanofluids. Nanofluids with cylindrical particles accounts for a greater increase in the viscosity which in turn yields increased pumping energy [213]. Kim et al. [40] investigated the influence of aspect ratio on the viscosity of nanofluids with fibrous and spherical alumina nanoparticles. They found that viscosity increment of fibrous alumina nanofluids was higher than that of the spherical one. Farbod et al. [214] investigated the influence of different morphologies of CuO (nanoparticles, nanorhombics, and nanorods) on the thermal properties of nanofluids. Abdelhalim et al. [215] found in his investigation that a rise in viscosity of water based gold (Au) nanofluids with larger nanoparticles.

5.4 Temperature

Many researchers studied on the effect of temperature on the viscosity of nanofluids along with the effects of other factors. Duangthongsuk and Wongwises [196] studied titanium oxide-water nanofluid in a temperature range of $15^{\circ}C$ to $50^{\circ}C$ and a volume of 0.2–3% and found that a decrease in viscosity causes an increase in temperature. Namburu et al. [64] concluded that nanofluids possess CuO particles in an ethylene glycol and water mixture, at temperature ranging from $35^{\circ}C$ to $50^{\circ}C$, with a volume fraction of 0–6% behave as non-Newtonian fluids where the viscosity decreases exponentially, with increasing temperature. Prasher et al. [20] and Chen et al. [63] showed the contradiction that the viscosity of nanofluids is independent of temperature. Putra et al. [216] investigated the effect of temperature on viscosity of aluminum oxide-water nanofluid and obtained the following relations:

$$\mu_{eff} = 0.034 - 2 \times 10^{-4} T + 2.9 \times 10^{-7} T^2, \phi = 1\%$$

$$\mu_{eff} = 0.039 - 2.3 \times 10^{-4} T + 3.4 \times 10^{-7} T^2, \phi = 4\%$$

Table 7 comprises some of the study carried out regarding the effect of temperature on the viscosity of nanofluids.

Table 7 Studies conducted on the impact of temperature on the viscosity of nanofluids and the related outcomes

Authors	Nanoparticles	Base fluid	Temperature range (°C)	Maximum relative viscosity
Namburu et al. [64]	SiO ₂	EG-water (60:40)	-35 to 50	1.625
He et al. [210]	TiO ₂	Water	22	1.0716
Prasher et al. [20]	Al ₂ O ₃	PG	30-60	1.3762
Oliveria et al. [217]	Ag	Water	Ambient	1.0458
Timofeeva et al. [218]	SiC	Water	15-45	1.857
Merilainen et al. [219]	Al ₂ O ₃	Water	10-50	1.65
Kwek et al. [42]	Al ₂ O ₃	Water	25	1.882
Jarahnejad et al. [16]	Al ₂ O ₃	Water	20-50	1.86
Minakov et al. [220]	SiO ₂	Water	25	1.43
Chevalier et al. [221]	SiO ₂	Ethanol	Ambient	1.99

Fig. 12 reveals the effect of temperature variations on the viscosity of various nanofluids. According to many research conducted, the nanofluids viscosity decreases by increasing the temperature. Although, few studies have shown that temperature variations have little impact on the relative viscosity of nanofluids, however some other experiments conducted revealed that this ratio will vary with temperature variation.

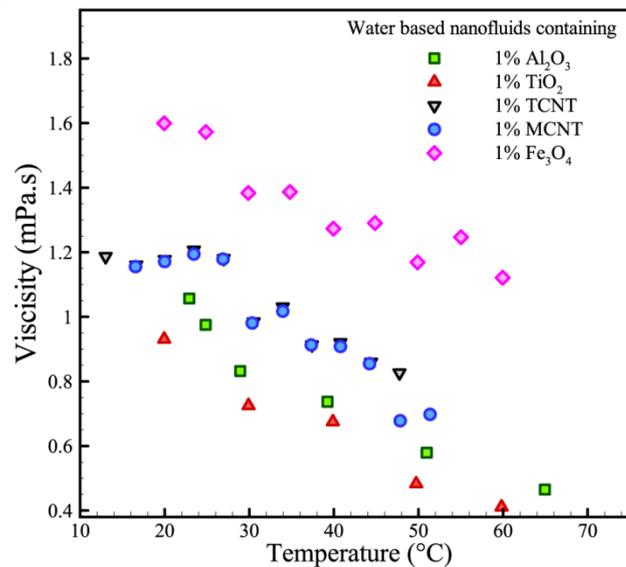


Fig. 12 The effect of temperature variations on the viscosity of water based nanofluids with different nano-additives (Khodadadi et al. [139])

5.5 pH

The pH of nanofluids affects the viscosity [222] well. Xian-Ju and Xin-Fang [222] studied the effect of pH on the viscosity of water-based *Cu* and *Al₂O₃* nanofluids. The outcome of the study is that an optimal pH value yields the lowest viscosity of the nanofluids with a better dispersion behavior.

5.6 Particle loading

Halefadi et al. [138] found that the CNT nanofluids exhibit Newtonian behavior at lower particle loading and a shear thinning behavior at higher loading.

5.7 Base fluid type

In an experiment carried out by Xie et al. [223] where nanoparticles dispersed in organic fluids similar to ethylene glycol it was observed that increased viscosity of ethylene glycol-based nanofluids was lower, compared to water-based nanofluids.

5.8 Nanoclustering

Because of Van der Waals forces, some nano-clusters are developed. As a result, a passageway with lower thermal resistance is established for the heat transfer [224]. The nanoclustering phenomenon offers a negative effect on nanofluids from two aspects. By creating large masses, this phenomenon can result instability of the suspension and also reduces the heat transfer by creating areas with no nanoparticles in the liquid and enhancing the thermal resistance. Clustering leads to an augmentation in the local volume fraction which in turn yield greater the viscosity of nanofluids [225].

