VISCOSITY OF HYBRID NANOFLUIDS
A Critical Review

by

Hamza BABAR, Muhammad Usman SAJID, and Hafiz Muhammad ALI *

Mechanical Engineering Department, University of Engineering and Technology, Taxila, Pakistan

Review paper
https://doi.org/10.2298/TSCI181128015B

The remarkable enhancement in heat transfer capabilities of conventional fluids with the addition of nanosized metallic and non-metallic particles appealed the attention of investigators towards the suspension of hybrid nanocomposites as a substitute of mono particles. Although these fluids manifest captivating thermal characteristics, the drawbacks associated with their application include high frictional effects and pumping power requirements. The major cause of aforementioned problems is the elevated viscosity. The current study summarizes the work of different investigators and discusses the critical factors affecting the viscosity of hybrid nanofluids such as temperature, particle concentration, pH value, particle size and morphology with a concise discussion on the reasons reported in the literature for the viscosity augmentation. Furthermore, the models developed by different investigators have also been discoursed with specified limitations. Comparison between the viscosity of mono and hybrid nanofluid is also presented comprehensively. It is observed that most of the studies considered the effect of particle concentration and temperature that the effect of these factors is more significant. Water-based nanofluids delivered better results in comparison of ethylene glycol-based nanofluids while the oil-based nanofluids preferred in the applications where the pumping power is not more significant. It has been noticed that the fluids containing tube shaped nanoparticles comparatively showed enhanced viscosity than that of spherically shaped nanoparticles. It has also been observed that the studies preferred to develop their own models for the prediction of viscosity rather than to use the existing models and failed to provide a universal correlation.

Key words: *hybrid nanofluids, viscosity, temperature, nanocomposites, particle concentration*

Introduction

It is clear from the research of different researchers on the thermal properties that the solid metals possess higher thermal conductivity as compared to the conventional fluids such as ethylene glycol (EG), water (W), propylene glycol (PG), and oil, *etc*. The requirement of the fluid that possesses unique thermal properties fascinated the investigators to work on the new class of fluids called nanofluids firstly introduced by Choi [1] in 1995. This new class of fluids is obtained by dispersing the nanoparticles (metallic, carbides, ceramics, non-metallic) of size not more than 100 nm into the base fluid. The introduced fluid gained popularity within a short period due to its unique properties like high heat transfer and less clogging in pipes. The research work of different investigators ensured the enhancement in thermal conductivity of conventional fluids with the

*Corresponding author, e-mail: h.m.ali@uettaxila.edu.pk

addition of nanoparticles [2-6]. However, the investigation of viscosity is also important to reveal its fluidic behavior. The applications of nanofluids are found in various fields like electronics [7-10], solar energy [11-15], nuclear reactors [16-20], pool boiling [21-24], automotive industry [25-30], medical [31-35], food industry [36-40], machining processes [41-45], and in heating and cooling of buildings [46, 47]. So, this field looks emerging for future studies.

The recent development in technology demands a new revolution in the field of heat transfer. The latest research on nanofluids introduced the advanced class of fluids with augmented thermal properties (extension of nanofluids) named hybrid nanofluids obtained by dispersing the nanocomposite or nanoparticles of different metals into the base fluid as shown in fig.1, with this advancement researchers started to report a number of challenges associated with hybrid nanofluids soon after they came into limelight.

The hybrid nanofluids showed the enhanced thermal properties as compared to the mono nanoparticles based nanofluids and conventional fluids [48-50]. A numerical investigation of Takabi and Salehi [51] on the heat transfer characteristics of unitary and hybrid nanofluids revealed that the nanofluids provided the augmented heat transfer rate due to the presence of nanoparticles and hybrid nanofluids delivered supplemented results. There is no doubt that the thermal conductivity of base fluids enhanced with the addition of nanoparticles, but it also raised some problems in the form of pumping power, erosion, convection heat transfer, stability, and pressure drop due to the enhancement in viscosity caused by the formation of clusters that increases the hydrodynamic diameter and reduces the specific surface area. The hybrid nanofluids exhibited higher viscosity as compared to the conventional fluids and most of the unitary nanofluids. However, it depends on the selected nanoparticles and their combinations. The study of Botha *et al*. [52] on the viscosity of oil-based unitary and hybrid nanofluids of Ag-SiO_2 revealed that the unitary nanofluid of SiO_2 relatively showed greater enhancement in viscosity as compared to its hybrid nanofluids with Ag. Furthermore, in case of hybrid nanofluids, there is no classical model that can predict the exact values for viscosity on the basis of different parameters like temperature, particle concentration, and particle size and shapes, *etc*. Takabi *et al*. [53] numerically investigated the effect of different types of working fluids including conventional, unitary, and hybrid nanofluids on the forced convection heat transfer by passing them through a uniformly heated test tube section. Hydrodynamic and thermal performance of the fluids was inspected while restricting the flow in the laminar regime. The results revealed that the classical models that are used for the estimation of thermophysical properties of nanofluids failed to predict the properties of hybrid nanofluids accurately, suspension of hybrid nanofluids comparatively exhibited enhanced heat transfer characteristics, heat transfer coefficient augmented with particle concentration and Reynolds number, and the wall temperature decreased along the length of the test tube. According to Megatif *et al*. [54], the

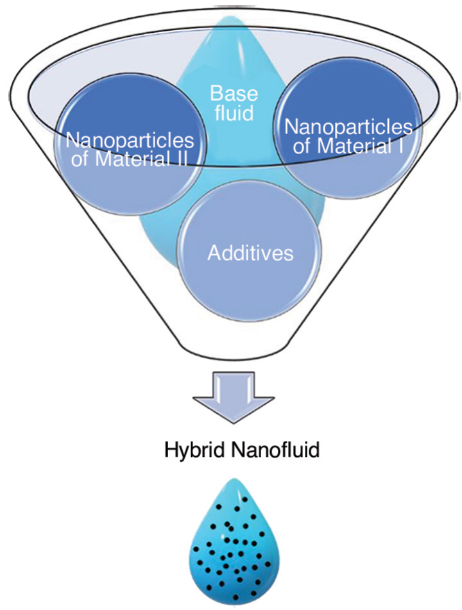


Figure 1. Graphical representation of Hybrid nanofluid

dynamic viscosity of the hybrid nanofluids of CNT-TiO_2-water increased linearly with the decrease in temperature and particle concentration. Esfe *et al*. [55] studied the rheological properties of the nanolubricant of CuO-MWCNT-10w40 and concluded that the effect of temperature on viscosity of hybrid nanofluids is more significant than that of the particle concentration. They also proposed a correlation for the prediction of the viscosity of prepared nanolubricant within the specified range of temperature and particle concentration. Nadooshan *et al*. [56] investigated the rheological behavior of the hybrid nanofluid of MWCNT-Fe_3O_4/EG by varying the particle concentration and temperature from 0.8 to 1.8 vol.% 25-50 °C, respectively, and found that the fluid viscosity showed a direct relation with the particle concentration and an inverse relation with temperature. They also observed that the behavior of the fluid changed from Newtonian to non-Newtonian above a certain limit of particle concentration and temperature.

The experimental studies proposed correlations to predict viscosity of nanofluids using curve fitting, linear and non-linear regression techniques on experimental results for specified ranges. On the other hand, a lot of inconsistencies in the results of different research groups have been noticed during the literature review even for the same hybrid nanofluid this could be due to the effect of preparation and dispersion techniques, particle shape and size, measuring techniques, agglomeration, and shear rate, *etc*. Authors noticed that the investigators focused the effect of particle concentration and temperature on the viscosity of hybrid nanofluids in their studies, although these are the important influencing factors, but the factors like pH value, sonication, particle size and shape, surfactant, clusters size, etc. are also important and needed a lot of work on them to exploit the potential of hybrid nanofluids in a wide range of applications.

In the recent epoch, a lot of research efforts have been carried out on hybrid nanofluids but most of the work encircled around the thermal conductivity enhancement [57-62]. The reviews published recently in the field of hybrid nanofluids also engrossed the attention of researchers towards the thermal conductivity, preparation, heat transfer, performance-effecting factors, applications and challenges [63-69], but no one thoroughly focused the viscosity although it seems to be a substantial property in the field of heat transfer. Figure 2 provides the statistics about the number of published articles and reviews by *ScienceDirect* that discussed the visosity and thermal conductivity of hybrid nanofluids.

The experimental studies proposed correlations to predict viscosity of nanofluids using curve fitting, linear and non-linear regression techniques on experimental results for specified ranges. On the other hand, a lot of inconsistencies in the results of different research groups has been noticed during the literature review even for the same hybrid nanofluid this could be due to the effect of preparation and dispersion techniques, particle shape and size, measuring techniques, agglomeration, and shear rate, *etc*. Authors noticed that the investigators focused the effect of particle concentration and temperature on the viscosity of hybrid nanofluids in their studies, although these are the important influencing factors, but the factors like pH value, sonication, particle size and shape, surfactant, clusters size, *etc*. are also important and needed a lot of work on them to exploit the potential of hybrid nanofluids in a wide range of applications.

In the recent epoch, a lot of research efforts have been carried out on hybrid nanofluids but most of the work encircled around the thermal conductivity enhancement [57-62]. The reviews published recently in the field of hybrid nanofluids also engrossed the attention of researchers towards the thermal conductivity, preparation, heat transfer, performance-effecting factors, applications and challenges [63-69], but no one thoroughly focused the viscosity although it seems to be a substantial property in the field of heat transfer. Figure 2 provides the statistics about the number of published articles and reviews by *ScienceDirect* that discussed the viscosity and thermal conductivity of hybrid nanofluids.

The presented study deliberated the effect of different parameters like temperature, particle concentration, pH value, surfactant, base fluid, sonication, particle shape and size on the viscosity of hybrid nanofluids. Furthermore, it enlightened the developed models of different investigators with the limitations and accuracy. The important aspects like hybrid nanofluid, particle size, temperature range, particle concentration range, viscosity measuring equipment, and viscosity enhancement of the discussed studies are summarized in tab. 3.

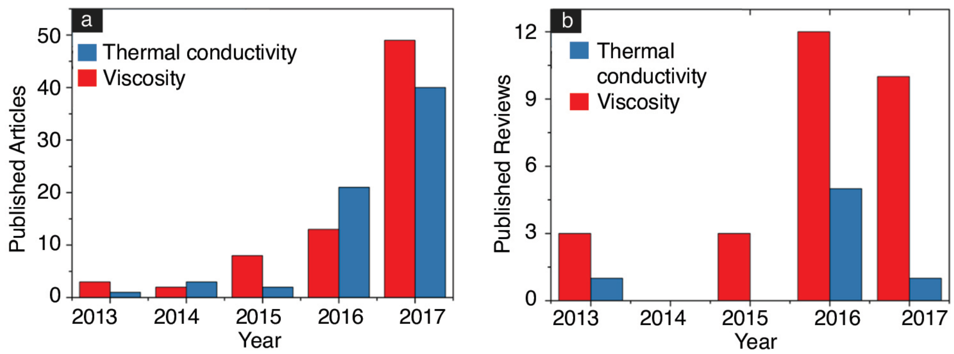


Figure 2. Number of (a) articles (b) reviews published reports by *ScienceDirect* from 2013 to 2017 retrieved with the keyword hybrid nanofluid with thermal conductivity and viscosity

Preparation and characterization techniques

Hybrid nanofluids are prepared by using the techniques called single step method and two-step method. The first one is mostly used to produce hybrid nanofluids on a small scale while the second one suitable for mass production. Ali *et al*. [4] provided a great graphical illustration of the nanofluids preparation methods in their study on the preparation and challenges of titania (TiO_2) nanofluids as shown in fig. 3.

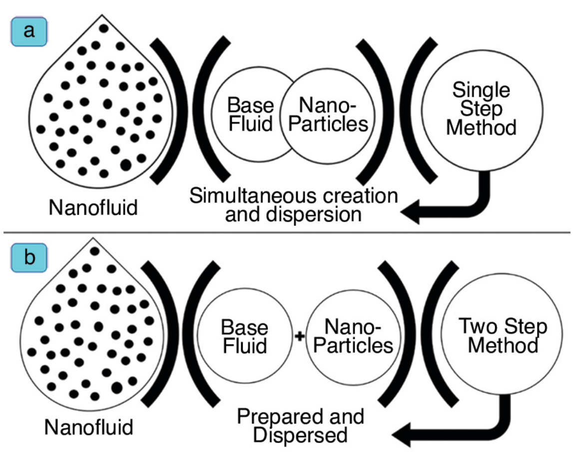


Figure 3. Preparation methods (a) Single-step method (b) Two-step method [4]

In single-step method, the processes of nanoparticles preparation and dispersion are carried out simultaneously. Pulsed wire evaporation (PWE) is the most prominent method of single step preparation technique that consists of a high voltage DC power supply, capacitor bank, wire feeding system, a high voltage gap switch and a condensation chamber. In this method, a high voltage pulse directed on a thin wire that melts and evaporates it within microseconds due to the effect of non-equilibrium heating. The vaporized particles made in contact with an inert gas (N_2 or Ar) inside the condensation chamber and condensed into nanosized powder. Hybrid nanofluid is then prepared by mixing the desired particle concentration of nanofluid with the nanosized powder prepared using the aforementioned technique after pouring it to an exploding container contained in the pulsed wire instrument [70]. Lee *et al*. [71] observed the following important characteristics of this technique while synthesizing the $NiFe_2O_4$ powder:

- The powder synthesized by this technique is pure and highly crystal line.
- The mean size of the obtained particles depends upon the pressure of an inert gas. As higher the pressure of inert gas smaller will be the particles size of the synthesized.
- The size of the particles reduced with the diameter of the induced wire.
- Particle size also depends on degree of superheat applied to the induced wire. It shows an inverse relation with the degree of superheat.

Aberoumand and Jafarimoghaddam [72] employed the one step electrical explosion of wire method for the preparation of the hybrid nanofluid of WO_3-Ag/transformer oil. The explosion of wire was carried out with the help of high pulsed electric voltage in the container of base fluid by operating the device PNC1K. Munkhbayar *et al*. [73] adopted the pulsed wire method for the fabrication of MWCNT-Ag-water hybrid nanofluid. For this purpose, they prepared the MWCNT-water nanofluid separately using a wet grinding method and installed it in the chamber of PWE apparatus. Chemical treatment was carried out with the help of H_2SO_4 and HNO_3 to stabilize the utilized solution of MWCNT. To get the hybrid nanofluid, the water-based Ag nanofluid was firstly prepared and then mixed with the already prepared nanofluid of MWCNT inside the chamber of the PWE apparatus. However, due to the usage of expensive instruments and complex nature of processes one-step method is avoided in most of the studies and therefore it is preferred to employ two-step method.

In two-step method literature reported the three different approaches for the preparation of hybrid nanofluids: dispersed the nanoparticles into the base fluid one after another, prepared the unitary nanofluids and then mixed together, and synthesized the nanocomposite and then dispersed it into base fluid. However, some studies exercised these techniques with some amendments for better dispersion of nanoparticles. Zhu *et al*. [74] used the two-step method for the preparation of alumina-based nanofluid in conjunction with chemical assistance for better dispersion of nanoparticles and long-term stability. Different chemicals like SDBS, HCl, and NaOH were introduced into the solution to avoid coagulation of nanoparticles. They observed that the supplementation of SDBS increased the repulsive forces between particles by negatively charging the powder surface. However, the pH value of the fluid was controlled by adjusting the concentration of HCl and NaOH. According to the results, chemical treatment of the fluid in conjunction with two-step method was very effective for rheological and thermal properties of nanofluids. They also concluded that the addition of chemicals above a certain limit may reverse the results. Wei *et al*. [75] purchased the nanopowder of selected materials from the market and then prepared the hybrid nanofluid by dispersing them into the base fluid of diathermic oil. Huang *et al*. [76] prepared the unitary nanofluids of Al_2O_3-water and MWCNT-water separately later on mixed them collectively to get the hybrid nanofluid of Al_2O_3-MWCNT-water. Kiruba *et al*. [77] prepared the polyethylenimine (PEI) based hybrid nanofluid of γ-Al_2O_3 by supplementing the specific amount of the PEI into the water-based nanofluid of γ-Al_2O_3 purchased from the market. Harandi *et al*. [78] firstly mixed the nanoparticles of the Fe_3O_4 and f-MWCNT then dispersed it into the EG to prepare the hybrid nanofluid. Later on, the solution was exposed to some mechanical processes like magnetic stirring and ultra-sonication for better dispersion of nanoparticles. Sundar *et al*. [79] synthesized the nanocomposite of GO/Co_3O_4 using chemical co-precipitation and in-situ method, afterward, prepared the hybrid nanofluid by dispersing the nanocomposite into the base fluid. Trinh *et al*. [80] used the EG-based unitary nanofluids of (Gr-COOH and MWCNT-OH) prepared and functionalized in laboratory with the assistance of some chemical and mechanical techniques. Finally, to get the hybrid nanofluid both the solutions mixed with a volume fraction of 1:1 and analyzed the microstructural and morphological characteristics of the fabricated nanofluid with the help of different techniques as shown in fig. 4.

The techniques that are used to estimate the size, chemical nature, agglomeration size, and surface morphology are called characterization techniques [81]. Literature reports the following important techniques for the estimation of different characteristics of the hybrid nanofluids.

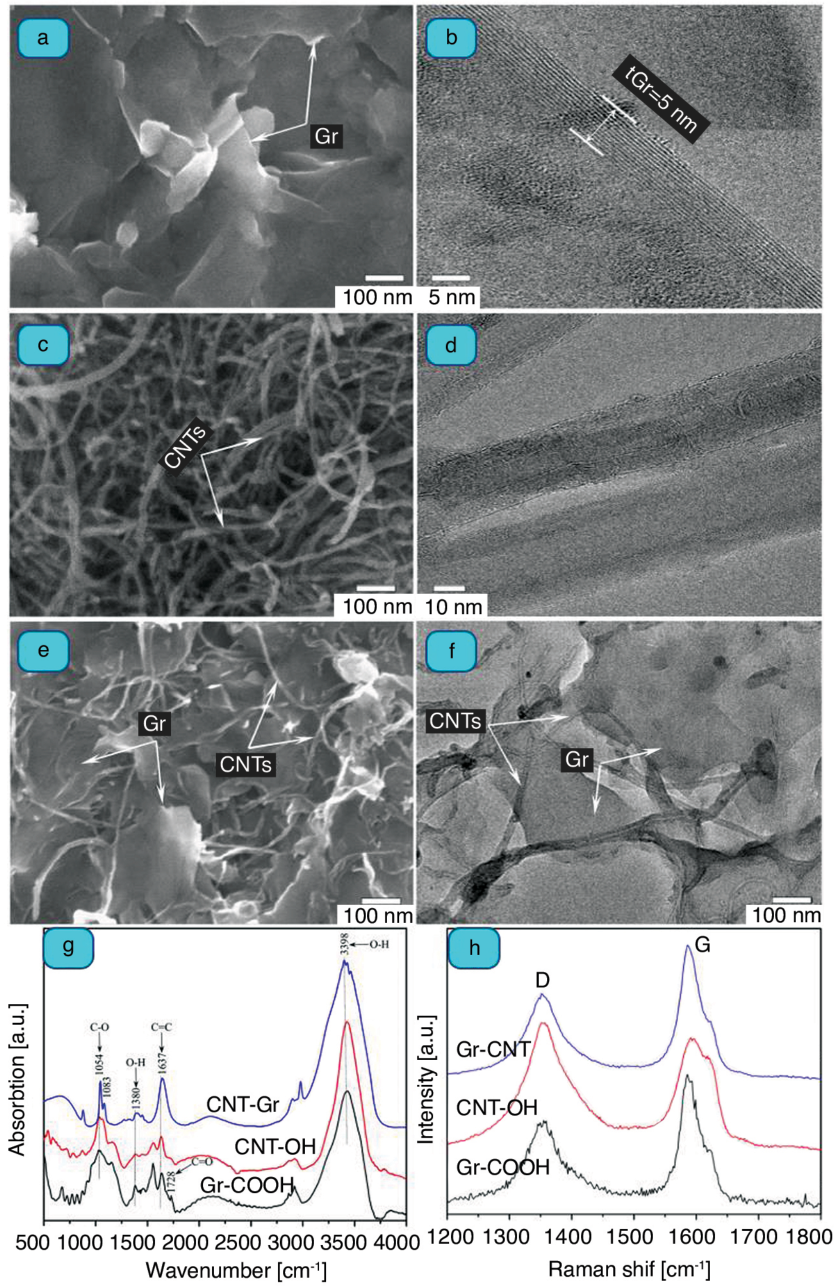


Figure 4. (a) SEM of graphene, (b) TEM of graphene, (c) SEM of CNT, (d) TEM of CNT, (e) SEM of Gr-CNT hybrid nanofluid, (f) TEM of Gr-CNT hybrid nanofluid, (g) FTIR spectrums, (h) Raman spectrum [80]

- The X-ray diffraction (XRD) used for crystallinity also provided information about a crystal size.
- The SEM used for the surface morphology of nanopowder.
- The TEM used for analysing the particle size and their distribution in the base fluid.
- The DLS used for the analysis of agglomeration state or dispersion of nanoparticles in base fluid.
- The VSM used for measuring the magnetic properties of the suspended particles.
- Energy dispersive X-ray spectroscopy (EDS) used for chemical characterization and elemental analysis.
- The UV-Vis spectroscopy used for assessing the particles dispersion.
- The FTIR technique used to identify the polymeric, organic and inorganic materials. This technique helps to identify the phase, functional groups, and chemical bonds [82, 83].
- Thermal analysis TG-DTA used to inspect the thermal stability.
- The DSC and rheometer used for measuring the specific heat and viscosity of the fluids respectively.
- Zeta potential, optical spectrum analysis (OPS), centrifugation, dynamic light spectrum are the methods commonly used for the measurement of stability of the hybrid nanofluids.

