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An investigation into the effects of temperature on the rheological characteristics of hybrid nanofluids

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ABSTRACT

AN INVESTIGATION INTO THE EFFECTS OF TEMPERATURE ON THE RHEOLOGICAL CHARACTERISTICS OF HYBRID NANOFLUIDS

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Over the past several decades, nanofluids have exhibited a great potential of enhanced heat transfer performance over conventional heat transfer fluids. These innovative nanofluids are synthesized through the dispersion of a variety of types of nanometer-sized materials throughout the base fluid that consists of either metal, metal-oxides, or non-metals particle suspensions. These nanoparticle suspensions play an important role in altering the intrinsic properties of a base fluid, and this especially true for its shear viscosity. Studies have shown that the rheological response of the base fluid under shear changes from a characteristic Newtonian behavior to non-Newtonian (shear thinning) behavior when there is an increase in particle suspension concentration. Other studies have shown that the dynamic viscosity of nanofluid increases with an augmentation of particle volume fraction (for a given temperature), but decreases with increasing temperature (for a given particle concentration). The present study experimentally determines how the particle concentration, type of particle, and temperature affect the viscosity of hybrid nanofluids which is the main parameter that influences the rheological properties of a fluid based on range of shear rates for various concentrations while focusing primarily the effect of temperature on viscosity. The experiment determines the effect of temperature (25°C – 80°C), nanoparticle type, and nanoparticle volumetric concentration (0.2% - 1.5%) on viscosity of Al_2O_3, TiO_2 and a mixture of Al_2O_3 – TiO_2 with paraffin oil as the base fluid. Brookfield Dv2T rotational viscometer with a cone (CPA-40Z) and plate apparatus is used to measure the viscosity and the temperature is varied by connecting a temperature bath to the viscometer externally. Results shows that the fluid behavior changes from Newtonian to non-Newtonian upon addition of nanoparticles, the nanofluid samples also followed the power law model with the consistency index and the flow behavior index obtained from the curve fitting of shear rate – viscosity and shear rate – temperature dependency.

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AN INVESTIGATION INTO THE EFFECTS OF TEMPERATURE ON THE RHEOLOGICAL CHARACTERISTICS OF HYBRID NANOFLUIDS

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CHAPTER 1

INTRODUCTION

Nanofluids

Nanofluids are engineered by suspending nanoparticles with the basefluid. The nanoparticles are generally metal, metal oxides and other compounds with the average size below 100 nm and the basefluids are generally heat transfer fluids such as water, oil, ethylene glycol, methylene glycol etc. When the nanoparticles are mixed with the basefluid, the nanoparticles are dispersed in a manner such that it makes the basefluid looks opaque as seen in Figure 1. These nanofluids are not natural but have to be made. So these stable suspensions of nanoparticles in the basefluids are produced by two methods: The single-step technique simultaneously prepares nanoparticles using physical methods like inert gas condensation, mechanical grinding and chemical method like chemical vapor deposition, chemical precipitation and disperse them into the base fluids (Nanofluids S&T). The two-step method first prepares the nanoparticles with the above mentioned techniques and then disperse them into the base fluids.

Figure 1: Nanofluid samples

Shear Stress and Shear Strain

The flow behavior of the above mentioned fluids can be described by the relation between shear stress and shear strain. The relationship between shear stress and shear strain determines whether the nanofluid is Newtonian or non-Newtonian. If it is Newtonian, a linear relationship between shear stress and shear rate is observed, if it is non-Newtonian other flow behavior like shear thickening, shear thinning, Bingham plastic and Bingham pseudoplastic are observed as seen in Figure 2. These fluids are used in a wide variety of applications where it undergoes a shear rate. The relationship between shear rate and the resulting shear stress gives the concept of viscosity and then depending on the fluid, the viscosity determines whether or not the response is Newtonian or non-Newtonian.

The relation between shear stress and shear rate is given by equation 1.1:

$$\tau = \mu\dot{\gamma} \qquad 1.1$$

Where μ is the dynamic viscosity

and where μ *could be*:

$\boldsymbol{\mu = constant}$ - Newtonian Fluid

$\boldsymbol{\mu = f(\dot{\gamma})}$ - Non-Newtonian Fluid

We are focusing solely on basefluids that are Newtonian on their own; the fluids that are non-Newtonian on their own are disregarded in this investigation. If the fluids become non-Newtonian, it is solely because we are adding nanoparticles into the system.