5.9 Aggregation

Kole and Dey [201] investigated on the effect of aggregation on the viscosity of copper oxide–gear oil nanofluids as a function of *CuO* nanoparticles volume fraction and temperature between 10 and 80°C. They found that aggregation of *CuO* nanoparticles and the average aggregate dimension is w7.15. Augmented volume fraction of *CuO* nanoparticles in gear oil enhances the viscosity of the nanofluids by nearly 3 times of the base fluid (gear oil). Newtonian feature of the base fluid changes to non-Newtonian one with increasing *CuO* volume fraction in the gear oil. Shear thinning behavior becomes prominent for nanofluid with higher *CuO* loading.

5.10 Use time

Said et al. [226] declared from their study that the use time plays a positive role in the viscosity of *TiO₂* nanofluids. This is because the viscosity of the stale *TiO₂* nanofluids after working in a solar collector for one month is lower than that of the fresh samples.

5.11 Ultrasonication

Ultrasonication baths or probes are commonly used to physically disperse nanoparticle clusters. Sound energy at an ultrasonication level of 20 kHz and above is applied for a predetermined period of time to disperse nanoparticles into a base fluid and to break clusters of nanoparticles [144]. Mahbulul et al. [17] examined the impact of ultrasonication time on the stability of water-based *Al₂O₃* nanofluid. They observed that increasing sonication time leads to better colloidal dispersion and a lower viscosity. Sezer and Koc et al. [227] studied the effect of ultrasonication time on viscosity and heat transfer performance of MWCNT nanofluid.

6. Conclusion

In this article, a comprehensive, comparative and critical review of the research findings and progress on the viscosity of nanofluids has been presented. Nanofluids and solid suspensions in liquid are widely applicable for various applications, including improvement in the heat transfer of liquids in heat exchangers. It is no doubt that nanoparticles of non-metals, metals, metal oxides, CNTs and diamonds have been investigated by numerous researchers. Many researchers have investigated the stability and thermophysical properties of nanofluids comprising different type of nanoparticles in different base fluids. The state-of-art review revealed that nanofluids exhibit different rheological behaviors (Newtonian and non-Newtonian) depending on various factors such as shear rate, nanoparticles concentration and size, temperature, surfactant, pH, sonication, dispersion state, particle loading and aggregation. Such pertinent factors also influence the viscosity of nanofluids.

As far as viscosity (a thermophysical property) is concerned, it is the most extensively investigated parameter in the research of nanofluids. In order to extract the best nanofluids the changes of viscosity and the resulting pressure loss must be studied. We must be prudent enough to consider the viscosity as the most significant thermal property of nanofluids since it affects the required pumping energy in potential heat transfer applications. In the existing literature, very high viscosity increments were recorded for nanodiamond and magnetic nanofluids. It is good that a decrease of viscosity was reported due to the addition of different types of nanoparticles in propylene glycol-based fluid. Interestingly, viscosities of all

nanofluids were found higher than their base fluids and augmented with increasing nanoparticles concentration. It was further revealed from other investigations that enhanced temperature belittles the viscosity of nanofluids. This result could be very useful in high-temperature applications in achieving better thermophysical properties. Investigations on low temperature behavior of nanofluids would be more advantageous to identify the potential low-temperature based applications of nanofluids. Theoretical and experimental studies carried out by previous researchers revealed that the increase in volume fraction and nanoparticles size results in higher nanofluid viscosity (negative influence), while the increase in temperature leads to lower viscosity (positive influence). Any decrease in viscosity of nanofluids with increasing temperature (positive influence) is highly desirable for their application at high temperature environments. Further, addition of surfactants can upgrade dispersion of nanoparticles in the base fluids like dispersion of CNTs in water or oxide particles in the oil. Surfactants act as a bridge to attach nanoparticles to the base fluids in order to avert particles aggregation (lowers the viscosity). Clustering leads to an augmentation in the local volume fraction which in turn yield greater the viscosity of nanofluids. Ultrasonication is implemented to disperse nanoparticles into a base fluid and to break clusters of nanoparticles. It is found from the research that increasing sonication time leads to better colloidal dispersion and a lower viscosity.

Experimental results from the existing literature have been compared with the predictions from different theoretical viscosity models. Classical models were found unable to predict the viscosity of nanofluids. The empirical models proposed by researchers in recent years for nanofluids were based on fitting their own experimental data. However, these empirical models are also not suitable for the predictions of viscosity of other types of nanofluids. Thus, it is of great concern to develop rigorous theoretical models by considering all potential factors for the predictions of viscosity of any type of nanofluids.

It is known that addition of nanoparticles may affect the viscosity which in turn affects the erosion and corrosion behavior of the fluid and the interacting surfaces. However, no study on the erosion and corrosion behavior of nanofluids has been reported yet. In view of industrial applications, the erosion and corrosion behavior of nanofluids in heat transfer systems should be investigated.

Moreover, studies performed on the effects of the said factors are very limited. Thus more studies are to be performed to explore the effect of all these factors and their combined effects on the viscosity of nanofluids. Due to large number of parameters influencing the Rheology of nanofluids, it is also essential to develop a uniform and standardized procedure for the preparation of nanofluids and rheological characterization. In addition to long-time stability, the development of practical use of nanofluids in advanced heat transfer is an eye-catching scientific challenge. Above all, more researches are required to accomplish more favorable outcomes from several kinds of nanofluids.

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