Performance affecting parameters

Temperature effect on viscosity

Literature reports a significant effect of temperature on the viscosity of hybrid nanofluids. Most of the studies inspect the viscosity of water and EG-based nanofluids at a lower temperature up to 60 °C while the viscosity variation of oil-based nanofluids analyzed at higher temperature values. Afrand *et al*. [84] examined the dynamic viscosity of SiO_2-MWCNT/engine oil for a temperature range of 25 °C to 60 °C with volume fractions of 0.0625, 0.125, 0.25, 0.50, 0.75, and 1 vol.%. The maximum enhancement in viscosity was 37.4%, which occurred at a temperature of 60 °C and particle concentration of 1%. Motahari *et al*. [85] reported that viscosity of MWCNT-SiO_2/oil hybrid nanofluid decreased with an increase in temperature for specified volume fraction. The viscosity of hybrid nanofluid was measured at a temperature range of 40 °C to 100 °C with a volume fraction of 0.05, 0.1, 0.2, 0.4, 0.8, and 1vol.%. About 171% increment in viscosity was achieved for 100 °C with 1% nanoparticles concentration. Esfe and Rostamian [86] investigated the effect of temperature on the viscosity of ZnO-MWCNT (55%-45%)/engine oil hybrid nanofluid. The temperature range used in experimentation was 5 °C to 55 °C with volume fraction of 0.05, 0.15, 0.25, 0.5, 0.75, and 1 vol.%. The viscosity was reduced as a result of increment in temperature.

Shahsavar *et al*. [87] found a decline in the viscosity of CNT-Fe_3O_4-water hybrid nanofluids for the rise in temperature from 25 °C to 55 °C during experimentation. Nabil *et al*. [88] performed an experimental study to determine the effect of temperature on the viscosity of water and EG-based nanofluid of SiO_2-TiO_2-water. The viscosity of hybrid nanofluid decreased with increase in temperature from 30 °C to 80 °C. The effect of base fluid and temperature variation on the viscosity of ND-Co_3O_4 hybrid nanofluids was experimentally investigated by Sundar *et al*. [89]. The base fluids used during experimentation included water, EG, 20EG:80 W, 40EG:60 W, and 60EG:40 W with a temperature range of 20 °C to 60 °C. Viscosity enhancement was in order of μ60EG:40W > μEG > μW > μ40EG:60W > μ20EG:80W.

Esfe *et al*. [90] determined that viscosity of MWCNT-SiO_2/engine oil was more sensitive to lower temperature instead of higher temperature. The solid volume fraction of 1% at temperature 40 °C showed maximum enhancement in viscosity of about 30.2%. Esfe *et al*. [91]

conducted an experimental study to measure the viscosity enhancement of MWCNT-ZnO/engine oil hybrid nanofluids for volume fractions of 0.05, 0.075, 0.1, 0.2, 0.4, 0.5, 0.75, 1 vol.% and temperature range of 20 °C to 50 °C. The maximum enhancement in viscosity was achieved at 40 °C because of nanoparticles clustering was reached at its climax. Further increase in temperature broke this clustering and thus a reduction in viscosity was observed. Afrand *et al*. [92] evaluated viscosity of Fe_3O_4-Ag/EG hybrid nanofluid under variation of temperature and volume fraction. The nanoparticle concentration was varied from 0.0375 to 1.2 vol.% with temperature range from 25 °C to 50 °C. For the non-Newtonian behavior of nanofluid (φ> 0.3%), consistency index was decreased with increase in temperature.

Baghbanzadeh *et al*. [93] reached to the conclusion that hybrid nanofluid of (50 wt.% silica–50 wt.% MWCNT-water) comparatively showed lower viscosity than that of (80 wt.% silica-20 wt.% MWCNT-water). For higher concentrations, 20 °C was found to be optimum operating temperature. Soltani and Akbari [94] prepared samples of MgO-MWCNT/ethylene glycol hybrid nanofluids with the volume fraction of 0.1, 0.2, 0.4, 0.8, and 1% and investigated the effect of temperature on the viscosity of prepared samples. Temperature was varied from 30°C to 60 °C and observed that the viscosity of hybrid nanofluids with the volume fraction of 0.8 and 1% was significantly affected by temperature. Hamid *et al*. [95] prepared TiO_2-SiO_2-water and ethylene glycol nanofluids having different mixture ratios of 80:20, 60:40, 50:50, 40:60, and 20:80. The experimental work was conducted to study the thermophysical properties of hybrid nanofluid. The dynamic viscosity of nanofluids was measured under variation of temperature from 30 °C to 80 °C. The viscosity ratio for mixtures 50:50, 80:20, and 20:80 remained constant for 30 °C -50 °C, whereas an increase was observed at 60-80 °C. Yarmand *et al*. [96] synthesized hybrid nanoparticles by decorating graphene nanoplatelets with platinum. The stability, viscosity and thermal conductivity of water-based hybrid nanofluid were evaluated for the temperature of 20 °C to 40 °C. Maximum enhancement in viscosity of hybrid nanofluid as compared to the viscosity of water was 33% for 0.1 wt.% and 40 °C. Kumar *et al*. [97] evaluated the viscosity and thermal conductivity of Cu-Zn hybrid nanofluids with different base fluids (vegetable oil, paraffin oil, and SAE oil) at 30 °C. Esfe *et al*. [98] investigated the nanodiamond/cobalt-oxide hybrid nanofluid to find out the optimum responses for viscosity and thermal conductivity by varying the temperature (20-60°C) and particle concentration (0-0.15 vol.%). For this purpose, they used the Design Expert software and the algorithm NSGA-II and found that the second one provided the optimal values more accurately. The results also exhibited that the optimal values for viscosity and thermal conductivity were found at the maximum temperature.

Qing *et al*. [52] prepared the naphthenic mineral oil-based hybrid nanofluid of SiO_2-graphene nanoparticles and examined the viscosity variation by varying the temperature from 20-100°C. The results revealed that viscosity of the fluid reduced with an increase in temperature due to the effect of increased particles Brownian motion. Aghaei *et al*. [99] found that the viscosity of the hybrid nanolubricant of CuO–MWCNT/SAE 5w–50 was augmented up to 12.52% even at a temperature of 55 °C and 35.52% at 5 °C. For the case of engine oil, the augmented viscosity is important because it assists in the lubrication process. Sundar *et al*. [100] conducted experimentation to measure enhancement in friction factor and heat transfer by application of MWCNT-Fe_3O_4 hybrid nanofluid in a circular tube. A decreasing trend in viscosity was observed with the enhancement in temperature. Yarmand *et al*. [101] elaborated thermo-physical properties of activated carbon/graphene hybrid nanofluid under variation of concentration and temperature. The decreased viscosity at elevated temperature was found to reduce the pumping power. Dardan *et al*. [102] investigated the effect of suspending Al_2O_3-MWCNT hybrid nanoparticles on the viscosity of SAE40 engine oil for different volume fractions (0-1 vol.%) and temperature ranges

(25-50 °C). The increase in temperature from 25 °C to 30 °C caused enhancement in the movement of hybrid nanoparticles, arranging nanotubes in direction of flow and thus providing low viscosity. However, further increase in temperature from 30 °C to 35 °C, made arrangement of nanotubes perpendicular to the direction of flow which led to an increase in viscosity.

Mechiri *et al*. [103] found the deteriorating effect of temperature on the viscosity of hybrid nanofluids (Cu-Zn/vegetable oil). Sundar *et al*. [104] measured enhancement in viscosity, thermal and electrical conductivities of hybrid nanofluids of (ND-Fe_3O_4) prepared by different base fluids (water, 80:20%, 60:40%, 40:60% W/EG). Nanofluid having 80:20% W/EG as base fluid showed maximum enhancement in viscosity of 203% at 20 °C which further enhanced to 219% at 60 °C compared to simple 80:20% W/EG for 0.2% volume fraction. Sunder *et al*. [79] also used water, 80:20%, 60:40%, 40:60% W/EG as base fluids to synthesize GO/Co_3O_4 hybrid nanofluids and investigated increase in viscosity of hybrid nanofluids with various base fluids. The experimentation was performed for a temperature range of 20-60 °C. The order of maximum enhancement in viscosity achieved for different base fluids was μW>μ20EG:80W>μEG>μ40EG:60W>μ60EG:40W. Akilu *et al*. [105] did an experimental study to measure viscosity enhancement of TiO_2-CuO/C ethylene glycol base hybrid nanofluid for different concentration of nanoparticles at the temperature range of 298-333K. At higher temperature, a significant decrease in viscosity was observed due to enfeeble intermolecular forces. Enhancement in Nusselt number and friction factor as a result of GNPs-Ag/water hybrid nanofluid application was computed by Yarmand *et al*. [106] using the circular tube. The flow of hybrid nanofluid was in the turbulent regime. About 1.3 times increase in viscosity was observed for nanofluids as compared to simple water at 40 °C. Soltani and Akbari [94] noticed the effect of temperature was more significant at a higher volume fraction of nanoparticles.

Ahammed *et al*. [107] elaborated entropy generation and different thermophysical properties of mono and hybrid nanofluids of (Graphene-Alumina) in the heat exchanger which was coupled with thermoelectric cooler under different temperatures. At 50 °C, graphene, alumina and hybrid nanofluid showed an enhancement of 33.75%, 10.28% and 18.86% in viscosity. Chandran *et al*. [108] developed novel hybrid nanofluids containing ZnO and encapsulated paraffin wax having melting temperature of 58-60 °C. The influence of temperature on the viscosity of hybrid nanofluid was investigated. The reduction in the viscosity of nanofluid was higher for a temperature range of 50-60 °C as compared to 25-50 °C.

Paraffin wax was in solid form up to 50 °C that's why viscosity reduction of nanofluid was relatively small at this temperature. The highest viscosity ratio of 1.615 was obtained for 1 vol.% of ZnO and 16 wt.% of paraffin wax at 60 °C. Asadi *et al*. [109] noticed a diminution in the dynamic viscosity of hybrid nanolubricant of MWCNT/$Mg(OH)_2$-engine oil with the increase in temperature at all the studied nanoparticles concentration. Figures 5-8 presented the viscosity of water, EG, oil, and water/EG-based hybrid nanofluids, respectively, reported in various studies with different combinations of nanoparticles against temperature for different particle concentrations.

Volume fraction effect on viscosity

Reported studies show a great agreement on the effect of particle concentration that the viscosity of hybrid nanofluids enhances with the augmentation of particle concentration. Afrand *et al*. [84] found the Newtonian behavior of SiO_2-MWCNT/engine oil hybrid nanofluids for 0 to 1% volume concentration of nanoparticles and proved that dynamic viscosity of hybrid nanofluid was increased with increasing volume fraction. The sensitivity of viscosity of hybrid nanofluid was observed to increase significantly for enhancement in volume fraction from 0.0625 to 1%.

Motahari *et al*. [85] also obtained Newtonian behavior of SiO_2-MWCNT/oil hybrid nanofluids for 0.05 to 1% volume fraction and viscosity showed an increase with enhancement in volume fraction.

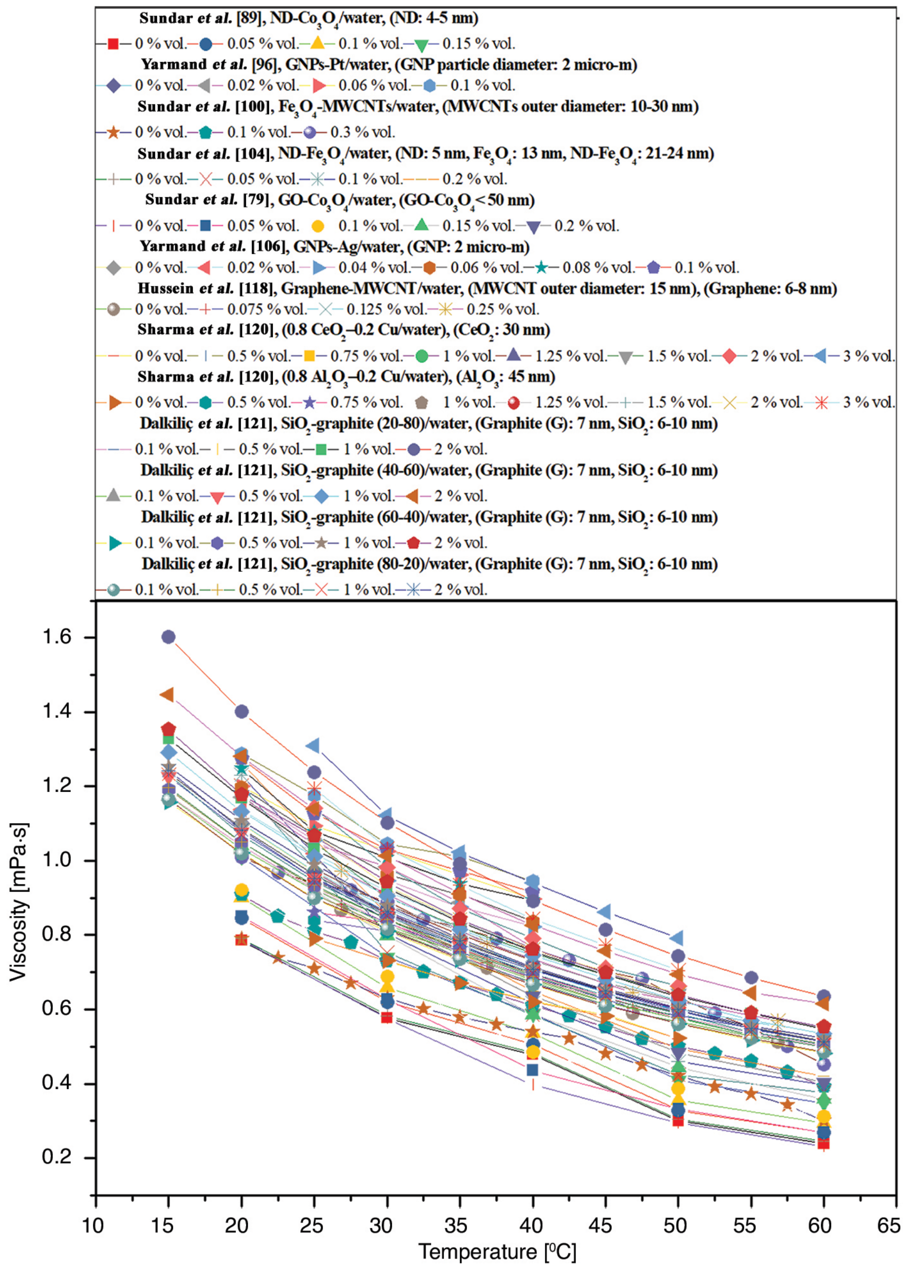


Figure 5. Viscosity variation of water-based hybrid nanofluids against temperature at different particle concentration [various studies]

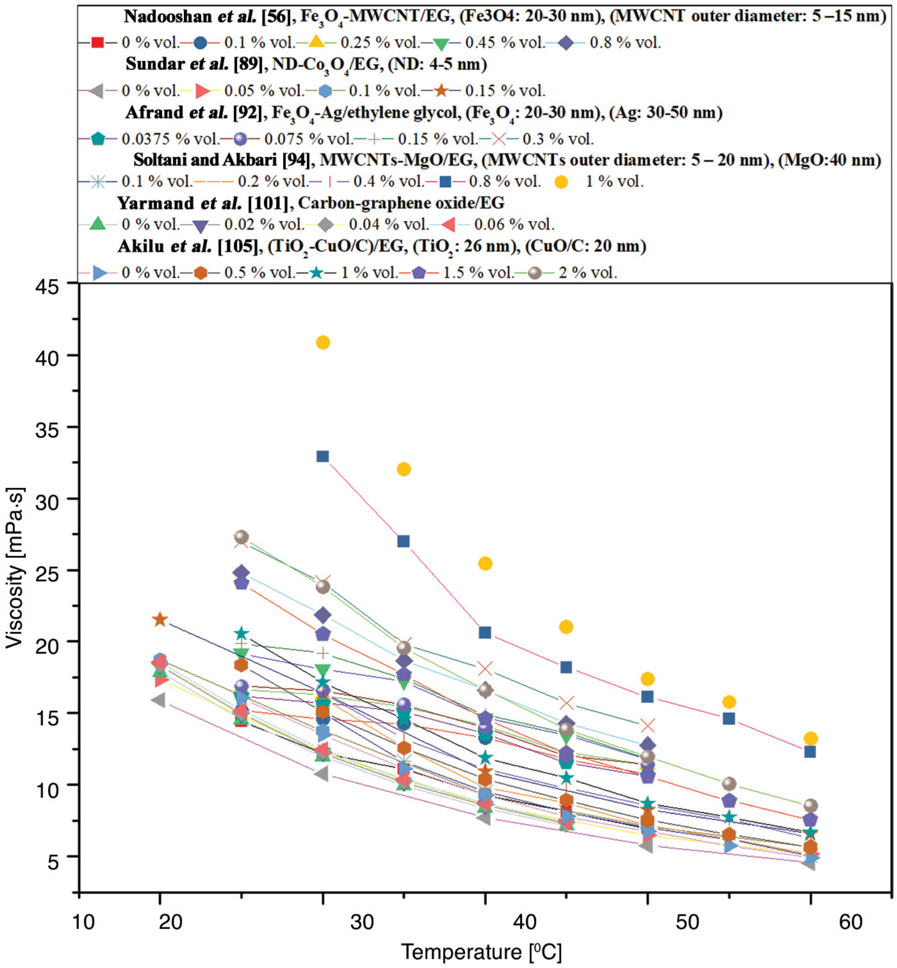


Figure 6. Viscosity variation of ethylene glycol-based hybrid nanofluids against temperature at different particle concentration [various studies]

Esfe and Rostamian [86] measured viscosity of ZnO-MWCNT/engine oil hybrid nanofluids by varying concentration from 0.05 to 1%. The hybrid nanofluid exhibited non-Newtonian behavior. Shahsavar *et al*. [87] stated that by increasing concentration of CNT in Fe_3O_4-CNT-water hybrid nanofluids, the viscosity of colloidal mixture increased due to the high interaction between particles. Maximum enhancement in viscosity achieved was 29.62% for (0.9% Fe_3O_4-1.35% CNT) the highest concentration. Newtonian behavior of hybrid nanofluid was observed for higher shear rates. Nabil *et al*. [88] reported that viscosity of TiO_2-SiO_2-water and ethylene glycol hybrid nanofluid increased with increase in concentration from 0.5 to 3 vol.%. The enhancement in viscosity of hybrid nanofluid was 25.9% and 62.5% for 0.5% and 3% concentration of nanoparticles at 80 °C, respectively. The hybrid nanofluid showed Newtonian behavior for volume fraction up to 3%. The variation in base fluid and weight concentration was found to have a direct effect on viscosity of ND-Co_3O_4 hybrid nanofluids by Sundar *et al*. [89]. The viscosities of water, ethylene glycol, 20EG:80W, 40EG:60W, and 60EG:40W base nanofluids was enhanced to 45, 46, 15, 19, and 51%, respectively, from their respective base fluids at 0.15%

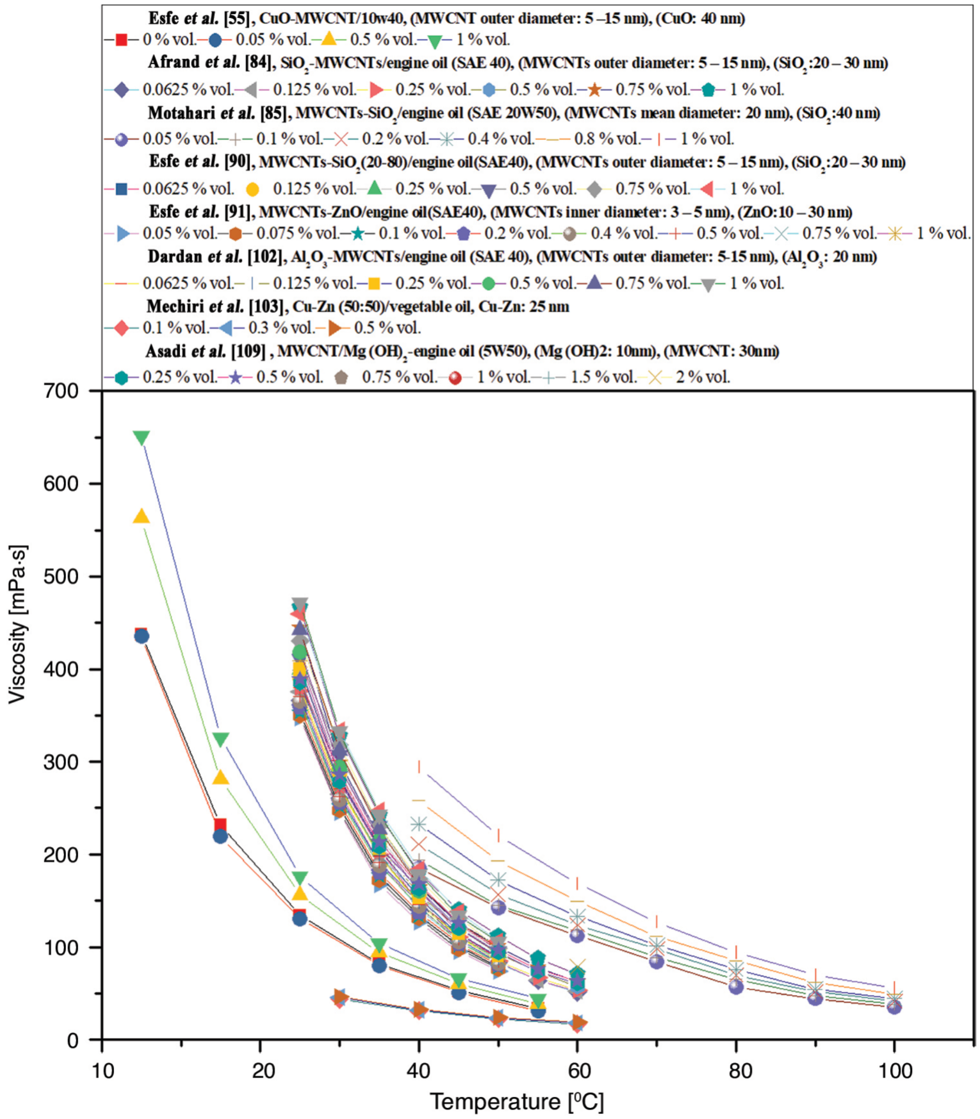


Figure 7. Viscosity variation of oil-based hybrid nanofluids against temperature at different particle concentration [various studies]

weight fraction of nanoparticles. Esfe *et al*. [90] carried out an experimental study to investigate the rheological behavior of MWCNT-SiO_2/engine oil hybrid nanofluid. The Newtonian behavior of nanofluid was observed for volume concentration up to 1%, whereas a further increase in concentration showed non-Newtonian behavior of nanofluid. Esfe *et al*. [91] determined maximum enhancement of 33.3% in viscosity of MWCNT-ZnO/engine oil hybrid nanofluid with the volume fraction of 1% at 40 °C. The hybrid nanofluid showed Newtonian behavior for an employed range of volume fraction. Afrand *et al*. [92] explored the Newtonian behavior of Fe_3O_4-Ag/EG hybrid nanofluid for volume fraction of less than 0.3%. The hybrid nanofluid with a concentration of nanoparticles greater than 0.3% showed non-Newtonian behavior. Consistency index increased while the power law index decreased with increase in volume fraction of nanoparticles.