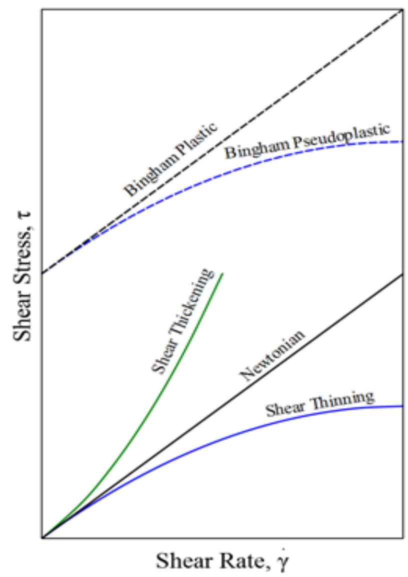

Figure 2: Shear stress as a function of shear rate for several kinds of fluids

Basefluid as a Function of Temperature

With an increase in temperature, there is a decrease in viscosity for liquids because there would be an increase in the molecular interchange as molecules move faster in higher temperatures (Fungilab). In a liquid there will be molecular interchange similar to those developed in a gas, but there are additional attractive, cohesive forces between the molecules of a liquid which are much closer together than those of a gas (Fungilab). Both cohesion and molecular interchange contribute to liquid viscosity. The impact of increasing the temperature of a liquid is to reduce the cohesive forces while simultaneously increasing the rate of molecular interchange, the reduction of cohesive forces causes a decrease in the shear stress while the increasing the rate of molecular interchange causes it to increase (Fungilab). The result is that liquids show a reduction in viscosity with increasing temperature.

CHAPTER 2

BACKGROUND

Rheological Behavior of TiO_2 – Water & TiO_2 – Ethylene Glycol Nanofluids

Understanding the rheological behavior of individual nanofluid with different basefluid is important. Water and EG are the most commonly used basefluid among all the base fluids, many researchers have investigated the rheological behavior of titanium oxide with water and EG as a basefluid. Duangthongsuk et al. investigated the rheological behavior of TiO_2 – water nanofluids with volume fractions of 0.2%, 0.6%, 1.0%, 1.5% and 2.0%, their experiments were performed at a shear rate ranging from 100 to 10000 s^{-1}. They reported that the nanofluid samples showed a shear thinning behavior. In another similar studies by Cabaleiro et al. the rheological behavior of TiO_2 – EG nanofluids at nanoparticle mass concentration of 5% - 25% in the shear rate range of 0.1 – 1000 s^{-1} showed that the nanofluid exhibited non-Newtonian behavior. Chen et al investigated TiO_2 – EG nanofluids at nanoparticle volume concentration 0.1 % - 1.8 % at the shear rate range of 0.05 – 200 s^{-1}, unlike Cabaleiro an interesting observation was seen by him. The non-Newtonian behavior for the nanofluids was observed only for nanofluids with volumetric concentration greater than 0.1%. The conclusion from the researchers for the shear thinning behavior was found out to be the nanoparticle agglomeration with the basefluid caused due to van der waals forces.

Rheological Behavior of Al_2O_3 – Water & Al_2O_3 – Ethylene Glycol Nanofluids

The rheological behavior of Al_2O_3 – water nanofluids were studied in the work by Alawi et al. the nanofluids of 1-5% volumetric concentration were considered at one unknown shear rate, a non-Newtonian behavior is exhibited by all the nanofuids that are considered. A similar observation was made from the study by Nguyen et al. for particle volume fraction lower than 4%. In the work by Sahoo et al. Al_2O_3 – Water nanofluids are investigated to understand the rheological behavior for volumetric concentration from 1-10% and in the shear rate range of 0 - 300 s^{-1}. The fluid behavior is non-Newtonian at all volumetric concentration and the viscosity increased with increase in particle concentrations and becomes four times the initially considered Volumetric concentration at 10% volumetric concentration. All the observation made for Al_2O_3 nanofluids is similar to what is been seen for the TiO_2 nanofluids.

Viscosity as a Function of Temperature for Al_2O_3 and TiO_2 Nanofluids

Viscosity as function of shear rate and volumetric concentration was seen in the previous section. Looking viscosity as a function of temperature is important to study the temperature dependence rheology of the nanofluids. Nguyen et al. have investigated effect of temperature on the dynamic viscosity of water based Al_2O_3 and CuO mixtures at the temperature range from 20 °C – 75 °C; they have seen at lower concentrations the tested nanofluids exhibited constant relative viscosities that are independent of temperature but at higher concentration a strong temperature dependence is observed. They have seen with the increase in temperature there is a decrease in viscosity of the tested nanofluids due to a weakening of inter-particle and inter-molecular adhesion forces.