Baghbanzadeh *et al*. [93] prepared hybrid nanofluids with two different mass ratios (50 wt.% silica – 50 wt.% MWCNT and 80 wt.% silica – 20 wt.% MWCNT) of nanoparticles in concentration of 0.1, 0.5, and 1 wt.%. Hybrid nanofluid with a mass ratio of (80 wt.% silica – 20 wt.% MWCNT) showed 8.8%, whereas (50 %wt. silica–50 %wt. MWCNT) hybrid nanofluid achieved 8.2% enhancement in viscosity as compared to water for 1 wt.% concentration. Soltani and Akbari [94] conducted an experimental study to investigate the effect of nanoparticles concentration on the viscosity of hybrid nanofluid (MgO-MWCNT/ethylene glycol). Increase in

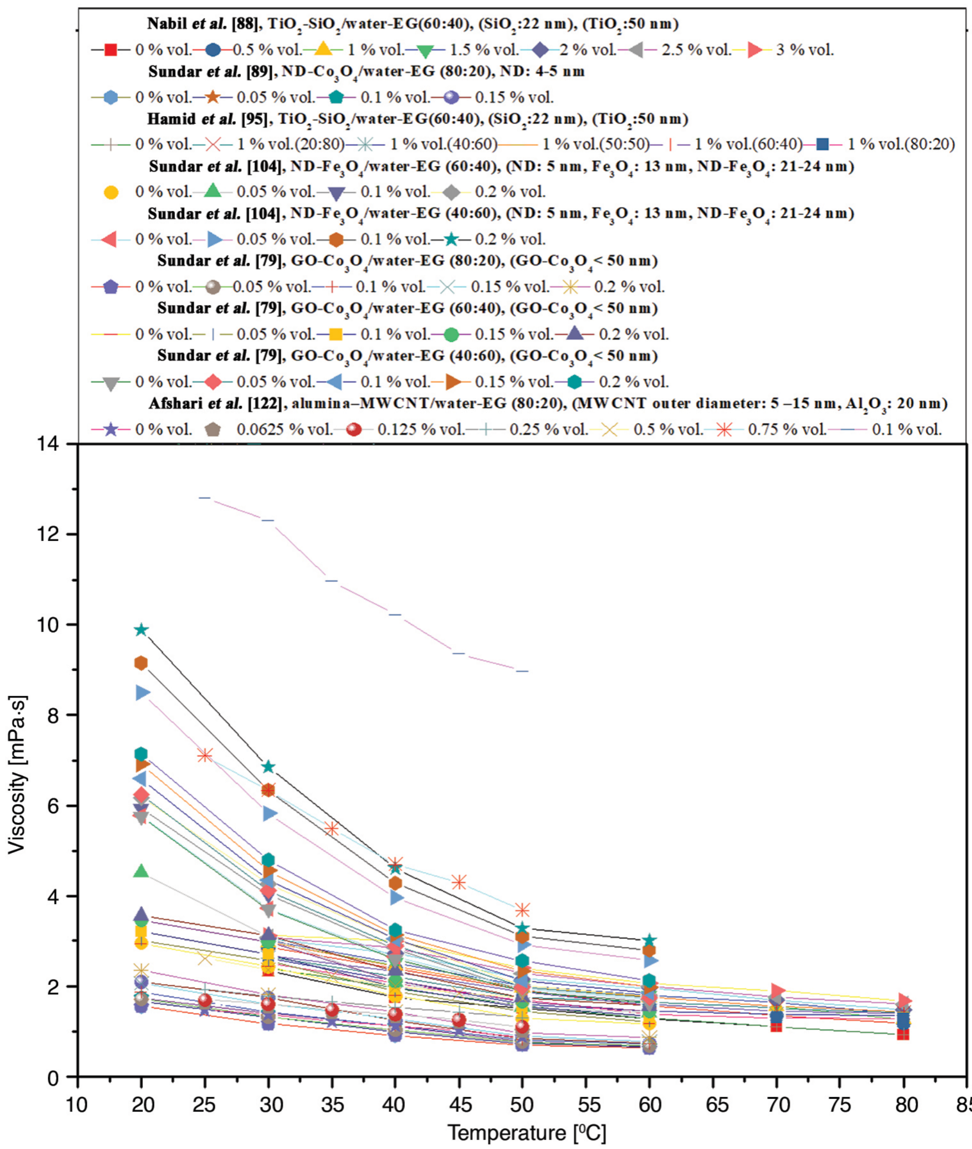


Figure 8. Viscosity variation of binary (water/EG)-based hybrid nanofluids against temperature at different particle concentration [various studies]

viscosity was significant at a higher concentration on nanoparticles (0.8% and 1%). Maximum enhancement in viscosity of hybrid nanofluid observed was 168% for 1 vol.% and 60 °C. The hybrid nanofluid showed Newtonian behavior for all concentrations. Among all mixture ratios prepared by Hamid *et al*. [95], TiO_2-SiO_2-water and ethylene glycol hybrid nanofluid with a mixture ratio of 50:50 showed the highest enhancement in dynamic viscosity. The hybrid nanofluid containing less percentage of silicon dioxide nanoparticles showed a marginal decrease in dynamic viscosity. The least increment in dynamic viscosity was observed for 80:20 mixture ratio. TiO_2-SiO_2 hybrid nanofluid behaved as Newtonian fluid for studied temperature range because viscosity was independent of shear rate.

Yarmand *et al*. [96] revealed that viscosity of GNP-Pt-water hybrid nanofluid increased by increasing volume fraction from 0 to 0.1% due to influence on the internal shear stress of fluid. Vegetable oil, paraffin oil, and SAE oil were used as base fluids by Kumar *et al*. [97] to synthesize Cu-Zn hybrid nanofluids with 0.1, 0.3, and 0.5% volume factions. The SAE oil-based hybrid nanofluid exhibited highest relative viscosity. Only vegetable oil based nanofluid behaved as a Newtonian fluid. Tahat and Benim [110] performed an experimental study to analyze thermophysical properties of Al_2O_3-CuO-water and ethylene glycol hybrid nanofluid. The viscosity enhancement as a function of volume fraction was measured. Enhancement in viscosity for volume concentration of 0.5, 1, 1.5, and 2% was 112%, 124%, 135%, and 159%, respectively, as compared to the viscosity of water. The Al_2O_3-CuO hybrid nanofluid behaved as a Newtonian fluid.

Suresh *et al*. [111] disclosed that the increase in viscosity of Al_2O_3-Cu-water hybrid nanofluid was considerably higher than enhancement in thermal conductivity. The viscosity enhancement for 0.1, 0.33, 0.75, 1, and 2% volume fraction of nanofluid was 8, 22, 54, 78%, and 115, respectively. For utilized nanoparticles concentration range, Newtonian behavior of hybrid nanofluid was observed. Esfe *et al*. [112] experimentally elaborated the effect of hybrid nanoparticle (Ag-MgO) concentration (0.5-2%) on dynamic viscosity and thermal conductivity of hybrid nanofluid. An increasing trend of viscosity was achieved for an increase in volume fraction. Maximum volume fraction of 2% showed the highest enhancement in viscosity of about 38.1%. Sundar *et al*. [100] flowed hybrid nanofluid (MWCNT-Fe_3O_4) through the circular tube and investigated the effect of concentration on thermal conductivity, viscosity, friction factor, and heat transfer rate. Maximum enhancement in viscosity of about 50% occurred at the highest concentration of 0.3% and temperature of 60 °C.

Yarmand *et al*. [101] found a nonlinear increase in viscosity of carbon/graphene oxide hybrid nanofluid by increasing weight concentration. The ACG/ethylene glycol hybrid nanofluid was qualified as Newtonian fluid for applied concentrations. The highest concentration of 0.06 wt.% intensified viscosity around 4.16%. Dardan *et al*. [102] obtained Newtonian behavior of Al_2O_3-MWCNT/engine oil hybrid nanofluid and increase in viscosity by increasing concentration. About 46% augmentation in viscosity was attained at 1% volume concentration of nanoparticles. Viscosity analysis revealed that viscosity was more sensitive to the variation of nanoparticles volume fraction. Cu-Zn hybrid nanoparticles with different weight ratios (50:50, 75:25, and 25:75) were prepared by Mechiri *et al*. [103] using a mechanical alloying method. Hybrid nanoparticles with a weight ratio of (50:50) showed higher viscosity than other hybrid alloys. More tendencies towards agglomeration were the reason behind higher viscosity of Cu-Zn (50:50).

Sundar *et al*. [104] obtained a non-linear behavior of viscosity enhancement by increase in (ND-Fe_3O_4) nanoparticle concentration from 0.05 to 0.2 vol.%. The viscosity enhancements for water, 80:20%, 60:40%, 40:60% W/EG were 172%, 219%, 150%, and 179%, respectively, at maximum concentration of 0.2 vol.%. The results showed that viscosity enhancement was dependent on nanoparticle concentration, temperature and type of base fluid used. Sundar *et al*. [79] also prepared GO/Co_3O_4 hybrid nanofluids in different base fluids to investigate an increase in viscosity due to the presence of nanoparticles. Hybrid nanoparticles having different concentration of 0.05, 0.1, 0.15, and 0.2 vol.% were dispersed in water, ethylene glycol, 80:20%, 60:40%, and 40:60% W/EG as base fluids. Water base hybrid nanofluid showed maximum enhancement in viscosity of 170%, whereas 40:60% W/EG base nanofluid showed the least enhancement of 131% for 0.2 vol.% and 60 °C. Akilu *et al*. [105] obtained Newtonian behavior of TiO_2-CuO/C ethylene glycol base hybrid nanofluids for applied concentrations and temperature ranges. The relative viscosity values achieved for concentrations of 0.5, 1, 1.5, and 2 vol.% were 1.13, 1.31, 1.56, and 1.77, respectively.

To avoid the disadvantages of high volume fraction such as an increase in viscosity, pressure drop, friction factor and pumping power, low volume fraction (0.02-0.1%) of nanoparticles was used by Yarmand *et al*. [106] in experimentation to investigate the effect of hybrid nanofluid on heat transfer. Friction factor enhancement was insignificant as compared to the increase in heat transfer. Sundar *et al*. [113] studied friction factor and turbulent heat transfer behavior of (ND-Ni) hybrid nanofluid flowing through the tube. Enhancement in viscosity was 23.24% as a result of the addition of 0.3 vol.% hybrid nanoparticles in water. Moldoveanu *et al*. [114] made a comparison between the viscosity of TiO_2, Al_2O_3 nanofluids and their hybrid for different volume concentrations at room temperature. The non-Newtonian behavior of nanofluids was observed for all samples. The TiO_2 nanofluid showed fewer enhancements in viscosity as compared to alumina nanofluid and their hybrid.

Low volume fraction of nanoparticles showed less enhancement in dynamic viscosity whereas this increase became significant for higher volume fraction [94]. Kannaiyan *et al*. [115] made a comparison of thermophysical properties of hybrid nanofluid (Al_2O_3/CuO) measured experimentally and calculated theoretically. The probability of nanoparticle agglomeration increased at higher volume fractions thus, causing an increase in dynamic viscosity of nanofluid. Kumar *et al*. [116] investigated the effect of spacing on the performance of plate heat exchangers by using nanofluids. For this purpose, TiO_2, Al_2O_3, ZnO, CeO_2, Cu+Al_2O_3, GNP, MWCNT nanofluids were prepared and their thermo-physical properties were evaluated at fix temperature of 35 °C. The order of increase in viscosity achieved for nanofluids was MWCNT < GNP < Cu + Al_2O_3 < CeO_2 < ZnO < Al_2O_3 < TiO_2.

Nabil *et al*. [117] found an insignificant increase of about 2% in dynamic viscosity of hybrid nanofluid (TiO_2-SiO_2-water and ethylene glycol) when the volume fraction of nanoparticles increased from 2 to 3% at a temperature of 30 °C. Hussien *et al*. [118] reported thermo-physical properties of hybrid nanofluid (MWCNT-GNP) by varying wt.% of MWCNT in hybrid nanocomposites. For an increase in the concentration of MWCNT in nanocomposite, the viscosity of hybrid nanofluid elevated from 2.8 to 10.3%. Hamid *et al*. [119] investigated the effect of nanoparticle (TiO_2-SiO_2) mixture ratio variation on thermophysical properties and heat transfer characteristics of hybrid nanofluids. For this purpose, hybrid nanoparticles containing mixture ratios of (TiO_2-SiO_2) 20:80, 40:60, 50:50, 60:40, and 80:20 were prepared. The mixture ratio (50:50) showed maximum enhancement in dynamic viscosity due to particles distribution. The study of Sharma *et al*. [120] on the viscosity of different types of hybrid nanofluids found that the viscosity of the fluids augmented in the following sequence (0.8 CeO_2 – 0.2 Cu) > (0.8 TiO_2 – 0.2 Cu) > (0.8 SiO_2 – 0.2 Cu) > (0.8 Al_2O_3 – 0.2 Cu) than that of base fluid.

Dalkilic *et al*. [121] inspected the viscosity of graphite-SiO_2 hybrid nanofluid and found that the addition of silica nanoparticle augmented the viscosity sharply as compared to the

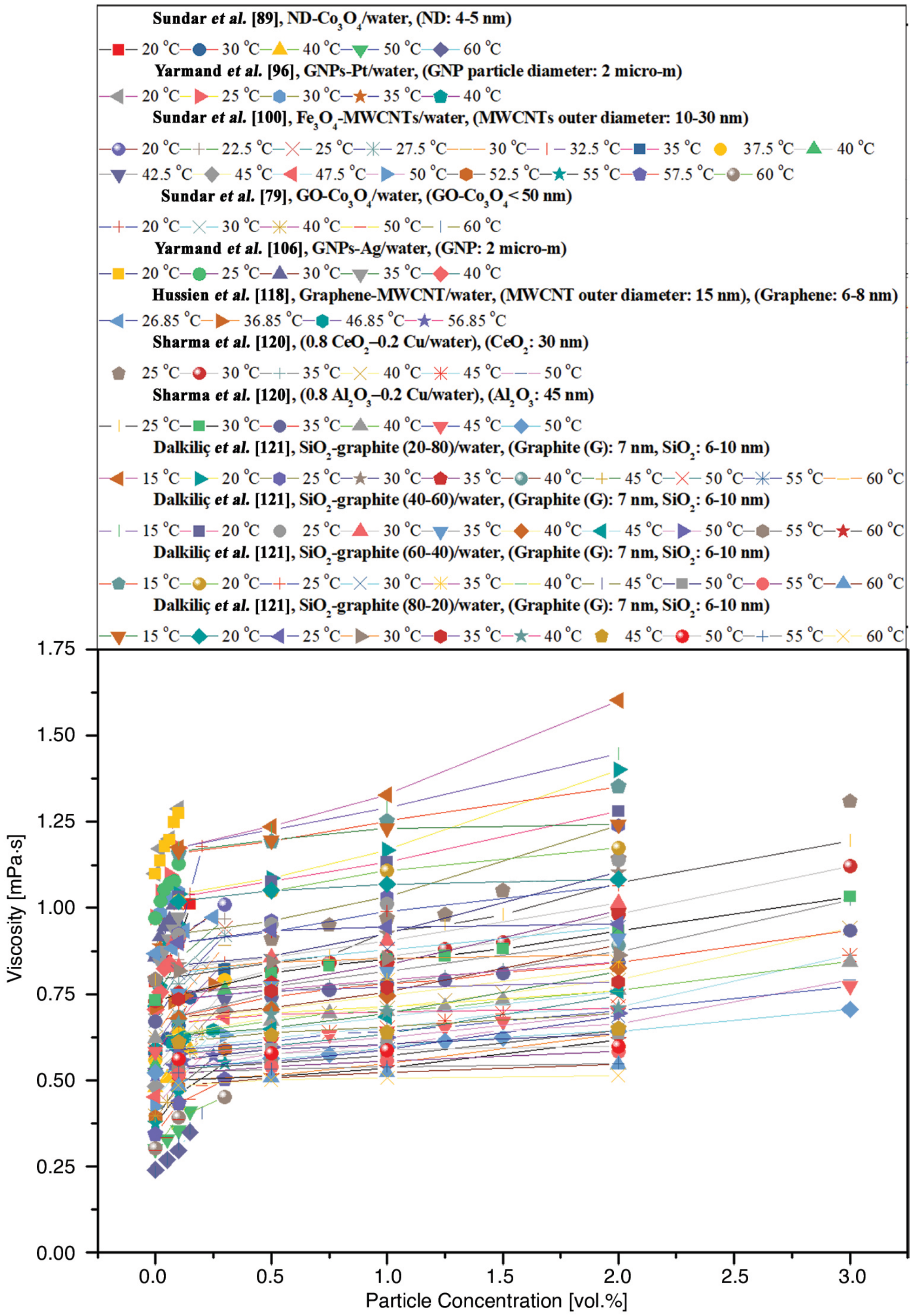


Figure 9. Viscosity variation of water-based hybrid nanofluids against particle concentration at different temperatures [various studies]

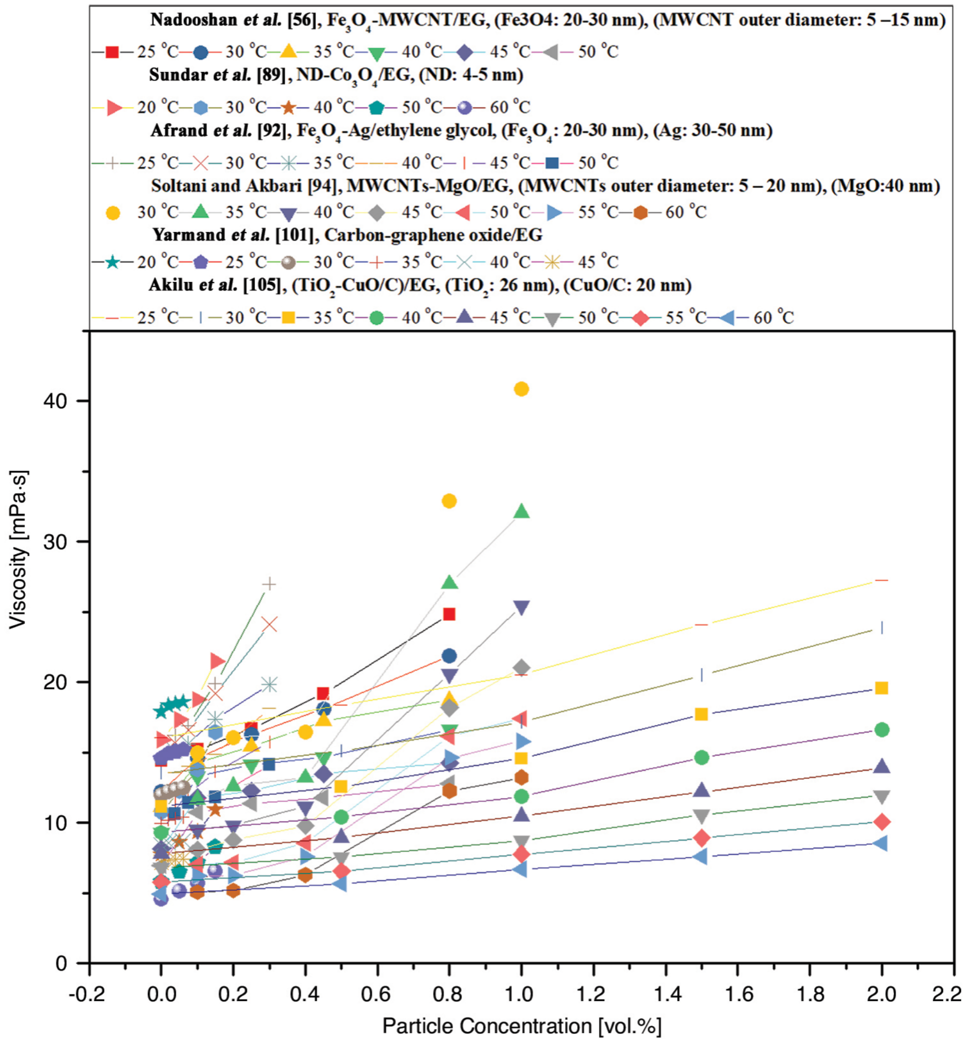


Figure 10. Viscosity variation of EG-based hybrid nanofluids against particle concentration at different temperatures [various studies]

nanoparticles of graphite. Afshari *et al*. [122] investigated the dynamic viscosity of the hybrid nanofluid of alumina– MWCNT/ethylene-glycol (20%)– water (80%) and found that the behavior of the fluid transformed from Newtonian to pseudoplastic non-Newtonian when the particle concentration surges past from 0.5 vol.%. They also observed that with the increase in shear rate viscosity of the fluid decreased. Ghasemi and Karimipour [123] revealed that the effect of particle concentration on the viscosity of CuO-paraffin nanofluid becomes significant at the particle concentration higher than 1.5 wt.% below of that it was not significant. They also stated that the viscosity of the analyzed nanofluid was more sensitive to particle weight fraction than that of the temperature. Viscosity variation of different water, EG, oil, and W/EG-based hybrid nanofluids against particle concentration at different temperatures reported in various studies are presented in figs. 9-12 respectively.

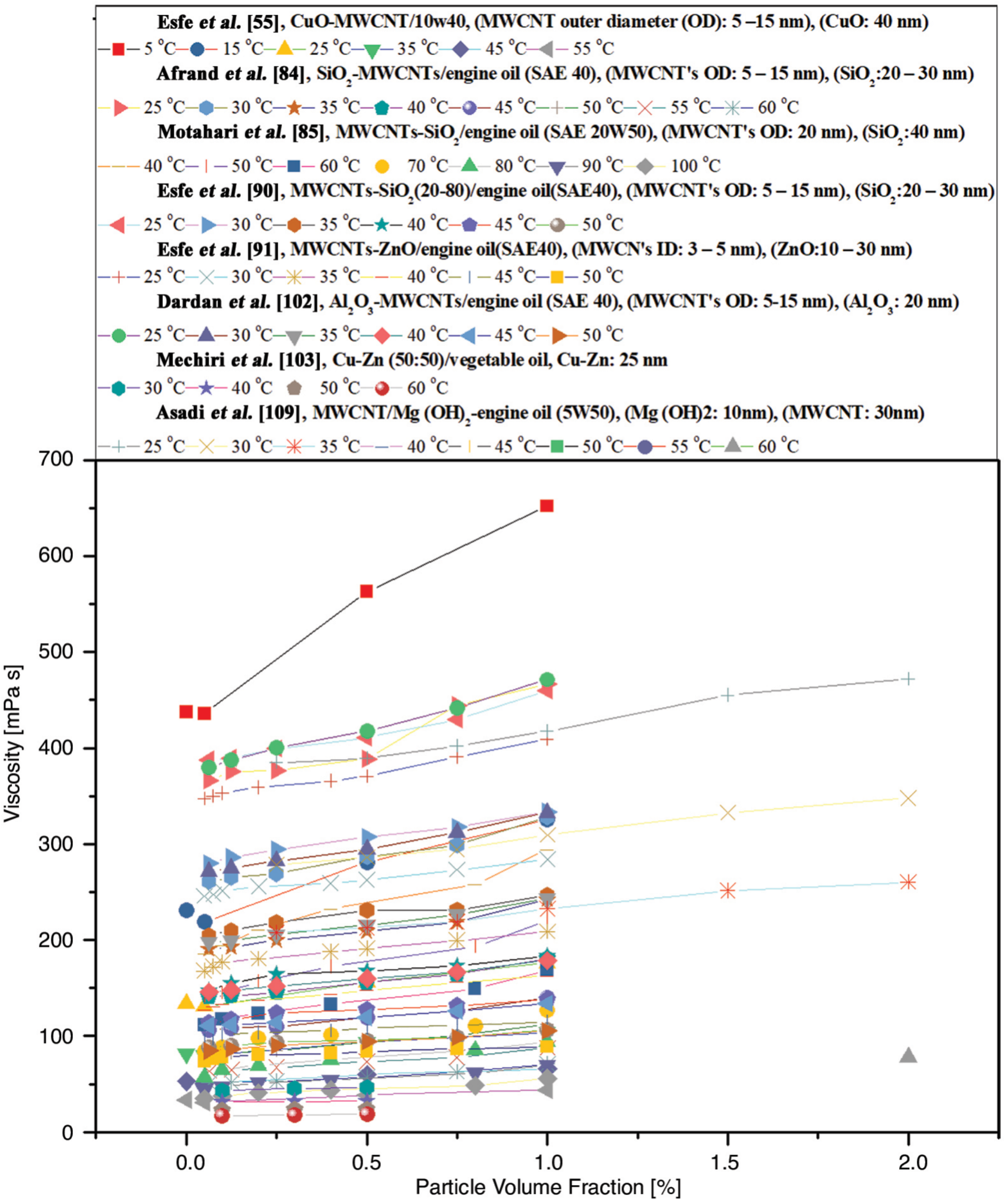


Figure 11. Viscosity variation of oil-based hybrid nanofluids against particle concentration at different temperatures [various studies]

Effect of base fluid

The best fluid is the one that provides the prodigious heat transfer, however, the selection of base fluid depends upon the application of hybrid nanofluids. It is clear from the figs. 5-12 that the water-based nanofluids comparatively performed well where the effect of pumping power is more significant as the viscosity variation of water-based hybrid nanofluids is not more than 2 mPas in most of the studies while for the case of EG-based hybrid nanofluids its value goes

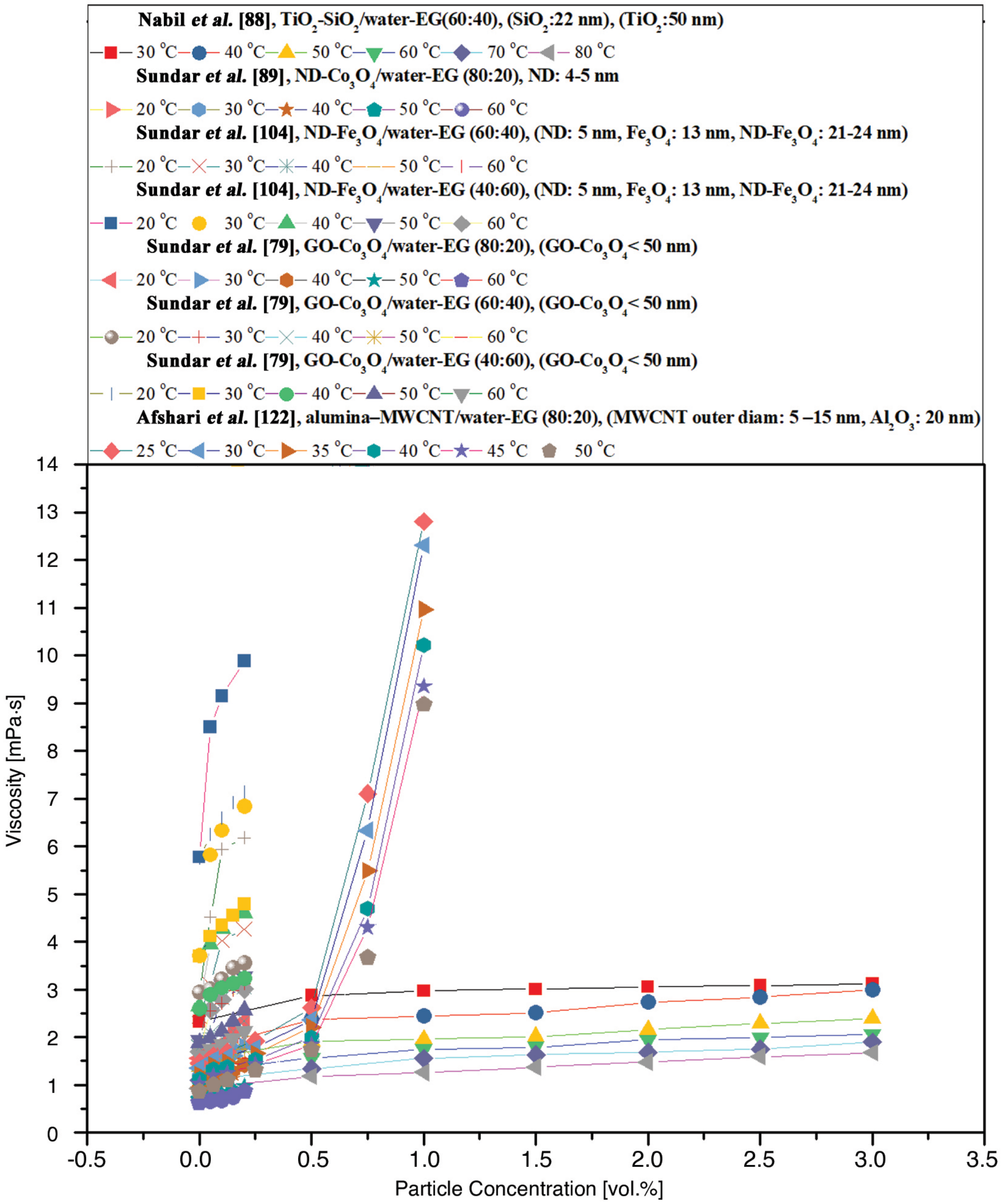


Figure 12. Viscosity variation of binary (water/EG)-based hybrid nanofluids against particle concentration at different temperatures [various studies]

up to 40 mPa.s. However, for the applications where the lubrication is also important with heat transfer oil-based nanofluids would be preferred. Atashrouz *et al.* [124] studied the effect of particle diameter, concentration and temperature on the relative viscosity of nine different nanofluids (Al_2O_3-EG, Al_2O_3-PG, TiO_2-EG, Al_2O_3-60% EG, and 40% water, CuO-water, SiO_2-water, Al_2O_3-water, TiO_2-water, CuO-60% EG, and 40% water) prepared by using the base fluids of ethylene glycol, water, and PG. For this purpose, they developed the hybrid self-organizing polynomial neural network based on the group method of data handling (GMDH). The results predicted with GMDH models showed a great agreement with the experimental results. Table 1 provided the Nodal expressions used for different nanofluids with an average absolute relative deviation and regression coefficient of 2.14% and 0.9978, respectively.

Kannaiyan *et al*. [115] investigated the thermal conductivity and viscosity of alumina/cupric oxide hybrid nanofluids by varying the temperature and particle concentration ranging from (20-70 °C) and (0.05-0.2 vol.%). They used the pure water and water-ethylene glycol mixture as the base fluids and found that the water-based nanofluids performed well and provided the better thermal conductivity values with a comparatively less augmentation in viscosity. In heat transfer applications where the lubrication is not important, the investigators preferred to use water-based hybrid nanofluids. However, oil-based nanofluids due to its high viscosity preferred in the applications where the lubrication is significant with heat transfer.

Other affecting parameters

Besides of aforementioned affecting parameters, there are a lot of other parameters that influence the viscosity of hybrid nanofluids like particle size and shape, pH value, surfactant addition, and particles aggregation. Literature reports very limited studies that discussed the effect of these parameters on the viscosity of hybrid nanofluids. However, for the case of unitary nanofluids handful studies is available that assists the investigators to comprehend the influence of these factors on the viscosity of nanofluids. The study of Koca *et al*. [125] on the effect of particle size drew the following important concluded remarks:

- Studies reported contradictory results about the effect of particle size on the viscosity of nanofluids. Some studies reported a decline in viscosity with an increase in particle size, while the others stated the augmentation with particle size. They mentioned that the different preparation, measurement techniques, consideration of two or three different sizes of nanoparticles, and limited studies are the restrictions that restraint to draw a clear conclusion of the effect of particle size in viscosity.
- Particles shapes like cylindrical, spherical *etc*. also influenced the viscosity of nanofluids.

Nwosu *et al*. [126] revealed that to develop a more general and accurate viscosity model consideration of the factors like particle size and shape, aggregation size, surfactant, and base fluid polarity with temperature and particle concentration could be very effective. However, Bashirnezhad *et al*. [81] suggested the consideration of some additional parameters like pH value and sonication time to generate a more accurate model.

Palabiyik *et al*. [127] studied the effect of sonication time on the particle size of TiO_2 and Al_2O_3 nanofluids and observed a noticeable reduction in size with an increase of sonication time, however, after a certain time this effect mitigated and further increase in sonication time reflected no influence on particle size as sown in fig. 13(a). Sharma *et al*. [128] reported that the optimization of particle size can be very valuable to get the nanofluids with superior rheological properties. To obtain a stable solution of nanofluids additive like surfactants also played a very effective role [129]. In some studies [130, 131] investigators observed that the addition of surfactants changed the behavior of the fluid flow from Newtonian to non-Newtonian. Jarahnejad *et al*. [132] analyzed the effect of surfactant and particle size on the viscosity of nanofluids of TiO_2 and Al_2O_3 respectively. For this purpose, they used the surfactants of tri-oxadecane acid and poly-carboxylate and found that the viscosity of utilized nanofluid enhanced with the addition of surfactants. Moreover, the tri-oxadecane acid supported nanofluid showed enriched viscosity values as compared to the surfactant free and poly-carboxylate supported nanofluid. However, for

Table 1. Nodal expressions for hybrid (GMDH-PNN) with limitations [124].

System	Related GMDH - polynomial	Range of variables	Number of data points
Al_2O_3-EG	μ_r = 57.7116 - 0.0705208d - 0660868$d\varphi$ + 0.00024175d + 162.223φ - 0.400933φT + 135.288φ^2 - 0.354906T + 0.000553982T^2	283.15 < T < 323.15 0.005 < φ < 0.066 d = 43.8	96
Al_2O_3 - 60% EG and 40% water	μ_r = 44.1534 - 0.274456T + 0.651533$T\varphi$ + 0.000437995T^2 - 177.958φ + 1210.41φ^2	298 < T < 133 0.0003 < φ < 0.01 d = 13	96
SiO_2 - water	μ_r = 2.11973 - 0.00343424T + 0.417004$T\varphi$ - *125.954*φ + *2336.92*φ^2 - 177.958φ + 1210.41φ^2	293 < T < 323 0.0045 < φ < 0.0224 d = 12	21
TiO_2 - EG	μ_r = 0.212463 + 0.0075517T - 0.0321391$T\varphi$ - 1.17438e -05T^2 - 18.2968φ + 106.324φ^2	293.15 < T < 333.15 0.0013 < φ < 0.0224 d = 25	45
CuO - water	μ_r = 0.792034 + 36.3781φ - 408.646φ^2 - 0.27359n_2 + *0.236136*N_2^2 N_2 = 49.9132 - 0.313024T - 0.22456$T\varphi$ + 0.000502159T^2 + 49.9962φ + 833.886φ^2	294 < T < 337 0.01 < φ < 0.07 d = 29	54
Al_2O_3 - PG	μ_r = 1.06129 - 0.00335679T - 0.00316163TN_2 - N*2* = 0.516211 + φ × 49.0593 - 761.957φ^2	303 < T < 333 0.02 < φ < 0.05 d = 39	36
TiO_2 - water	μ_r = 0.439835 + T × 0.00491987 - 0.206399$T\varphi$ - 55.5471φ	288 < T < 308 0.002 < φ < 0.02 d = 27	15
CuO - 60% EG and 40% water	μ_r = 0.923585 + 16.4819φ + 30.4847φN_2 - 1017.31φ^2 - 0.0930604 N_2^2 N_2 = 0.151871 + 0.0038256T - 0.342882$T\varphi$ + *93.8755*φ +*740.151*φ^2	238 < T < 323 0.01 < φ < 0.0612 d = 29	60
Al_2O_3 - water	μ_r = 23.1077 - 0.14405T + 0.00148085TN_2 - 0.000223842T^2 + *0.543275*N_2 N_2 = - 0.00268592 - 0.043*8904*dN_4 + 0.0438062dN_3 + 1.88848N_4 - *0.881516*N_3 N_3 = 1.79002 + 14.0621φ - 0.00360243dN_4 - 0.927421N_4 + 0.333461N_4^2 N_4 = 34.9901 - 0.213667T - 0.0874713$T\varphi$ + 0.000339022T^2 + 602.534 φ^2	294 < T < 343 0.01 < φ < 0.094 d = 36,47	138

the case of particle size, they failed to draw a clear conclusion. The effect of surfactants and particle size on the viscosity of employed nanofluids represented in figs. 13(a) and 13(b), respectively. In past, a lot of studies were carried out on different types of nanofluids that reported the augmentation in viscosity with an increase of particle size [133-135]. Ferrouillat *et al*. [136] studies the effect of particle shape on the viscosity of water-based ZnO and found that the fluid containing polygonal shaped nanoparticles suspension exhibited slightly more viscosity than that of rod-shaped nanoparticles suspended fluid. While for water-based SiO_2 nanofluids the suspension of banana-shaped nanoparticles showed marginally more viscosity in comparison of spherically shaped nanoparticles. Figures 14(a) and 14(b) demonstrated the effect of particle shape on the viscosity of SiO_2 and ZnO nanofluids respectively. Timofeeva *et al*. [137] acquired higher viscosity of the platelets nanoparticles as compared to brick-shaped nanoparticles while investigating the water-EG based nanofluid of Al_2O_3. Wang and Li [138] investigated the effect of pH value on the viscosity of water-based nanofluids of Al_2O_3 and Cu and found that particles formed clusters below the pH value of 7 that not only increased the viscosity but also reduced the stability period. According to the results, nanofluids of alumina exhibited great stability at the pH values between 7.5-8.9 and the nanofluids of copper provided better particles dispersion at the pH > 7.5. The aggregation effect of nanoparticles also influenced the viscosity of the nanofluid. The

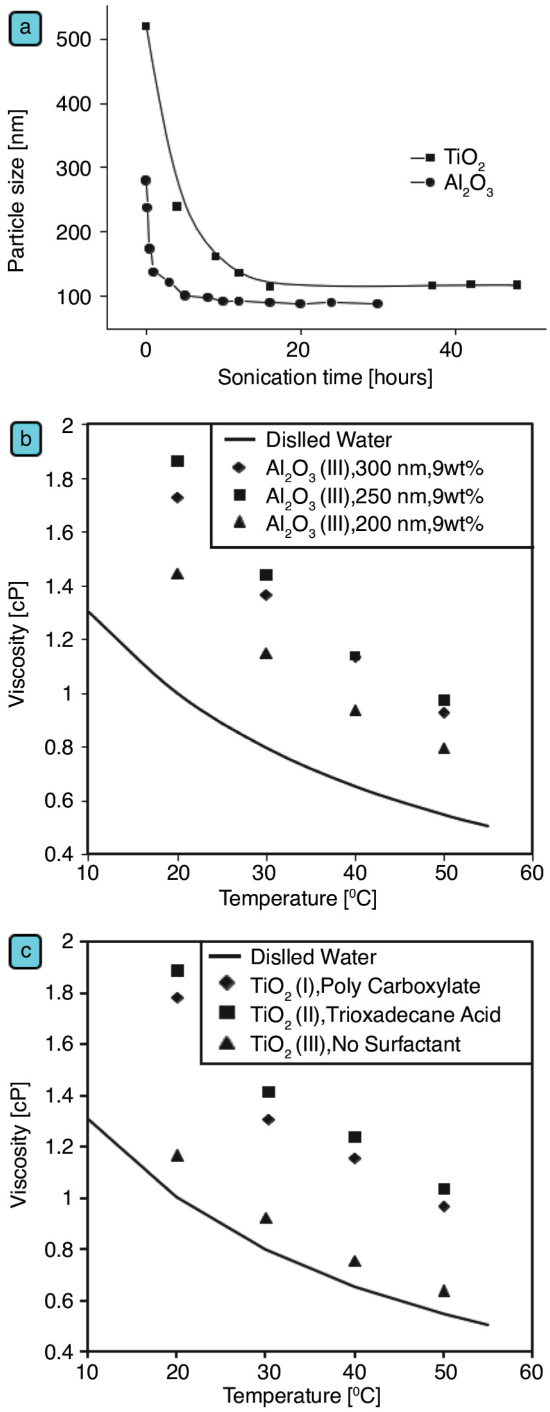


Figure 13. Effect of (a) sonication time on particle size [127], (b) particle size, and (c) surfactant on the viscosity of nanofluid [132]

study of Duan *et al*. [139] on the effect of particles aggregation revealed that formation of aggregates augmented the viscosity of the nanofluid.

Viscosity comparison of hybrid nanofluids with mono nanofluids

This section comprised the studies that provided a comparison between the viscosity values of different unitary and hybrid nanofluids. The viscosity of hybrid nanofluid depends upon the selected nanoparticles, concentration, and temperature. Results of most of the studies revealed that viscosity of hybrid nanofluids found in between the viscosity of mono nanofluids of utilized nanoparticles which are combined to prepare the hybrid and it can be optimized by adjusting the weight percent (wt.%) of each type of nanoparticles. However, its effect is more significant at a lower temperature and high particle volume fraction. Afrand *et al*. [84] experimentally investigated viscosity of hybrid nanofluid SiO_2-MWCNT/engine oil and compared it with viscosities of mono nanofluids SiO_2/engine oil and MWCNT/engine oil. Results showed that relative viscosity of hybrid nanofluid was greater than SiO_2/engine oil nanofluid, whereas less than from MWCNT/engine oil nanofluid. Shahsavar *et al*. [87] empirically found that viscosity of 1.35% CNT-0.9% Fe_3O_4-water hybrid nanofluid was about 28.60% greater than (0.9% Fe_3O_4-water) nanofluid. The increased viscosity of hybrid nanofluid was due to the presence of CNT. At an optimum operating temperature of 20 °C and maximum concentration of 1 wt.%, Baghbanzadeh *et al.* [93] concluded from experimentation that viscosity enhancement of mono nanofluids was greater than hybrid nanofluids. Viscosity enhancement for MWCNT, silica, (80 wt.% silica – 20 wt.% MWCNT), (50 wt.% silica – 50 wt.% MWCNT) nanofluid was 18.9%, 9.7%, 8.8%, and 8.2%, respectively. The structure of MWCNT was the main reason behind much increase in viscosity of nanofluid.