Equation 2.1 was proposed by them to compute the dynamic viscosity of the tested nanofluids.

$$\mu_{eff} = \mu_f(2.1275\text{-}0.0215T+0.0002T^2) \qquad 2.1$$

where μ_{eff} is the effective viscosity and T is the temperature.

Another study by Pastoriza-Gallego et al. studied temperature dependence viscosity of ethylene glycol based Al_2O_3 nanofluids with concentrations up to 25% in mass fraction and temperature range from 283.15 K – 323.15 K. They have seen with the increase in temperature the viscosity diminishing.

Equation 2.2 has been developed to describe the dependence of viscosity for different nanofluids with temperature.

$$\mathrm{Ln}(\mu_f) = A + \frac{B}{T - T_0} \qquad 2.2$$

where μ_f is the dynamic viscosity, T is the temperature, and A, B, and T_0 are adjustable parameters.

Fundamentally the base fluid viscosity decreases with increasing temperature. However, from the above studies suggest that even in the presence of nanoparticles the viscosity is still only a function of temperature and that's what the above equation 2.1 and equation 2.2 say. However, in most cases when the nanoparticles are present in the system the viscosity is not just the function of temperature but also volumetric concentration.

Rheological Behavior of Hybrid Nanofluids

Hybrid systems are nothing but when two or more nanoparticles are mixed together at a certain ratio with the basefluids to form a new class of nanofluids that can enhance the heat transfer and flow characteristics together. In terms of literature, hybrid nanofluids are not explored to a greater extent and needs attention. Dardan et al. developed hybrid nanofluids by suspending 0.0625% - 1% volumetric concentration of 75% alumina nanoparticles and 25% MWCNT's in SAE40 engine oil, a Newtonian behavior was observed in favor of the application for improving the pumping power of the engine oil. Bahrami et al. studied hybrid nanofluids made of iron and copper oxide in a binary mixture of water and ethylene glycol at a volumetric concentration of 0.05% - 1.5%, the samples showed a Newtonian behavior at lower concentration and a non-Newtonian shear thinning behavior at higher concentration. From various other research's hybrid nanofluids proved to have a better heat transfer applications and have a great potential to solve problems associated with the rheology of single-particle nanofluids for successful application.

Table 1 illustrates the additional investigations from various researchers where viscosity is shown as function of various parameters. Two investigations stand out from the group, one from Raja Sekhar who has seen viscosity as a function of particle diameter and Cabaleiro who seen viscosity as a function of shear rate in the shear rate range of 0.1 – 1000 s^{-1}.

Table 1

Rheological behavior of nanofluids as a function of various parameters

Reference#	Year	Investigator(s)	Particle	Base fluid	Temperature Range	Volumetric Concentration	Notes
1	2017	Alawi, O., *et al.*	Al_2O_3	Water	26.85 °C - 46.85 °C	1%-5%	μ=f (ϕ, T)
2	2013	Y. Raja Sekhar & K.V. Sharma	Al_2O_3	Water	25 °C - 45 °C	0.01%-1%	μ=f (ϕ, T, D)
3	2012	Bahiraei, M., *et al.*	Al_2O_3	Water	25 °C - 70 °C	0.1%-1%	μ=f (ϕ, T)
4	2011	Pastoriza-Gallego, M., *et al.*	Al_2O_3	Ethylene Glycol	10 °C - 50 °C	0%-25%	μ=f (ϕ, T)
5	2013	Cabaleiro, D., *et al.*	TiO_2	Ethylene Glycol	10 °C - 50 °C	5%-25%	μ=f (ϕ, γ, T) Shear rate range (0.1 – 1000 S^{-1})
6	2013	Yiamsawas, T., *et al.*	TiO_2,Al_2O_3	Ethylene glycol/Water (EG–Water, 20/80 wt%).	15 °C - 60 °C	0 % - 4 %	μ=f (ϕ, T)

Power Law Fluid

Ostwald-de Waele equation is of the form

$$\mu = K\dot{\gamma}^{n-1}$$

where

K – Flow consistency index

n – Flow behavior Index

This mathematical equation is used to express the power law region of a flow curve model or describes the behavior of the real non-Newtonian fluid, this region shows a constant linearity on a log plot but exhibits a power lab dependence on a linear scale plot(panalytical). Any power law dependence nonlinear equation can be converted into a linear equation whose slope and intercept are related to unknown value of n and k.