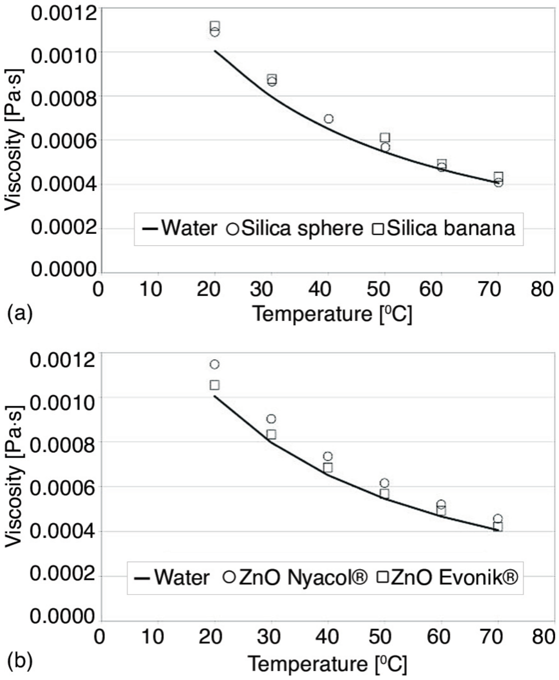


Figure 14. Effect of particle shape on the viscosity of nanofluid (a) SiO_2, (b) ZnO [136]

Suresh *et al*. [111] obtained higher viscosity enhancement in Al_2O_3-Cu-water hybrid nanofluids as compare to Al_2O_3-water mono nanofluid. Sundar *et al*. [79] determined that viscosity enhancement of hybrid nanofluid (GO-Co_3O_4) was similar to GO nanofluid. The TiO_2-Al_2O_3 hybrid nanofluid showed more increase in viscosity enhancement than mono nanofluids [114]. Kumar *et al*. [116] obtained viscosity enhancement of mono nanofluids (TiO_2, Al_2O_3, ZnO, and CeO_2) to be greater than hybrid nanofluid (Cu + Al_2O_3) for studied volume fractions of nanoparticles. Ahammed *et al*. [107] found viscosity of Graphene-alumina hybrid nanofluid to be greater than alumina nanofluids, while less than graphene nanofluids. Akilu *et al*. [140] compared the viscosity of the unitary nanofluid of SiO_2/EG-glycerol(G) and the hybrid nanofluid of carbon-ceramic copper oxide/G-EG and revealed that the hybrid nanofluid provided the enhanced thermal conductivity with a comparatively less increase in viscosity. According to the results, hybrid and unitary nanofluids showed an enhancement of 1.15-times and 1.33-times in viscosity than that of the base fluid.

Moldoveanu *et al*. [114] developed a comparative study of the viscosity of the unitary nanofluid of TiO_2 and Al_2O_3 and their hybrids at different particle concentration while keeping them at room temperature. Table 2 presents the comparative study of Moldoveanu *et al*. – [114] representing the viscosity values of the examined unitary and hybrid nanofluids. It is revealed that the titania-based nanofluids offered comparatively less augmentation in the viscosity values as compared to alumina-based nanofluids that exhibited maximum enhancement while the viscosity of hybrid nanofluids depends upon the particle volume fraction.The study of Moldoveanu *et al*. [141] on the viscosity of mono nanofluids of SiO_2 and Al_2O_3 and their hybrid nanofluids also depicted that the alumina-based nanofluids showed augmented viscosity values than that of unitary SiO_2 and hybrid (SiO_2+Al_2O_3) nanofluids. Moreover, silica-based nanofluid exhibited shear-thickening while the alumina-based mono and hybrid nanofluids showed shear thinning behavior. Table 2 presented the graphical representation of the viscosity comparison of mono and hybrid nanofluids by considering a number of studies.

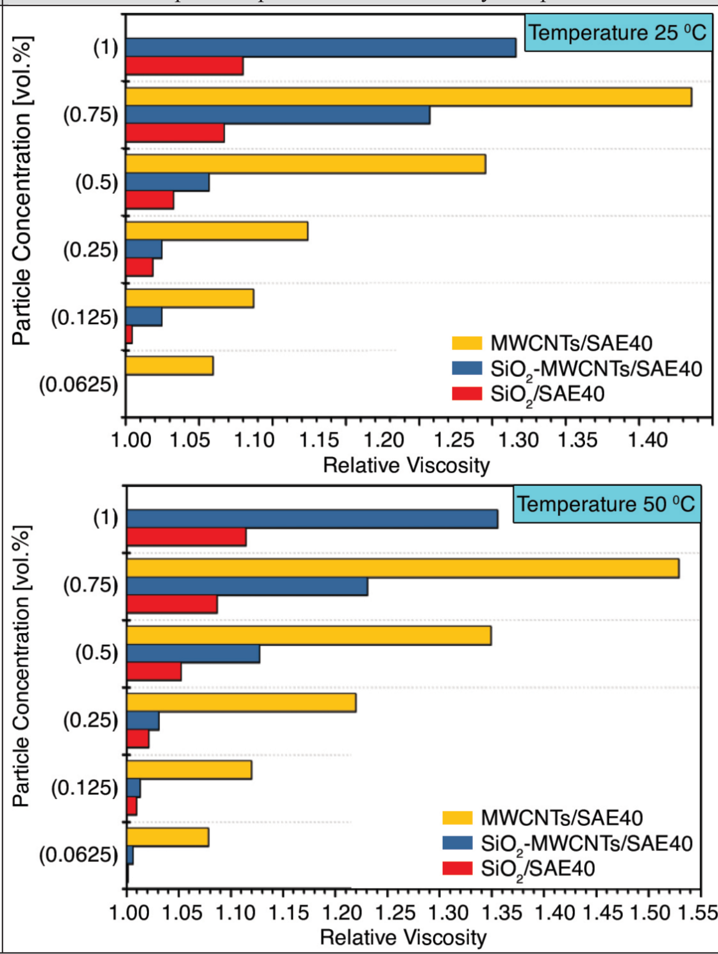
Correlations to predict the viscosity of hybrid nanofluids

This section presents the correlations reported in the literature to predict the viscosity of hybrid nanofluids within a specified range of temperature, particle concentration, and shear rate with the prediction accuracy. Afrand *et al*. [142] presented a comparative study between the viscosity values predicted by empirical correlation and the optimal artificial neural network (ANN) model of the hybrid nanofluid of MWCNT-SiO_2/AE40 while considering the margin of deviation as a decisive factor. They found that the ANN model can predict the viscosity values best in comparison of empirical correlation. Asadi *et al*. [54] examined the thermal and rheological properties of the hybrid nanolubricant of Al_2O_3-MWCNT/thermal oil for the automotive and manufacturing applications. The results revealed that the viscosity of the lubricant augmented with the particle concentration and the prepared nanofluid exhibited Newtonian behavior over the examined range of temperature and particle concentration from 40-100 °C and 0.125-1.5 vol.%, respectively. According to the results, the maximum enhancement in viscosity was found to be 81% all over the experiment at the particle volume fraction of 1.5%. The increase in dynamic viscosity of the fluid was examined using the eq. (1).

$$\text{dynamic viscosity increase} = \left[\frac{\mu_{\text{nf}}}{\mu_{\text{nf}}} - 1\right]100\% \tag{1}$$

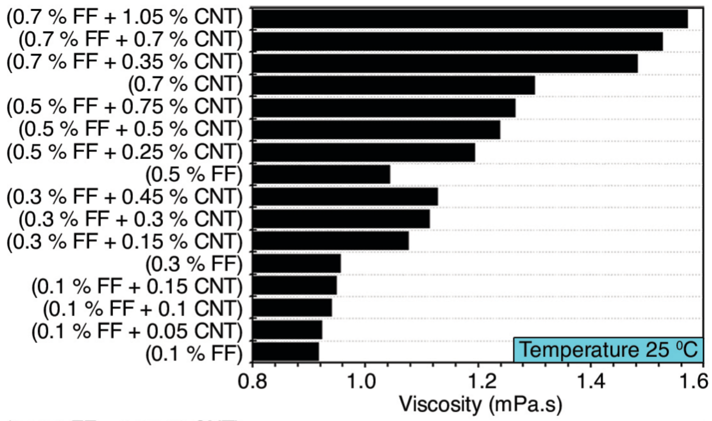
Esfe and Hajmohammad [99] developed a correlation to predict the viscosity of the hybrid nanofluid of nanodiamond-Co_3O_4/EG (40:60). They also considered the determination of optimum values of viscosity and thermal conductivity (maximum thermal conductivity and

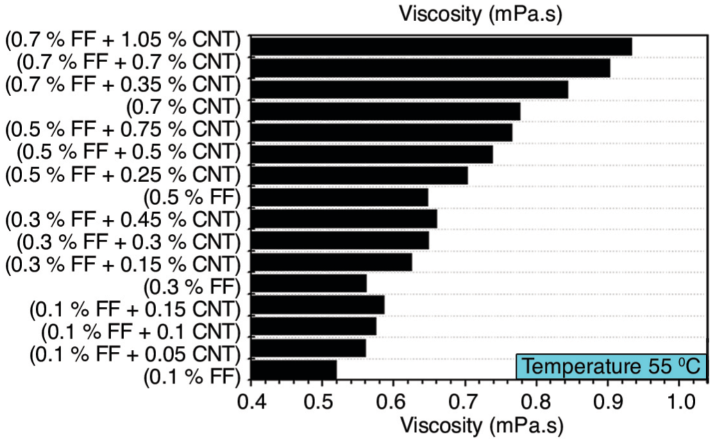
Table 2. Viscosity comparison of unitary and hybrid nanofluids.

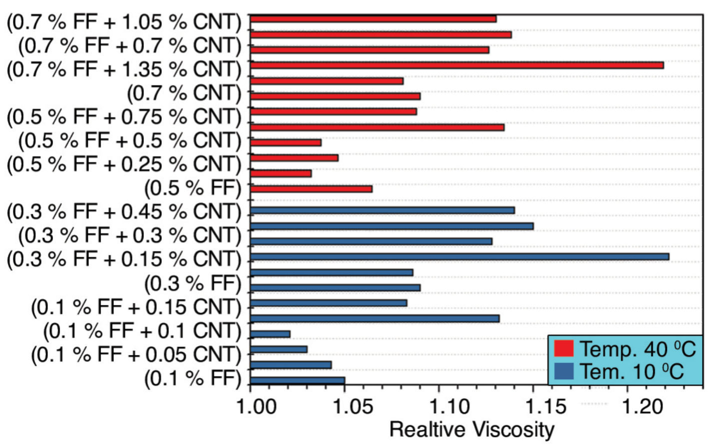
References	Graphical representation of viscosity comparision	Remarks
[84]		The results reveals that the hybrid nanofluids presents the viscosity in between the MWCNT's and silica nanofluids. Viscosity variation for the case of MWCNT's is due to the large length of cylindrical shape tubes that restrict them to flow between the layers of base fluid. However, for the case of SiO_2 nanofluids, the shape of particles is spherical that provides less resistance to the flow and move easily between the layers. At lower particle concentration, the viscosity of hybrid nanofluid nearly equal to unitary SiO_2 nanofluid that becomes more significant at higher concentration.

→

Table 2. (Continuos)

<table>
<tr>
<td>[87]</td>
<td>


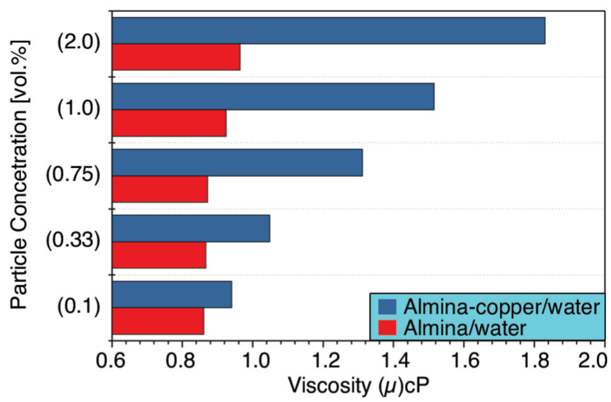
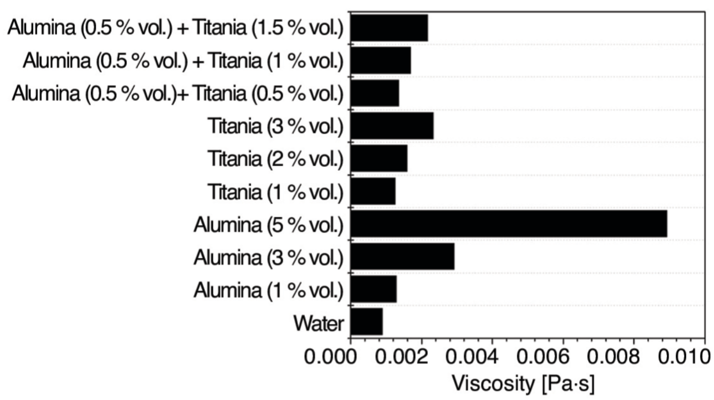
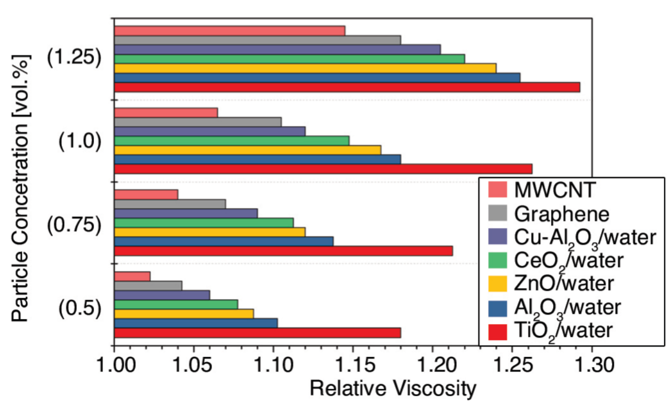


</td>
<td>The viscosity of ferrofluid increases with particle concentration and reduces with temperature. However, viscosity augments with the concentration of CNTs that is more significant at a lower temperature. The enhancement in viscosity is more at higher particle concentration due to the effect of hydrodynamic interaction between the dispersed particles.</td>
</tr>
<tr>
<td>[93]</td>
<td>


</td>
<td>Viscosity of the unitary nanofluids of MWCNTs and silica is more than that of their hybrid prepared with 50% wt. concer. of MWCNTs for particle volume fraction of 0.5 and 1 %vol. However, for lower temp. (10^{o}C) and particle concentration (0.1% vol) hybrid nanofluid with 50% wt. CNT shows comparatively enhanced viscosity.</td>
</tr>
</table>

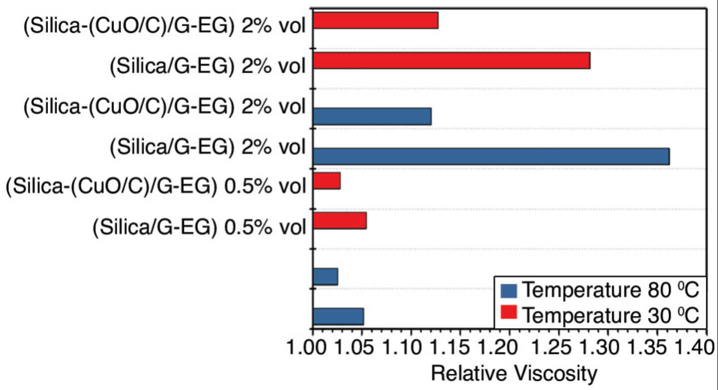
⟶

Table 2. (Continuos)

<table>
<tr><td>[111]</td><td>
</td><td>Provides a comparison between the viscosity values of water-based mono nanofluid of alumina and its hybrid with copper. Hybrid nanofluids at all examined particle concentrations exhibited higher viscosity and the difference between the viscosity values increases with an increase in particle volume fraction.</td></tr>
<tr><td>[114]</td><td>
</td><td>Presents a comparison of the unitary nanofluids of alumina, titania and their hybrid with different particle concentration. The nanofluids of titania offer comparatively less viscosity than that of alumina. The viscosity of hybrid nanofluid depends upon the mass concentration of the dispersed particles.</td></tr>
<tr><td>[116]</td><td>
</td><td>Reports some contradictory results as the viscosity of titania nanofluids show higher viscosity and MWCNT's nanofluid exhibit lowest viscosity values at all examined concentration of particles.</td></tr>
</table>

→

Table 2. (Continous)

[140]		The hybrid nanofluid of (80%wt. SiO_2-20% wt. CuO/C) shows relatively less viscosity than that of the 100 wt. SiO_2 nanofluid. It is due to the less density of SiO_2 nanoparticles because the number of particles would reduce when 20%wt. SiO_2 nanoparticles are replaced with the same the amount of denser CuO/C nanoparticles.

minimum viscosity) and found the best results at the highest temperature and particle concentration (60 °C and 0.15 vol.% correspondingly). The developed correlation of viscosity could predict the viscosity of the examined nanofluid with a great accuracy against the values of temperature and particle concentration.

Aghaei *et al*. [143] examined the experimental data to develop the new correlation for the prediction of viscosity of non-Newtonian hybrid nanofluid of MWCNT-SiO_2/EG-water. They also considered the ANN technique for the forecasting of rheological behavior and made a comparison with the developed correlation that which one provides the more accurate results. The results showed that the ANN technique was the most suitable and accurate in comparison of the developed model. Sharma *et al*. [120] examined the viscosity of hybrid nanofluids prepared using different combination of nanoparticles like (0.8 CeO_2–0.2 Cu), (0.8 Al_2O_3–0.2 Cu), (0.8 TiO_2–0.2 Cu), and (0.8 SiO_2–0.2 Cu) and observed that the values obtained during the experimental work always showed notable augmentation than that of the values predicted with the available models.

Nadooshan *et al*. [144] assessed the viscosity of hybrid nanolubricant of SiO_2-MWCNT/10W40 and found that the developed model used for the prediction of nanofluids viscosity failed to predict the values for cases of hybrid nanofluids. So, they used the ANN technique for the prediction of viscosity while considering the temperature, particle concentration and shear rate as input parameters. The employing technique provided great results with the value of R^2 = 0.9948. Esfe and Arani [145] considered shear rate, particle concentration, and temperature to develop a correlation for viscosity prediction of SiO_2-MWCNT (0.6:0.4)/5W50 hybrid nano-lubricant.

The study of Esfe *et al*. [146] on the viscosity of the nanolubricant of ZnO-MWCNT (0.9:0.1)/5W50 used the Design Expert software and statistical models to find out the optimized maximum and minimum viscosity values against the parameters temperature, shear rate, and particle concentration. They used the ANN technique for the designing of viscosity prediction model and also compared with the mathematical correlation. According to the results, the maximum optimal value of viscosity was 598.095 (mPa.s) at the temperature, shear rate, and particle concentration of 5.09 °C, 774.58 $s^{-1}$and 0.95 vol.%, respectively, while the optimal minimum value was found at the 54.29 °C, 1029.89 s^{-1}, and 0.1% vol.%, respectively. Esfe *et al*. [147] developed a study to predict the viscosity of the hybrid nanolubricant of Al_2O_3-MWCNT/5W50 using ANN technique and proposed a new correlation. They considered the effect of more influential parameters like temperature, particle concentration, and shear rate and revealed that the ANN technique was more effective for the prediction of relative viscosity as compared to the empirical correlation. Esfe *et al*. [148] also developed a correlation to predict the viscosity of hybrid nanolubricant of Al_2O_3 (90%) – MWCNT (10%)/5W50

Table 3. Important aspects of the discussed studies.

References	Nanofluid	Particle size	Variable parameters	Measuring equipment	Viscosity enhancement
[54]	SiO_2-graphene / naphthenic mineral oil	Graphene nanoparticles: 12 nm	Weight fraction: 0.01, 0.04, 0.08% Temperature: 20 - 100 °C		29.7% for 0.04 wt.%
[55]	CuO - MWCNT / 10w40	MWCNT outer diameter: 5 - 15 nm CuO: 40 nm	Volume fraction: 0 - 1% Temperature: 5 - 55 °C	Brookfield CAP 2000 +	49% for 1 vol.% at 5 °C
[56]	Fe_3O_4 - MWCNT/EG	Fe_3O_4: 20-30 nm MWCNT outer diameter: 5 - 15 nm	Volume fraction: 0.1 - 1.8% Temperature: 25 - 50 °C	Brookfield DV-I	63% for 0.8 vol.%
[84]	SiO_2 - MWCNTs / engine oil (SAE 40)	MWCNTs outer diameter: 5 - 15 nm SiO_2: 20 - 30 nm	Volume fraction: 0.0625 - 1% Temperature: 25 - 60 °C Nanofluid behavior: Newtonian Shear rate range: 667– 6667 s^{-1}	The CAP 2000 + viscometer. Accuracy: ±2%	37.4% for 1 vol.% and 60 °C
[85]	MWCNTs - SiO_2 / engine oil (SAE 20W50)	MWCNTs mean diameter: 20 nm SiO_2: 40 nm	Volume fraction: 0.05 - 1% Temperature: 40 - 100 °C Nanofluid behavior: Newtonian	MYR V2L rotary viscometer. Accuracy: ±2%	171% for 1 vol.% and 100 °C
[87]	CNTs - Fe_3O_4 / water	MWCNTs outer diameter: 10 - 30 nm	Volume fraction of CNTs: 0.05 - 1.35% Volume fraction of Fe_3O_4: 0.1 - 0.9% Temperature: 25 - 55 °C Nanofluid behavior: Newtonian Shear rate range: 10 - 100 s^{-1}	Paar physica MCR 300 parallel disc rheometer. Accuracy: ±0.5%	29.62% for 0.9% Fe_3O_4 - 1.35% CNT
[88]	TiO_2 - SiO_2 / water and ethylene glycol (60:40)	SiO_2: 22 nm TiO_2: 50 nm	Volume fraction: 0.5 - 3% Temperature: 30 - 80 °C Nanofluid behavior: Newtonian Shear rate range: 25 - 187.5s^{-1}	LVDV III ultra - rheometer.	62.5% for 3 vol.% and 80 °C
[89]	ND-CO_2O_4 / water, EG, water and EG	ND: 4-5 nm	Weight fraction: 0.05 - 0.15% Temperature: 20 - 60 °C	The A&D vibro viscometer SV-10.	51% for 0.15 wt.%, 60 °C and (60% water: 40% EG)
[90]	MWCNTs - SiO_2 (20 - 80) / engine oil (SAE40)	MWCNTs outer diameter: 5 - 15 nm SiO_2: 20 - 30 nm	Volume fraction: 0.0625 - 2% Temperature: 25 - 50 °C Nanofluid behavior: Newtonian up to 1 vol.% and Non-Newtonian for vol.% > 1	The CAP 2000 + viscometer. Accuracy: + 2%	30.2% for 1 vol.% and 40 °C

→

Table 3. (Continous)

[91]	MWCNTs - ZnO / engine oil SAE40	MWCNTs inner diameter: 3 - 5 nm ZnO: 10 - 30 nm	Volume fraction: 0.05 - 1% Temperature: 25 - 60 °C Nanofluid behavior: Newtonian Shear rate range: 1333 - 13333 s^{-1}	The CAP 2000 + viscometer. Accuracy: +2%	33.3% for 1 vol.% and 40 °C
[92]	Fe_3O_4-Ag / ethylene glycol	Fe_3O_4: 20 - 30 nm Ag: 30 - 50 nm	Volume fraction: 0.0375 - 1.2% Temperature: 25 - 50 °C Nanofluid behavior: Newtonian up to 0.3 vol.% and Non-Newtonian for vol.% > 0.3 Shear rate range: 12.23 - 122.3 s^{-1}	DV-I prime digital viscometer. Accuracy: ±1%	27 mPa.s for 0.3 vol.% and 25 °C
[93]	Silica - MWCNTs (80%-20%) / water Silica - MWCNTs (50%-50%) / water	MWCNTs outer diameter: <10 nm Silica: 10 nm	Weight fraction: 0.1- 1% Temperature: 10 - 40 °C Surfactant: SDBS	Capillary viscometer.	8.8% for Silica - MWCNTs (80% - 20%) with 1 wt.% and 20 °C
[94]	MWCNTs - MgO / ethylene glycol	MWCNTs outer diameter: 5 - 20 nm MgO: 40 nm	Volume fraction: 0.1 - 1% Temperature: 30 - 60 °C Nanofluid behavior: Newtonian Shear rate range: 24.46 - 122.3 s^{-1}	Brookfield viscometer. Accuracy: ± 1 %	168% for 1 vol.% and 60 °C
[95]	TiO_2 - SiO_2 / water and ethylene glycol (60:40)	TiO_2: 50 nm SiO_2: 22 nm	Volume fraction: 1% Temperature: 30 - 80 °C Mixture ratios of TiO_2 - SiO_2 = (20:80, 40:60, 50:50, 60:40, 80:20) Nanofluid behavior: Newtonian Shear rate range: 61.15 - 122.3 s^{-1}	LVDV III ultra rheometer. Range: 1 - 10^6 mPa.s	52% for 1 vol.% of (50:50) mixture ratio and 80 °C and
[96]	GNPs - Pt / water	GNP particle diameter: 2 µm	Weight fraction: 0.02 - 0.1% Temperature: 20 - 40 °C Nanofluid behavior: Newtonian Shear rate range: 500 s^{-1}	Physica MCR rheometer.	33% for 0.1 wt.% and 40 °C
[97]	Cu-Zn / vegetable oil, paraffin oil, SAE oil	Cu-Zn: 25 nm	Volume fraction: 0.1 - 0.5% Nanofluid behavior: Newtonian for vegetable oil base nanofluids Shear rate range: 0 - 100 s^{-1} Surfactant: SDS	Anton paar rheometer.	~37% for 0.5 vol.% SAE oil base nanofluid
[99]	CuO - MWCNTs / SAE 5w-50	CuO outer diameter: 40 nm MWCNT outer diameter: 5 -15 nm	Volume fraction: 0.05 - 1% Temperature: 5 - 55 °C	Brookfield viscometer	35.52% at 5 °C and 12.92% at 55 °C for 1 vol.%

⟶

Table 3. (Continous)

[100]	Fe_3O_4 - MWCNTs / water	MWCNTs outer diameter: 10-30 nm	Volume fraction: 0.1 and 0.3% Temperature: 20 - 60 °C Surfactant: Nanosperse AQ	A&D vibro viscometer SV-10.	50% for 0.3 vol.% and 60 °C
[101]	Carbon - graphene oxide / ethylene glycol		Weight fraction: 0.02 - 0.06 % Temperature: 20 - 45 °C Nanofluid behavior: Newtonian Shear rate range: 20 - 500 s^{-1}	Physica MCR Anton Paar rheometer.	4.16% for 0.06 wt.%
[102]	Al_2O_3 - MWCNTs / engine oil (SAE 40)	MWCNTs outer diameter: 5 - 15 nm Al_2O_3: 20 nm	Volume fraction: 0.0625 - 1% Temperature: 25 - 50 °C Nanofluid behavior: Newtonian Shear rate range: 1333 - 13,333 s^{-1}	The CAP 2000 + viscometer. Accuracy: ±2%	46% for 1 vol.%
[103]	Cu-Zn (50:50, 75:25 and 25:75) / vegetable oil	Cu - Zn (50:50): 25 nm Cu - Zn (75:25): 19 nm Cu - Zn (25:75): 23 nm	Volume fraction: 0.1 - 0.5% Temperature: 30 - 60 °C Nanofluid behavior: Newtonian		46.5 mPa.s for 0.5 vol.% (50:50) and 30 °C
[104]	ND - Fe_3O_4 / water, EG and water mixture	ND: 5 nm Fe_3O_4: 13 nm ND - Fe_3O_4: 21 - 24 nm	Volume fraction: 0.05 - 0.2% Temperature: 20 - 60 °C	A&D vibro - viscometer. Range: 0.3 - 10,000 mPa.s Accuracy: ± 0.01 mPa.s	219% for 0.2 vol.% of (80:20% W/EG) at 60 °C
[79]	GO - Co_3O_4 / water, EG and water mixture	GO - CO_3O_4 < 50 nm	Volume fraction: 0.05 - 0.2% Temperature: 20 - 60 °C	A&D vibro - viscometer.	170% for 0.2 vol.% of water base nanofluid at 60 °C
[105]	(TiO_2 - CuO/C) / ethylene glycol	TiO_2: 26 nm CuO / C: 20 nm	Volume fraction: 0.5 - 2% Temperature: 298 - 333K Nanofluid behavior: Newtonian Shear rate range: 0.1 - 100 s^{-1}	Physica MCR 302.	80% for 2 vol.% and 313.15K
[106]	GNPs - Ag / water	GNP: 2 μm	Volume fraction: 0.02 - 0.1% Temperature: 20 - 40 °C Shear rate: 500 s^{-1}	Physica MCR, Anton Paar.	30% for 0.1 vol.% and 40 °C
[107]	Graphene - alumina / water	Al_2O_3: 50 nm Graphene: 5 nm	Volume fraction: 0.1% Temperature: 30 - 50 °C	LV-DE rotary viscometer	18.86% for 0.1 vol.% and 50 °C
[109]	MWCNT / Mg $(OH)_2$ - engine oil (5W50)	Mg $(OH)_2$: 10 nm MWCNT: 30 nm	Volume fraction: 0.25 - 2% Temperature: 25 - 60 °C	Brookfield cone and plate viscometer	about 50% for 2 vol.% at 60 °C
[110]	Al_2O_3 - CuO / water and ethylene glycol (75:25)	CuO: 29 nm Al_2O_3: 40 nm	Volume fraction: 0.5 - 2%	ARESLS	159% for 2 vol.%

→

Table 3. (Continous)

[111]	Al_2O_3 - Cu (90:10) / water	Al_2O_3 - Cu: 17 nm	Volume fraction: 0.1 - 2% Nanofluid behavior: Newtonian Shear rate range: 0 - 750 s^{-1} Surfactant: SLS	LVDV-I prime Viscosity range: 0.3 - 1028 cP. Accuracy: ± 1 %	115% for 2 vol.% and 32 °C
[112]	Ag - MgO / water	MgO: 40 nm Ag: 25 nm	Volume fraction: 0.5 - 2% Surfactant: CTAB	Cone and plate viscometer. Range: 0.3 - 1028 cP.	38.1% for 2 vol.%
[116]	Cu - Al_2O_3 / water		Volume fraction: 0.5 - 1.25% Temperature: 35 °C	LVDV-II + pro Brookfield viscometer	~21% for 1.25 vol.% and 35 °C
[117]	TiO_2 - SiO_2 / water - ethylene glycol	TiO_2: 50 nm SiO_2: 22 nm	Volume fraction: 2 - 3% Temperature: 30 °C	LVDV-III ultra rheometer	2% for 3 vol.% and 30 °C
[118]	Graphene - MWCNT / water	MWCNT outer diameter: 15 nm Graphene: 6 - 8 nm	Weight fraction of graphene: 0.35% Weight fraction of MWCNTs: 0.075 - 0.25% Temperature: 27 - 57 °C	RVDV-III U, viscometer Brookfield	10.3% for 0.35 wt.% graphene - 0.25 wt.% MWCNT
[120]	(0.8 CeO_2-0.2 Cu)	CeO_2: 30 nm Al_2O_3: 45 nm SiO_2: 10 nm	Volume fraction: 0.5-3% Temperature: 25 - 50 °C	LVDV-II+Pro Brookfield viscometer	52.8 % for 3.0 vol.%
	(0.8 Al_2O_3-0.2 Cu)				36.9 % for 3.0 vol.%
	(0.8 TiO_2-0.2 Cu)				43.2 % for 3.0 vol.%
	(0.8 SiO_2-0.2 Cu)				38.6 % for 3.0 vol.%
[121]	SiO_2 - graphite / water	Graphite (G): 7 nm SiO_2: 6 - 10 nm	Volume fraction: 0.1- 2% Temperature: 15 - 60 °C	Capillary tube viscometer	36.12% for 2 vol.% at 15 °C
[122]	alumina - MWCNT / ethylene - glycol - water	MWCNT outer diameter: 5 -15 nm Al_2O_3: 20 nm	Volume fraction: 0.0625 - 1% Temperature: 25 - 50 °C	DV-I PRIME Brookfield	774% for 1 vol.% at 25 °C
[123]	CuO - paraffin	CuO: 15-30 nm	Weight fraction: 0. 25 - 6% Temperature: 25 - 100 °C	Brookfield	63% for 6 wt.%
[140]	(SiO_2 - CuO) - C / EG - G	SiO_2: 12-25 nm CuO / C: 17-35 nm Nanocomposite of (SiO_2-CuO) - C: 25 nm	Volume fraction: 0.1% Temperature: 30-50 °C	LV-DE rotary viscometer	18.86% for 0.1 vol.% and 50 °C

and observed that the effect of temperate was more than that of the factors particle concentration and shear rate. The maximum and minimum optimal values of viscosity was found relatively at the values of (5 °C, 1 vol.%, 11996.99 s^{-1}) and (54.6 °C, 0.02 vol.%, 1948.9 s^{-1})) for temperature, particle concentration and shear rate respectively. Table 4 summarized the models presented by different investigators with the limitations (for temperature, particle concentration and shear rate) and accuracy. However, further work is needed to develop the more appropriate models that also considered the effect of other effecting parameters like pH value, particle size, shape etc. with temperature and particle concentration.

Reasons for enhancement in viscosity of hybrid nanofluids

Studies reported the following important facts about the augmentation of viscosity of hybrid nanofluids.

– High volume fraction of nanoparticles triggered the development of larger nano-clusters due to Van der Waals forces existing between the particles that could cause the viscosity augmentation by reducing the movement of fluid layers [84].

- Increase in volume fraction of nanoparticles caused internal shear stress to enhance which will, in turn, increases the viscosity of hybrid nanofluid [86, 88, 96].
- The increase in hydrodynamic diameter of nanoparticles as a result of adsorption and clustering will lead to enhance the viscosity [111].
- High resistance between two fluid layers due to the presence of nanoparticles caused enhancement in viscosity of hybrid nanofluid [79]. At lower concentration of nanoparticles, this resistance is low, whereas high for higher concentration.

Table 4. Correlations developed by different investigators for the prediction of viscosity of hybrid nanofluid with limitations and accuracy.

References	Particle Concentration	Temperature	Correlation	Accuracy
[54]	0.125 - 1.5 vol.%	25 - 50 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = \mathrm{a} + b\varphi$ $\begin{array}{ccc} T\,(^0C) & a & b \\ \hline 25 & 417.71 & 76.566 \\ 30 & 280.79 & 69.027 \\ 35 & 207.9 & 54.585 \\ 40 & 158.3 & 39.5 \\ 45 & 124.29 & 20.952 \\ 50 & 93.602 & 20.372 \end{array}$	maximum margin of devation = 5%
[55]	0 - 1 vol.%	5 - 55 ^{0}C	$\mu_{nf} = 633.8379 + 280.1511\varphi - 38.4183T - 6.17707\varphi T - 305.838\varphi^2 + 0.888891T^2 + 0.807687\varphi^2 T + 0.05807\varphi T^2 + 166.6123\varphi^3 + 0.00714T^3$	$R^2 = 0.9850$
[56]	0.8 - 1.8 vol.%	25 - 50 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = \frac{-2.0987+(4.65\varphi)^{0.0969}+(0.8702T)^{0.2633}+(62323.1365\varphi^2)}{(143.1076T^2)}$	$R^2 = 0.99$
[85]	0.05 - 1 vol.%	40 - 100 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 0.09422 - \left[\left(\frac{T}{\varphi}\right)^2 + 0.100556T^{0.8827}\varphi^{0.3148}\right]$ $\exp\,(72474.75T\varphi^{3.7951}$	$R^2 = 0.9943$
[86]	0.05 - 1 vol.%	5 - 55 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 1.035 + \frac{\varphi \exp\,(-1.023\varphi)\left[2.0460\frac{\varphi}{T} + 0.4015\varphi^2 T\right]}{T^{0.8441}}$	$R^2 = 0.9822$
[88]	0.5 - 3 vol.%	30 - 70 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 37\,(0.1 + \frac{\varphi}{100})^{1.59}\,(0.1 + \frac{T}{80})^{0.31}$	Max margin of deviation = 9.5%
[90]	0 - 2 vol.%	25 - 50 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = a_o + a_1\varphi + a_2\varphi^2 + a_3\varphi^3$	Max margin of deviation = 1.2%
[91]	0 - 1 vol.%	25 - 60 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = A + A_1\varphi + A_2\varphi^2 + A_3\varphi^3$ $\begin{array}{ccccc} T\,(^0C) & A_1 & A_2 & A_3 & A \\ \hline 25 & 0.1553 & -0.0334 & 0.0631 & 1.0087 \\ 30 & 0.2499 & -0.2865 & 0.2043 & 1.0085 \\ 35 & 0.5341 & -0.6313 & 0.366 & 1.0223 \\ 40 & 0.5376 & -0.5013 & 0.261 & 1.0382 \\ 45 & 0.6448 & -0.9427 & 0.5225 & 1.013 \\ 50 & 0.6596 & -0.913 & 0.4822 & 1.0132 \end{array}$	Max margin of deviation = 2%

→

Table 4. (Continous)

<table>
<tr><td>[94]</td><td colspan="2">< 1 vol.%</td><td>30 - 60 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}}=\left[0.191\varphi + 0.240\ (T^{-0.342}\varphi^{-0.473})\right] \exp\ (1.45T^{0.120}\varphi^{0.158})$</td><td></td></tr>
<tr><td>[95]</td><td colspan="2">TiO_2 - SiO_2 (1 vol%) 20:80, 40:60, 50:50, 60:40, and 80:20</td><td>30 - 80 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = 1.42 + (1+R)^{-0.1063}\ (\frac{T}{80})^{0.2321}$
R represented the fraction of particle in the mixture</td><td>Max margin of deviation = 14.89%</td></tr>
<tr><td>[99]</td><td colspan="2">0.05 - 1.15 vol.%</td><td>20 - 60 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = 0.50437 + 4.38836\varphi - 0.04183T - 0.26696\varphi.T + 22.66087\varphi^2 - 0.00121T^2 + 0.003325\varphi^2.T + 0.00332T^2.\varphi - 0.00001\ T^3$</td><td>$R^2 = 0.994$</td></tr>
<tr><td>[102]</td><td colspan="2">0.0625 - 1 vol.%</td><td>25 - 50 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = 1.123 + 0.3251\varphi - 0.08994T + 0.002552T^2 - 0.00002386T^3 + 0.9695\ (\frac{T}{\varphi})^{0.01719}$</td><td>Maximum margin of deviation = 2%</td></tr>
<tr><td rowspan="3">[103]</td><td rowspan="3">0.1, 0.3, and 0.5 vol. %</td><td>Cu-Zn (50:50)</td><td rowspan="3">30 - 60 ^{0}C</td><td>$\mu_{nf} = 101.2 - 2.532T + 17.06\varphi + 0.01862T^2 - 0.1413T - 10.42\varphi^2$</td><td>$R^2 = 0.998$</td></tr>
<tr><td>Cu-Zn (75:25)</td><td>$\mu_{nf} = 101.2 - 2.532T + 17.06\varphi + 0.01862T^2 - 0.1413T - 10.42\varphi^2$</td><td>$R^2 = 0.999$</td></tr>
<tr><td>Cu-Zn (25:75)</td><td>$\mu_{nf} = 96.13 - 2.309T + 39.39\varphi + 0.01628T^2 - 0.08T\varphi - 24.71\varphi^2 + 0.008996T^2\varphi + 0.2169T + 10.19\varphi^3$</td><td>$R^2 = 0.999$</td></tr>
<tr><td>[104]</td><td colspan="2">0.05 - 0.2 vol.%</td><td>20 - 60 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = ae^{b\varphi}$
<table><tr><th>T (^0C)</th><th>a</th><th>b</th></tr><tr><td>20</td><td>1.444</td><td>1.402</td></tr><tr><td>30</td><td>1.368</td><td>1.472</td></tr><tr><td>40</td><td>1.277</td><td>1.625</td></tr><tr><td>50</td><td>1.288</td><td>1.771</td></tr><tr><td>60</td><td>1.388</td><td>1.655</td></tr></table></td><td></td></tr>
<tr><td>[109]</td><td colspan="2">0.25 - 2 vol.%</td><td>25 - 60 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = 1604 + 256.8\varphi + 24.73\ \varphi^3 + 1.615T^2 + 0.07343\varphi T^3 - 83.2\ T - 7.389\varphi^2 - 0.01123T^3 - 74.19\varphi^2$</td><td>Max margin of deviation = 6.5%</td></tr>
<tr><td>[112]</td><td colspan="2">0 - 2 vol.%</td><td></td><td>$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 32.795\ \varphi_p - 7214\varphi_p^2 + 714600\varphi_p^3 - 0.1941 \times 10^8\varphi_p^4)$</td><td>Max margin of deviation = 2%</td></tr>
<tr><td>[114]</td><td colspan="2">1 - 2 vol.% (0.5:0.5,0.5:1, 0.5:1.5)</td><td>25 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = 2.06 - 1.32\varphi_{Al2O3} - 0.96\ \varphi_{TiO2} + 0.58\varphi^2_{Al2O3} + 0.39\varphi^2_{TiO2} + 1.89\ \varphi_{Al2O3}\varphi_{TiO2}$</td><td>$R^2 = 0.9992$</td></tr>
<tr><td>[121]</td><td colspan="2">0.1 - 2 vol.%</td><td>15 - 60 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = 1.00527 \times (T^{0.00035}) \times (1+\varphi)^{9.36265} \times (\frac{w_G}{w_{SiO2}})^{-0.028935}$</td><td>Average Standard Deviation: 2.4%</td></tr>
<tr><td>[122]</td><td colspan="2">0.0625 - 1 vol%</td><td>25 - 50 ^{0}C</td><td>$\frac{\mu_{nf}}{\mu_{bf}} = a + (b\varphi^c) + (\varphi^d)^5$
<table><tr><th>T (^0C)</th><th>a</th><th>b</th><th>c</th><th>d</th></tr><tr><td>25</td><td>1.0560</td><td>8.5662</td><td>3.0971</td><td>8.5662</td></tr><tr><td>30</td><td>1.1262</td><td>9.0211</td><td>3.3657</td><td>9.0211</td></tr><tr><td>35</td><td>1.1699</td><td>8.8939</td><td>3.4919</td><td>8.8939</td></tr><tr><td>40</td><td>1.2245</td><td>9.1468</td><td>3.8255</td><td>9.1468</td></tr><tr><td>45</td><td>1.2913</td><td>9.3580</td><td>3.8180</td><td>9.3580</td></tr><tr><td>50</td><td>1.3038</td><td>9.5283</td><td>4.2613</td><td>9.5283</td></tr></table></td><td>$R^2 = 0.997$</td></tr>
</table>

⟶

Table 4. (Continous)

[123]	0.25 - 6 wt.%	25 - 100 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = A_1 T^a + A_2 w^b + A_3 w^c \times T^d + A_4$ $A_1 = -1.735$, $A_2 = -0.027$, $A_3 = 0.039$, $A_4 = 2.956$ $a = -0.017$, $b = 0.418$, $c = 1.543$, $d = 0.033$	Maximum margin of deviation = 5%
[142]	0 - 1.0 vol.%	25 - 60 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 0.00337 + \exp(0.07731\varphi^{1.452}T^{0.3387})$	Maximum margin of deviation = 4%
[143]	0.0625 - 2 vol.%	27.5 - 50 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 15.88\varphi^{0.851}T^{-1.189}\gamma^{-0.5639}$ $\gamma = shear\ rate\ (0.612\ s^{-1} - 122.2\ s^{-1})$	$R^2 = 0.987$
[146]	0 - 1 vol.%	5 - 55 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 1.02 + 0.054\varphi + 9.57\times10^{-3}\ T - 0.029\gamma + 1.56 \times 10^{-3}\varphi T + 0.032T\gamma - 0.045\varphi^2 - 0.014\ T^2 - 0.027\gamma^2 - 0.015\varphi^2 T + 0.036T^2\gamma + 0.067\varphi^3 - 0.019\gamma^3$	$R^2 = 0.9467$
[147]	0 - 1 vol.%	5 - 55 ^{0}C	$\mu_{nf} = (\frac{T}{\varphi})^{(\frac{\varphi}{T})} \times (\mu_{bf} - 2.,4148)$	Maximum margin of deviation = 7.3%
[148]	0.05 - 1 vol.%	5 - 55 ^{0}C	$\mu_{nf} = 697.4317382 + 431.879068\varphi - 33.39840555T - 0.01346927\gamma - 10.77912341\varphi T - 0.006913725\varphi\gamma + 0.001487159T\gamma - 334.024913\varphi^2 + 0.623341666T^2 + 1.33838\times10^{-6}\gamma^2 + 0.000149409\varphi T\gamma + 2.908513579\varphi^2 T + 0.076573924T^2\varphi - 1.20931\times 10^{-7}\gamma^2 T + 121.11947\varphi^3 - 0.004802059T^3$	$R^2 = 0.99703$
[140]	0.05 - 1 vol.%	50 - 80 ^{0}C	$\frac{\mu_{nf}}{\mu_{bf}} = 0.9894\left[1 + \frac{\varphi}{100}\right]^{6.6301} \times \left[\frac{T_{nf}}{T_o}\right]^{0.064}$	Average absolute deviation (AAD): 0.85%
[141]	0.5 - 2 vol.%	25 ^{0}C	$\mu_{nf} = 0.2111\ \gamma^{-0.547}$ $\mu_{nf} = 0.2597\ \gamma^{-0.609}$ $Share\ rate = \gamma = 0.01 - 1000\ s^{-1}$	$R^2 = 0.84$

- The viscosity of hybrid nanofluid augmented with an execution of a permanent magnetic field that accumulated the magnetic particles and also caused the enhancement of heat transfer coefficient [149].
- Functionalization of nanoparticles influenced the viscosity as well. The suitable selection of functionalized material is also important. Amiri *et al*. [150] studied the viscosity of MWCNT by functionalizing them with cysteine and silver. According to the results, nanoparticles functionalized with silver showed relatively more viscosity values than that of MWCNT-cysteine. However, after functionalization, the viscosity of MWCNT's was reduced. Qing *et al*. [52] observed that coated nanoparticles of graphene showed augmented viscosity values as compared to non-functionalized ones. They observed this while investigating the SiO_2 coated graphene nanoparticles and reported that the upsurge in viscosity was due to the increase in particle size and density of the fluid.
- At a lower temperature, the particles interaction is strong due to the strong Van der Waals forces that augmented the viscosity while with the increase in temperature the interaction between the particles become lesser that caused the reduction in the dynamic viscosity of the fluid [54].

Conclusions

The comprised study drew the following important concluding remarks about the viscosity of hybrid nanofluids

- The existing experimental studies clearly show that the viscosity of hybrid nanofluids augmented with an increase of particle concentration and diminished with temperature rise.
- Dispersion of spherically shaped nanoparticles comparatively exhibited less viscosity enhancement than that of cylindrically shapes nanoparticles like CNT.
- Needs a lot of work to acquire the optimum value of viscosity against temperature and particle concentration.
- Single-step preparation method offered less viscous nanofluid but most of the studies preferred two-step method for the preparation of hybrid nanofluids with the assistance of mechanical (stirring, sonication) and chemical (surfactant addition) processes to get better dispersion of nanoparticles due to the involvement of expensive and complex instruments in single-step method.
- Among water, EG, and oil-based hybrid nanofluids that are studied in this article, water-based nanofluids presented relatively fewer viscosity values than that of EG-based nanofluid. However, oil-based nanofluids showed viscosity up to 650 mPas.
- Need to work for the optimum values of affecting factors like pH value, temperature, particle concentration, sonication time and particle size to get better thermal properties with a small increase in viscosity that will be very helpful in the heat transfer applications where the fluid transfers heat while flowing. Studies reported the effect of various factors on the viscosity of hybrid nanofluids and someone also reported the optimum values for these factors like Xian-Ju and Xin-Fang [138] provided the optimum pH values while investigating the viscosity of water-based Cu and alumina.
- Reasons for viscosity augmentation are the formation of clusters as a result of Van der Waals forces present between the particles that increased the hydrodynamic diameter of particles, internal shear stresses, density of the dispersed nanoparticles, particles shape, functionalization and coating of the particles, and pH value.
- Most of the studies considered the effect of two or three factors like temperature, particle volume fraction and shear rate etc. To develop the more general correlations we need to consider the more affecting factors for future studies.
- Available classical models that are used for the prediction of viscosity of unitary nanofluids failed to predict the viscosity of hybrid nanofluids
- .Instead of that a lot of work has been carried out on the viscosity of nanofluids but for hybrid nanofluids still needed a lot of work.

Nomenclature

W – water
EG – ethylene glycol
G – glycerol
ND – nanodiamond
GO – graphene oxide
ANN – artificial neural network
T – temperature
SiO_2 – silica
Ag – silver
$NiFe_2O_4$ – nickel ferrite
VSM – vibrating sample magnetometer
RM – raman microscope
SAE – society of automotive engineers
GNP – graphene nanoplatelet
FTIR – fourier transform infrared spectroscopy
TEM – transmission electron microscopy
SDBS – sodium dodecylbenzene sulfonate

Greek latters

μ – viscosity
φ – concentration %
γ – shear rate

Subscript

nf – nanofluid
bf – base fluid

DLS – dynamic light scattering
EDS – energy dispersive spectroscopy
DSC – differential scanning calorimetry
hnf – hybrid nanofluid
nc – nanocomposite

References

[1] Choi, S. U. S., Eastman, J. A., Enhancing Thermal Conductivity of Fluids with Nanoparticles, *Proceedings*, Asme Int. Mech. Eng. Congr. Expo., San Francisco, Cal., USA, 1995
[2] Bakhshan, Y., *et al*., Experimental Study on the Thermal Conductivity of Silver Nanoparticles Synthesized Using Sargassum Angostifolium, *Iran. J. Sci. Technol. Trans. Mech. Eng.*, *1* (2018), 4, pp. 1-7
[3] Vakilinejad, A., *et al*., Experimental and Theoretical Investigation of Thermal Conductivity of Some Water-Based Nanofluids, *Chem. Eng. Commun.*, *205* (2018), 5, pp. 610-623
[4] Ali, H. M., *et al*., Preparation Techniques of TiO_2 Nanofluids and Challenges: A Review, *Appl. Sci.*, *8* (2018), 4, 587
[5] Jin, J., *et al*., Experimental Investigation and Prediction of the Thermal Conductivity of Water-Based Oxide Nanofluids with Low Volume Fractions, *J. Therm. Anal. Calorim.*, *135* (2018), 1, pp. 257-269
[6] Sajid, M. U., Ali, H. M., Thermal Conductivity of Hybrid Nanofluids: A Critical Review, *Int. J. Heat Mass Transf.*, *126* (2018), Part A, pp. 211-234
[7] Nguyen, C. T., *et al*., Heat Transfer Enhancement Using Al_2O_3-Water Nanofluid for an Electronic Liquid Cooling System, *Appl. Therm. Eng.*, *27* (2007), 8-9, pp. 1501-1506
[8] Jeng, L. Y., Teng, T. P., Performance Evaluation of a Hybrid Cooling System for Electronic Chips, *Exp. Therm. Fluid Sci.*, *45* (2013), Feb., pp. 155-162
[9] Ahammed, N., *et al*., Thermoelectric Cooling of Electronic Devices with Nanofluid in A Multiport Minichannel Heat Exchanger, *Exp. Therm. Fluid Sci.*, *74* (2016), June, pp. 81-90
[10] Sarafraz, M. M., *et al*., On the Convective Thermal Performance of a CPU Cooler Working with Liquid Gallium and Cuo/Water Nanofluid: A Comparative Study, *Appl. Therm. Eng.*, *112* (2017), Feb., pp. 1373-1381
[11] Ali, H. M., *et al*., Application of Nanofluids for Thermal Management of Photovoltaic Modules: A Review, *Microfluid. Nanofluidics*, (2018)
[12] Shende, R. C., Ramaprabhu, S., Application of Few-Layered Reduced Graphene Oxide Nanofluid as a Working Fluid for Direct Absorption Solar Collectors, *J. Nanosci. Nanotechnol.*, *17* (2017), 2, pp. 1233-1239
[13] Zeiny, A., *et al*., A Comparative Study of Direct Absorption Nanofluids for Solar Thermal Applications, *Sol. Energy*, *161* (2018), Feb., pp. 74-82
[14] Khullar, V., *et al*., Solar Energy Harvesting Using Nanofluids-Based Concentrating Solar Collector, *J. Nanotechnol. Eng. Med.*, *3* (2013), 3, 031003
[15] Han, D., *et al*., Thermal Properties of Carbon Black Aqueous Nanofluids for Solar Absorption, *Nanoscale Res. Lett.*, *6* (2012), 1, pp. 1-7
[16] Buongiorno, J., *et al*., Nanofluids for Enhanced Economics and Safety of Nuclear Reactors: An Evaluation of the Potential Features, Issues, and Research Gaps, *Nucl. Technol.*, *162* (2008), 1, pp. 80-91
[17] Hadad, K., Kowsar, Z., Twofold Application of Nanofluids as the Primary Coolant and Reactivity Controller in a PWR Reactor: Case Study VVER-1000 in Normal Operation, *Ann. Nucl. Energy*, *97* (2016), Nov., pp. 179-182
[18] Saadati, H., *et al*., Safety Margin and Fuel Cycle Period Enhancements of Vver-1000 Nuclear Reactor Using Water/Silver Nanofluid, *Nucl. Eng. Technol.*, *50* (2018), 5, pp. 639-647
[19] Ebrahimian, M., Ansarifar, G. R., Investigation of the Nano Fluid Effects on Heat Transfer Characteristics in Nuclear Reactors with Dual Cooled Annular Fuel Using CFD (Computational Fluid Dynamics) Modeling, *Energy*, *98* (2016), C, pp. 1-14
[20] Mahmud, K. M., *et al*., Analytical Study of Forced Convection in Fluid Cooling Use Nanofluid Al_2O_3–Water on Nuclear Reactor Core Based Fuel Cylinder with Hexagonal Sub Channel, *Int. J. Energy Eng.*, *6* (2016), 1, pp. 8-15
[21] Manetti, L. L., *et al*., Evaluation of the Heat Transfer Enhancement During Pool Boiling Using Low Concentrations of Al_2O_3-Water Based Nanofluid, *Exp. Therm. Fluid Sci.*, *87* (2017), Oct., pp. 191-200
[22] Ham, J., *et al*., Experimental Investigation of Pool Boiling Characteristics in Al_2O_3 Nanofluid According to Surface Roughness and Concentration, *Int. J. Therm. Sci.*, *114* (2017), Apr., pp. 86-97
[23] Ali, H. M., *et al*., Experimental Investigation of Nucleate Pool Boiling Heat Transfer Enhancement of TiO_2-Water Based Nanofluids, *Appl. Therm. Eng.*, *113* (2017), Feb., pp. 1146-1151
[24] Karimzadehkhouei, M., *et al*., The Effect of Nanoparticle Type and Nanoparticle Mass Fraction on Heat Transfer Enhancement in Pool Boiling, *Int. J. Heat Mass Transf.*, *109* (2017), June, pp. 157-166

[25] Ali, H. M., *et al*., Heat Transfer Enhancement of Car Radiator Using Aqua Based Magnesium Oxide Nanofluids, *Thermal Science*, *19* (2015), 6, pp. 2039-2048
[26] Subhedar, D. G., *et al*., Exp. Investigation of Heat Transfer Potential of Al_2O_3/Water-Mono Ethylene Glycol Nanofluids as a Car Radiator Coolant, *Case Stud. Therm. Eng.*, *11* (2018), June, pp. 26-34
[27] Hussein, A. M., *et al*., Study of Forced Convection Nanofluid Heat Transfer in the Automotive Cooling System, *Case Stud. Therm. Eng.*, *2* (2014), Mar., pp. 50-61
[28] Hemmat Esfe, M., *et al*., Experimental Investigation, Model Development and Sensitivity Analysis of Rheological Behavior of ZnO/10w40 Nano-Lubricants for Automotive Applications, *Phys. E Low-Dimensional Syst. Nanostructures*, *90* (2017), June, pp. 194-203
[29] Hussein, A. M., *et al*., Numerical Study on Turbulent Forced Convective Heat Transfer Using Nanofluids TiO_2 in an Automotive Cooling System, *Case Stud. Therm. Eng.*, *9* (2017), Oct., pp. 72-78
[30] Ray, D. R., Das, D. K., Superior Performance of Nanofluids in an Automotive Radiator, *J. Therm. Sci. Eng. Appl.*, *6* (2014), 4, 041002
[31] Saleh, H., *et al*., Medical Applications for the Flow of Carbon-Nanotubes Suspended Nanofluids in the Presence of Convective Condition Using Laplace Transform, *J. Assoc. Arab Univ. Basic Appl. Sci.*, *24* (2017), Oct., pp. 206-212
[32] Kothandapani, M., Prakash, J., The Peristaltic Transport of Carreau Nanofluids Under Effect of a Magnetic Field in a Tapered Asymmetric Channel: Application of the Cancer Therapy, *J. Mech. Med. Biol.*, *15* (2015), 03, 1550030
[33] Abbas, M. A., *et al*., Application of Drug Delivery in Magnetohydrodynamics Peristaltic Blood Flow of Nanofluid in a Non-Uniform Channel, *J. Mech. Med. Biol.*, *16* (2016), 04, 1650052
[34] Khan, W. A., *et al*., Bioconvective Non-Newtonian Nanofluid Transport over a Vertical Plate in a Porous Medium Containing Microorganisms in a Moving Free Stream, *J. Porous Media*, *18* (2015), 4, pp. 389-399
[35] Akbar, N. S., *et al*., Anti-Bacterial Applications for New Thermal Conductivity Model in Arteries with CNT Suspended Nanofluid, *J. Mech. Med. Biol.*, *16* (2016), 05, 1650063
[36] Jafari, S. M., *et al*., Heat Transfer Enhancement in Thermal Processing of Tomato Juice by Application of Nanofluids, *Food Bioprocess Technol.*, *10* (2017), 2, pp. 307-316
[37] Jabari, S. S., *et al*., Changes in Lycopene Content and Quality of Tomato Juice During Thermal Processing by a Nanofluid Heating Medium, *J. Food Eng.*, *230* (2018), Aug., pp. 1-7
[38] Jafari, S. M., *et al*., Evaluation of Performance and Thermophysical Properties of Alumina Nanofluid as a New Heating Medium for Processing of Food Products, *J. Food Process Eng.*, *40* (2017), 5, pp. 1-9
[39] Taghizadeh-Tabari, Z., *et al*., The Study on Application of Ti_{O2}/Water Nanofluid in Plate Heat Exchanger of Milk Pasteurization Industries, *Renew. Sustain. Energy Rev.*, *58* (2016), May, pp. 1318-1326
[40] Jafari, S. M., *et al*., Nano-Fluid Thermal Processing of Watermelon Juice in a Shell and Tube Heat Exchanger and Evaluating Its Qualitative Properties, *Innov. Food Sci. Emerg. Technol.*, *42* (2017), Aug., pp. 173-179
[41] Shen, B., *et al*., Application of Nanofluids in Minimum Quantity Lubrication Grinding Application of Nanofluids in Minimum Quantity Lubrication Grinding, *2004* (2016), Mar., pp. 1-7
[42] Sidik, N. A. C., *et al*., Recent Progress on the Application of Nanofluids in Minimum Quantity Lubrication Machining: A Review, *Int. J. Heat Mass Transf.*, *108* (2017), Part A, pp. 79-89
[43] Shokoohi, Y., Shekarian, E., Application of Nanofluids in Machining Processes -A Review, *J. Nanosci. Technol.*, *2* (2016), 21, pp. 59-63
[44] Sharma, A. K., *et al*., Progress of Nanofluid Application in Machining: A Review, *Mater. Manuf. Process.*, *30* (2015), 7, pp. 813-828
[45] Sinha, M. K., *et al*., Application of Eco-Friendly Nanofluids During Grinding of Inconel 718 through Small Quantity Lubrication, *J. Clean. Prod.*, *141* (2017), Jan., pp. 1359-1375
[46] Kulkarni, D. P., *et al*., Application of Nanofluids in Heating Buildings and Reducing Pollution, *Appl. Energy*, *86* (2009), 12, pp. 2566-2573
[47] Firouzfar, E., *et al*., Energy Saving in Hvac Systems Using Nanofluid, *Appl. Therm. Eng.*, *31* (2011), 8-9, pp. 1543-1545
[48] Xie, H., *et al*., An Investigation on the Tribological Performances of the SiO_2/MoS_2 Hybrid Nanofluids for Magnesium Alloy-Steel Contacts, *Nanoscale Res. Lett.*, *11* (2016), 1, 329
[49] Bellos, E., Tzivanidis, C., Thermal Analysis of Parabolic Trough Collector Operating with Mono and Hybrid Nanofluids, *Sustain. Energy Technol. Assessments*, *26* (2018), Nov., pp. 105-115
[50] Tayebi, T., Chamkha, A. J., Natural Convection Enhancement in an Eccentric Horizontal Cylindrical Annulus Using Hybrid Nanofluids, *Numer. Heat Transf. Part A Appl.*, *71* (2017), 11, pp. 1159-1173

[51] Takabi, B., Salehi, S., Augmentation of the Heat Transfer Performance of a Sinusoidal Corrugated Enclosure by Employing Hybrid Nanofluid, *Adv. Mech. Eng.*, *6* (2014), Mar., pp. 1-16
[52] Qing, S. H., *et al.*, Thermal Conductivity and Electrical Properties of Hybrid SiO_2-Graphene Naphthenic Mineral Oil Nanofluid as Potential Transformer Oil, *Mater. Res. Express*, *4* (2017), 1, 015504
[53] Takabi, B., *et al.*, Hybrid Water-Based Suspension of Al_2O_3 and Cu Nanoparticles on Laminar Convection Effectiveness, *J. Thermophys. Heat Transf.*, *30* (2016), 3, pp. 523-532
[54] Asadi, A., *et al.*, Heat Transfer Efficiency of Al_2O_3-MWCNT/Thermal Oil Hybrid Nanofluid as a Cooling Fluid in Thermal and Energy Management Applications: An Experimental and Theoretical Investigation, *Int. J. Heat Mass Transf.*, *117* (2018), Feb., pp. 474-486
[55] Hemmat Esfe, M., *et al.*, Experimental Investigation and Model Development of the Non-Newtonian Behavior of CuO-MWCNT-10w40 Hybrid Nano-Lubricant for Lubrication Purposes, *J. Mol. Liq.*, *249* (2018), Jan., pp. 677-687
[56] Ahmadi Nadooshan, A., *et al.*, Measuring the Viscosity of Fe_3O_4-MWCNTs/Eg Hybrid Nanofluid for Evaluation of Thermal Efficiency: Newtonian and Non-Newtonian Behavior, *J. Mol. Liq.*, *253* (2018), Mar., pp. 169-177
[57] Leong, K. Y., *et al.*, Thermal Conductivity of an Ethylene Glycol/Water-Based Nanofluid with Copper-Titanium Dioxide Nanoparticles: An Experimental Approach, *Int. Commun. Heat Mass Transf.*, *90* (2018), Nov., pp. 23-28
[58] Hemmat Esfe, M., *et al.*, Experimental Evaluation, New Correlation Proposing and ANN Modeling of Thermal Properties of Eg Based Hybrid Nanofluid Containing ZnO-DWCNT Nanoparticles for Internal Combustion Engines Applications, *Appl. Therm. Eng.*, *133* (2018), mar., pp. 452-463
[59] Esfahani, N. N., *et al.*, A New Correlation for Predicting the Thermal Conductivity of Zno–Ag (50%–50%)/Water Hybrid Nanofluid: An Experimental Study, *Powder Technol.*, *323* (2018), Jan., pp. 367-373
[60] Hemmat Esfe, M., *et al.*, Empirical Study and Model Development of Thermal Conductivity Improvement and Assessment of Cost and Sensitivity of Eg-Water Based Swcnt-ZnO (30%:70%) Hybrid Nanofluid, *J. Mol. Liq.*, *244* (2017), Oct., pp. 252-261
[61] Bahiraei, M., *et al.*, Thermal and Hydraulic Characteristics of a Minichannel Heat Exchanger Operated with a Non-Newtonian Hybrid Nanofluid, *J. Taiwan Inst. Chem. Eng.*, *84* (2018), Mar., pp. 149-161
[62] Minea, A. A., El-Maghlany, W. M., Influence of Hybrid Nanofluids on the Performance of Parabolic Trough Collectors in Solar Thermal Systems: Recent Findings and Numerical Comparison, *Renew. Energy*, *120* (2018), May, pp. 350-364
[63] Sarkar, J., *et al.*, A Review on Hybrid Nanofluids: Recent Research, Development and Applications, *Renew. Sustain. Energy Rev.*, *43* (2015), mar., pp. 164-177
[64] Sidik, N. A. C., *et al.*, Recent Progress on Hybrid Nanofluids in Heat Transfer Applications: A Comprehensive Review, *Int. Commun. Heat Mass Transf.*, *78* (2016), Nov., pp. 68-79
[65] Minea, A. A., Challenges in Hybrid Nanofluids Behavior in Turbulent Flow: Recent Research and Numerical Comparison, *Renew. Sustain. Energy Rev.*, *71* (2017), Dec., pp. 426-434
[66] Sundar, L. S., *et al.*, Hybrid Nanofluids Preparation, Thermal Properties, Heat Transfer and Friction Factor – A Review, *Renew. Sustain. Energy Rev.*, *68* (2017), Mar., pp. 185-198
[67] Leong, K. Y., *et al.*, Synthesis and Thermal Conductivity Characteristic of Hybrid Nanofluids – A Review, *Renew. Sustain. Energy Rev.*, *75* (2017), May, pp. 868-878
[68] Hamzah, M. H., *et al.*, Factors Affecting the Performance of Hybrid Nanofluids: A Comprehensive Review, *Int. J. Heat Mass Transf.*, *115* (2017), Part A, pp. 630-646
[69] Ranga Babu, J. A., *et al.*, State-of-Art Review on Hybrid Nanofluids, *Renew. Sustain. Energy Rev.*, *77* (2017), Mar., pp. 551-565
[70] Lee, G. H., *et al.*, Fabrication of Al Nano Powders by Pulsed Wire Evaporation (PWE) Method, *Ind. Eng. Chem. Res.*, 9 (2003), 1, pp. 71-75
[71] Lee, P. Y., *et al.*, Magnetic and Gas Sensing Property of Nanosized $NiFe_2O_4$ Powders Synthesized by Pulsed Wire Discharge, *J. Nanoparticle Res.*, *8* (2006), 1, pp. 29-35
[72] Aberoumand, S., Jafarimoghaddam, A., Tungsten (III) Oxide (WO_3) – Silver/Transformer Oil Hybrid Nanofluid: Preparation, Stability, Thermal Conductivity and Dielectric Strength, *Alexandria Eng. J.*, *57* (2018), 1, pp. 121-130
[73] Munkhbayar, B., *et al.*, Surfactant-Free Dispersion of Silver Nanoparticles Into MWCNT-Aqueous Nanofluids Prepared by One-Step Technique and their Thermal Characteristics, *Ceram. Int.*, *39* (2013), 6, pp. 6415-6425

[74] Zhu, D., *et al*., Dispersion Behavior and Thermal Conductivity Characteristics of Al_2O_3-H_2O Nanofluids, *Curr. Appl. Phys.*, *9* (2009), 1, pp. 131-139

[75] Wei, B., *et al*., Thermo-Physical Property Evaluation of Diathermic Oil Based Hybrid Nanofluids for Heat Transfer Applications, *Int. J. Heat Mass Transf.*, *107* (2017), Apr., pp. 281-287

[76] Huang, D., *et al*., Effects of Hybrid Nanofluid Mixture in Plate Heat Exchangers, *Exp. Therm. Fluid Sci.*, *72* (2016), Apr., pp. 190-196

[77] Kiruba, R., *et al*., Stability and Rheological Properties of Hybrid -Al_2O_3 Nanofluids with Cationic Polyelectrolyte Additives, *Colloids Surfaces A Physicochem. Eng. Asp.*, *555* (2018), May, pp. 63-71

[78] Sarbolookzadeh Harandi, S., *et al*., An Experimental Study on Thermal Conductivity of F-MWCNTs-Fe_3O_4/Eg Hybrid Nanofluid: Effects of Temperature and Concentration, *Int. Commun. Heat Mass Transf.*, *76* (2016), Aug., pp. 171-177

[79] Syam Sundar, L., *et al*., Experimental Investigation of the Thermal Transport Properties of Graphene Oxide/Co_3O_4 Hybrid Nanofluids, *Int. Commun. Heat Mass Transf.*, *84* (2017), May, pp. 1-10

[80] Van Trinh, P., *et al*., Experimental Study on the Thermal Conductivity of Ethylene Glycol-Based Nanofluid Containing Gr-CNT Hybrid Material, *J. Mol. Liq.*, *269* (2018), Nov., pp. 344-353

[81] Bashirnezhad, K., *et al*., Viscosity of Nanofluids: A Review of Recent Experimental Studies, *Int. Commun. Heat Mass Transf.*, *73* (2016), Apr., pp. 114-123

[82] Yu, P. Y., *et al*., The Synthesis of Solvent-Free TiO_2 Nanofluids through Surface Modification, *Soft Nanosci. Lett.*, *01* (2011), 02, pp. 46-50

[83] Premalatha, M., Jeevaraj, A. K. S., Preparation and Characterization of Hydroxyl (–OH) Functionalized Multi-Walled Carbon Nanotube (MWCNT)–Dowtherm a Nanofluids, *Part. Sci. Technol.*, *36* (2018), 5, pp. 523-528

[84] Afrand, M., *et al*., Effects of Temperature and Solid Volume Fraction on Viscosity of SiO_2-MWCNTs/SAE40 Hybrid Nanofluid as a Coolant and Lubricant in Heat Engines, *Appl. Therm. Eng.*, *102* (2016), june, pp. 45-54

[85] Motahari, K., *et al*., Experimental Investigation and Development of New Correlation for Influences of Temperature and Concentration on Dynamic Viscosity of MWCNT-SiO_2(20-80)/20w50 Hybrid Nano-Lubricant, *Chinese J. Chem. Eng.*, *26* (2018), 1, pp. 137-143

[86] Hemmat Esfe, M., *et al*., A Novel Study on Rheological Behavior of ZnO-MWCNT/10w40 Nanofluid for Automotive Engines, *J. Mol. Liq.*, *254* (2018), Mar., pp. 406-413

[87] Shahsavar, A., *et al*., Effect of Temperature and Concentration on Thermal Conductivity and Viscosity of Ferrofluid Loaded with Carbon Nanotubes, *Heat Mass Transf.*, *52* (2016), 10, pp. 2293-2301

[88] Nabil, M. F., *et al*., An Experimental Study on the Thermal Conductivity and Dynamic Viscosity of TiO_2-SiO_2 Nanofluids in Water: Ethylene Glycol Mixture, *Int. Commun. Heat Mass Transf.*, *86* (2017), Aug., pp. 181-189

[89] Sundar, L. S., *et al*., Thermal Conductivity and Viscosity of Hybrid Nanfluids Prepared with Magnetic Nanodiamond-Cobalt Oxide (ND-Co_3O_4) Nanocomposite, *Case Stud. Therm. Eng.*, *7* (2016), Mar., pp. 66-77

[90] Hemmat Esfe, M., *et al*., Effects of Temperature and Concentration on Rheological Behavior of Mwcnts/SiO_2(20-80)-SAE40 Hybrid Nano-Lubricant, *Int. Commun. Heat Mass Transf.*, *76* (2016), Aug., pp. 133-138

[91] Hemmat Esfe, M., *et al*., Examination of Rheological Behavior of MWCNTs/ZnO-SAE40 Hybrid Nano-Lubricants Under Various Temperatures and Solid Volume Fractions, *Exp. Therm. Fluid Sci.*, *80* (2017), Jan., pp. 384-390

[92] Afrand, M., *et al*., Effects of Temperature and Nanoparticles Concentration on Rheological Behavior of Fe_3O_4-Ag/Eg Hybrid Nanofluid: An Experimental Study, *Exp. Therm. Fluid Sci.*, *77* (2016), Oct., pp. 38-44

[93] Baghbanzadeh, M., *et al*., Investigating the Rheological Properties of Nanofluids of Water/Hybrid Nanostructure of Spherical Silica/Mwcnt, *Thermochim. Acta*, *578* (2014), Feb., pp. 53-58

[94] Soltani, O., Akbari, M., Effects of Temperature and Particles Concentration on the Dynamic Viscosity of MgO-MWCNT/Ethylene Glycol Hybrid Nanofluid: Experimental Study, *Phys. E Low-Dimensional Syst. Nanostructures*, *84* (2016), Oct., pp. 564-570

[95] Hamid, K. A., *et al*., Experimental Investigation of Thermal Conductivity and Dynamic Viscosity on Nanoparticle Mixture Ratios of TiO_2-SiO_2 Nanofluids, *Int. J. Heat Mass Transf.*, *116* (2018), Jan., pp. 1143-1152

[96] Yarmand, H., *et al*., Study of Synthesis, Stability and Thermo-Physical Properties of Graphene Nanoplatelet/Platinum Hybrid Nanofluid, *Int. Commun. Heat Mass Transf.*, *77* (2016), Oct., pp. 15-21

[97] Kumar, M. S., *et al.*, Thermal Conductivity and Rheological Studies for Cu–Zn Hybrid Nanofluids with Various Basefluids, *J. Taiwan Inst. Chem. Eng.*, *66* (2016), Sept., pp. 321-327
[98] Hemmat Esfe, M., *et al.*, The Optimization of Viscosity and Thermal Conductivity in Hybrid Nanofluids Prepared with Magnetic Nanocomposite of Nanodiamond Cobalt-Oxide (ND-Co_3O_4) using NSGA-II and RSM, *Int. Commun. Heat Mass Transf.*, *79* (2016), Dec., pp. 128-134
[99] Hemmat Esfe, M., Hajmohammad, M. H., Thermal Conductivity and Viscosity Optimization of Nanodiamond-Co_3O_4/Eg (40:60) Aqueous Nanofluid Using NSGA-II Coupled with RSM, *J. Mol. Liq.*, *238* (2017), July, pp. 545-552
[100] Sundar, L. S., *et al.*, Enhanced Heat Transfer and Friction Factor of MWCNT-Fe_3O_4/Water Hybrid Nanofluids, *Int. Commun. Heat Mass Transf.*, *52* (2014), Mar., pp. 73-83
[101] Yarmand, H., *et al.*, Nanofluid Based on Activated Hybrid of Biomass Carbon/Graphene Oxide: Synthesis, Thermo-Physical and Electrical Properties, *Int. Commun. Heat Mass Transf.*, *72* (2016), Mar., pp. 10-15
[102] Dardan, E., *et al.*, Effect of Suspending Hybrid Nano-Additives on Rheological Behavior of Engine Oil and Pumping Power, *Appl. Therm. Eng.*, *109* (2016), Part A, pp. 524-534
[103] Mechiri, S. K., *et al.*, Investigation of Thermal Conductivity and Rheological Properties of Vegetable Oil Based Hybrid Nanofluids Containing Cu–Zn Hybrid Nanoparticles, *Exp. Heat Transf.*, *30* (2017), 3, pp. 205-217
[104] Sundar, L. S., *et al.*, Nanodiamond-Fe_3O_4 Nanofluids: Preparation and Measurement of Viscosity, Electrical and Thermal Conductivities, *Int. Commun. Heat Mass Transf.*, *73* (2016), Apr., pp. 62-74
[105] Akilu, S., *et al.*, Experimental Measurements of Thermal Conductivity and Viscosity of Ethylene Glycol-Based Hybrid Nanofluid with TiO_2-CuO/C Inclusions, *J. Mol. Liq.*, *246* (2017), Nov., pp. 396-405
[106] Yarmand, H., *et al.*, Graphene Nanoplatelets-Silver Hybrid Nanofluids for Enhanced Heat Transfer, *Energy Convers. Manag.*, *100* (2015), Aug., pp. 419-428
[107] Ahammed, N., *et al.*, Entropy Generation Analysis of Graphene–Alumina Hybrid Nanofluid in Multiport Minichannel Heat Exchanger Coupled with Thermoelectric Cooler, *Int. J. Heat Mass Transf.*, *103* (2016), Dec., pp. 1084-1097
[108] Chandran, M. N., *et al.*, Novel Hybrid Nanofluid with Tunable Specific Heat and Thermal Conductivity: Characterization and Performance Assessment for Energy Related Applications, *Energy*, *140* (2017), Part 1, pp. 27-39
[109] Asadi, A., *et al.*, An Experimental and Theoretical Investigation on Heat Transfer Capability of Mg $(OH)_2$/MWCNT-Engine Oil Hybrid Nano-Lubricant Adopted as a Coolant and Lubricant Fluid, *Appl. Therm. Eng.*, *129* (2018), Jan., pp. 577-586
[110] Tahat, M. S., Benim, A. C., Experimental Analysis on Thermophysical Properties of Al_2O_3/CuO Hybrid Nano Fluid with Its Effects on Flat Plate Solar Collector, *Defect Diffus. Forum*, *374* (2017), Apr., pp. 148-156
[111] Suresh, S., *et al.*, Synthesis of Al_2O_3-Cu/Water Hybrid Nanofluids Using Two Step Method and Its Thermo Physical Properties, *Colloids Surfaces A Physicochem. Eng. Asp.*, *388* (2011), 1-3, pp. 41-48
[112] Hemmat Esfe, M., *et al.*, Experimental Determination of Thermal Conductivity and Dynamic Viscosity of Ag-MgO/Water Hybrid Nanofluid, *Int. Commun. Heat Mass Transf.*, *66* (2015), Aug., pp. 189-195
[113] Sundar, L. S., *et al.*, Turbulent Heat Transfer and Friction Factor of Nanodiamond-Nickel Hybrid Nanofluids Flow in a Tube: An Experimental Study, *Int. J. Heat Mass Transf.*, *117* (2018), Feb., pp. 223-234
[114] Moldoveanu, G. M., *et al.*, Experimental Study on Viscosity of Stabilized Al_2O_3, TiO_2 Nanofluids and Their Hybrid, *Thermochim. Acta*, *659* (2018), Nov., pp. 203-212
[115] Kannaiyan, S., *et al.*, Comparison of Experimental and Calculated Thermophysical Properties of Alumina/Cupric Oxide Hybrid Nanofluids, *J. Mol. Liq.*, *244* (2017), Oct., pp. 469-477
[116] Kumar, V., *et al.*, Effect of Variable Spacing on Performance of Plate Heat Exchanger Using Nanofluids, *Energy*, *114* (2016), Nov., pp. 1107-1119
[117] Nabil, M. F., *et al.*, Heat Transfer and Friction Factor of Composite TiO_2-SiO_2 Nanofluids in Water-Ethylene Glycol (60:40) Mixture, *Iop Conf. Ser. Mater. Sci. Eng.*, *257* (2017), Conference 1, 012066
[118] Hussien, A. A., *et al.*, Experiment on Forced Convective Heat Transfer Enhancement Using MWCNTs/GNPs Hybrid Nanofluid and Mini-Tube, *Int. J. Heat Mass Transf.*, *115* (2017), Part B, pp. 1121-1131
[119] Hamid, K. A., *et al.*, Experimental Investigation of Nanoparticle Mixture Ratios on TiO_2-SiO_2 Nanofluids Heat Transfer Performance Under Turbulent Flow, *Int. J. Heat Mass Transf.*, *118* (2018), Mar., pp. 617-627
[120] Sharma, S., *et al.*, Viscosity of Hybrid Nanofluids: Measurement and Comparison, *J. Mech. Eng. Sci. Issn*, *12* (2018), 2, pp. 2289-4659

[121] Dalkilic, A. S., *et al*., Experimental Investigation on the Viscosity Characteristics of Water Based SiO_2-Graphite Hybrid Nanofluids, *Int. Commun. Heat Mass Transf.*, *97* (2018), Oct., pp. 30-38
[122] Afshari, A., *et al*., Experimental Investigation of Rheological Behavior of the Hybrid Nanofluid of MWCNT–Alumina/Water (80%)–Ethylene-Glycol (20%): New Correlation and Margin of Deviation, *J. Therm. Anal. Calorim.*, *132* (2018), 2, pp. 1001-1015
[123] Ghasemi, S., Karimipour, A., Experimental Investigation of the Effects of Temperature and Mass Fraction on the Dynamic Viscosity of CuO-Paraffin Nanofluid, *Appl. Therm. Eng.*, *128* (2018), Jan., pp. 189-197
[124] Atashrouz, S., *et al*., Estimation of the Viscosity of Nine Nanofluids Using a Hybrid Gmdh-Type Neural Network System, *Fluid Phase Equilib.*, *372* (2014), June, pp. 43-48
[125] Koca, H. D., *et al*., Effect of Particle Size on the Viscosity of Nanofluids: A Review, *Renew. Sustain. Energy Rev.*, *82* (2018), July, pp. 1664-1674
[126] Nwosu, P. N., *et al*., A Review and Parametric Investigation Into Nanofluid Viscosity Models, *J. Nanotechnol. Eng. Med.*, *5* (2014), 3, pp. 031008
[127] Palabiyik, I., *et al*., Dispersion Stability and Thermal Conductivity of Propylene Glycol-Based Nanofluids, *J. Nanoparticle Res.*, *13* (2011), 10, pp. 5049-5055
[128] Sharma, A. K., *et al*., Rheological Behaviour of Nanofluids: A Review, *Renew. Sustain. Energy Rev.*, *53* (2016), Jan., pp. 779-791
[129] Mingzheng, Z., *et al*., Analysis of Factors Influencing Thermal Conductivity and Viscosity in Different Kinds of Surfactant Solutions, *Exp. Therm. Fluid Sci.*, *36* (2012), Jan., pp. 22-29
[130] Wang, J., *et al*., Heat Transfer and Pressure Drop of Nanofluids Containing Carbon Nanotubes in Laminar Flows, *Exp. Therm. Fluid Sci.*, *44* (2013), Jan., pp. 716-721
[131] Phuoc, T. X., *et al*., Viscosity and Thermal Conductivity of Nanofluids Containing Multi-Walled Carbon Nanotubes Stabilized By Chitosan, *Int. J. Therm. Sci.*, *50* (2011), 1, pp. 12-18
[132] Jarahnejad, M., *et al*., Experimental Investigation on Viscosity of Water-Based Al_2O_3 And TiO_2 Nanofluids, *Rheol. Acta*, *54* (2015), 5, pp. 411-422
[133] Abdelhalim, M. A. K., *et al*., Rheological and Dielectric Properties of Different Gold Nanoparticle Sizes, *Lipids Health Dis.*, *10* (2011), 10, 208
[134] He, Y., *et al*., Heat Transfer and Flow Behaviour of Aqueous Suspensions of TiO_2 Nanoparticles (Nanofluids) Flowing Upward through a Vertical Pipe, *Int. J. Heat Mass Transf.*, *50* (2007), 11-12, pp. 2272-2281
[135] Nguyen, C. T., *et al*., Viscosity Data for Al_2O_3-Water Nanofluid-Hysteresis: Is Heat Transfer Enhancement Using Nanofluids Reliable?, *Int. J. Therm. Sci.*, *47* (2008), 2, pp. 103-111
[136] Ferrouillat, S., *et al*., Influence of Nanoparticle Shape Factor on Convective Heat Transfer and Energetic Performance of Water-Based SiO2 and ZnO Nanofluids, *Appl. Therm. Eng.*, *51* (2013), 1-2, pp. 839-851
[137] Timofeeva, E. V., *et al*., Particle Shape Effects on Thermophysical Properties of Alumina Nanofluids, *J. Appl. Phys.*, *106* (2009), 1, 014304
[138] Wang, X.-J., Li, X.-F., Influence of PH on Nanofluids' Viscosity and Thermal Conductivity Influence of PH on Nanofluids' Viscosity and Thermal Conductivity, *Chin. Phys. Lett.*, *26* (2009), 5, pp. 1-5
[139] Duan, F., *et al*., Viscosity Affected by Nanoparticle Aggregation in Al_2O_3-Water Nanofluids, *Nanoscale Res. Lett.*, *6* (2011), 1, pp. 248
[140] Akilu, S., *et al*., Properties of Glycerol and Ethylene Glycol Mixture Based SiO_2-CuO/C Hybrid Nanofluid for Enhanced Solar Energy Transport, *Sol. Energy Mater. Sol. Cells*, *179* (2018), Dec., pp. 118-128
[141] Moldoveanu, G. M., *et al*., Viscosity Estimation of Al_2O_3, SiO_2 Nanofluids and their Hybrid: An Experimental Study, *J. Mol. Liq.*, *253* (2018), Mar., pp. 188-196
[142] Afrand, M., *et al*., Prediction of Dynamic Viscosity of a Hybrid Nano-Lubricant by an Optimal Artificial Neural Network, *Int. Commun. Heat Mass Transf.*, *76* (2016), Aug., pp. 209-214
[143] Aghaei, A., *et al*., Measurement of the Dynamic Viscosity of Hybrid Engine Oil-CuO-MWCNT Nanofluid, Development of a Practical Viscosity Correlation and Utilizing the Artificial Neural Network, *Heat Mass Transf. Und Stoffuebertragung*, *54* (2018), 1, pp. 151-161
[144] Ahmadi Nadooshan, A., *et al*., Prediction of Rheological Behavior of SiO_2-MWCNTs/10w40 Hybrid Nanolubricant by Designing Neural Network, *J. Therm. Anal. Calorim.*, *131* (2018), 3, pp. 2741-2748
[145] Hemmat Esfe, M., Abbasian Arani, A. A., An Experimental Determination and Accurate Prediction of Dynamic Viscosity of MWCNT(%40)-SiO_2(%60)/5w50 Nano-Lubricant, *J. Mol. Liq.*, *259* (2018), June, pp. 227-237
[146] Hemmat Esfe, M., *et al*., Evaluation of MWCNTs-ZnO/5w50 Nanolubricant by Design of an Artificial Neural Network for Predicting Viscosity and Its Optimization, *J. Mol. Liq.*, 277 (2018), Mar., pp. 921-931

[147] Hemmat Esfe, M., *et al*., Modeling and Prediction of Rheological Behavior of Al_2O_3-MWCNT/5w50 Hybrid Nano-Lubricant by Artificial Neural Network Using Experimental Data, *Phys. A Stat. Mech. Its Appl.*, *510* (2018), Nov., pp. 625-634

[148] Hemmat Esfe, M., *et al*., Optimization of MWCNTs (10%) – Al_2O_3(90%)/5w50 Nanofluid Viscosity Using Experimental Data and Artificial Neural Network, *Phys. A Stat. Mech. Its Appl.*, *512* (2018), Dec., pp. 731-744

[149] Sadeghinezhad, E., *et al*., Experimental Study on Heat Transfer Augmentation of Graphene Based Ferrofluids in Presence of Magnetic Field, *Appl. Therm. Eng.*, *114* (2017), Mar., pp. 415-427

[150] Amiri, A., *et al*., Highly Dispersed Multiwalled Carbon Nanotubes Decorated with Ag Nanoparticles in Water and Experimental Investigation of the Thermophysical Properties, *J. Phys. Chem. C*, *116* (2012), 5, pp. 3369-3375

Paper submitted: November 18.2018.
Paper revised: November 19.2018.
Paper accepted: December 20. 2018.