Thesis Objective

- Perform a qualitative analysis on how the interaction of temperature, shear rate, and nanoparticle type affects the viscosity of the base fluid mineral (paraffin) oil.
- Perform a quantitative analysis to curve fit the experimental data to obtain the flow consistency index and flow behavior index.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

Materials

Nanoparticles

Al_2O_3 and TiO_2 nanoparticles were selected for the experimental investigation. These nanoparticles are chemically stable, have high mechanical strength enhancement and they have proven ability to enhance heat transfer application of the base fluid. The nanoparticles of 5nm were purchased from US research nanomaterials, Inc. different sizes were considered thinking it may influence the physiochemical properties of the basefluid. because they affect key colloid properties such as rheology, film gloss, surface area and packing density. The density of the 5nm nanoparticle is 3.89 g/cm^3 (US Nano).

Figure 3: 5nm Al_2O_3 nanoparticles and 5nm TiO_2 nanoparticle

Basefluid

Paraffin oil, white, was chosen as a basefluid for its high heat transfer capacity and potential application as a nanofluid. Paraffin mineral is widely used as a coolant liquid for heat exchangers, it can also be used as a transformer oil, cutting fluid and lubricant. It was purchased from Carolina Biological Company. The density of the oil is 0.8 g/cm^3(CBC).

Figure 4: Paraffin oil, white

Procedure for Preparing Nanofluids

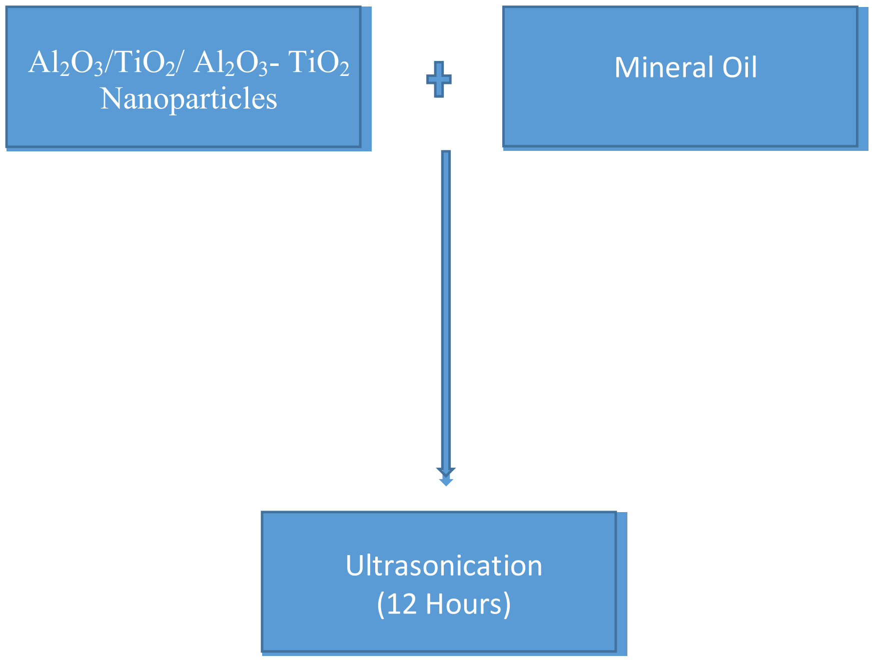

Figure 5: Two-step method to prepare nanofluids

These nanoparticles are mixed with the paraffin oil to form nanofluids. The nanoparticles and the basefluid are weighed up in such a way that a 0.2%, 0.5%, 1%, 1.5% volumetric concentration solutions of nanofluids are formed for individual Al_2O_3 and TiO_2 Nanoparticles. Hybrid nanofluids were also studied which are mixed in a similar fashion as above to form 25% 5nm Al_2O_3 and 75% 5nm TiO_2, 50% 5nm Al_2O_3 and 50% 5nm TiO_2, 75% 5nm Al_2O_3 and 25% 5nm TiO_2 to form a 0.2%, 0.5%, 1%, 1.5% volumetric concentration solutions of nanofluids. The following formulas are used to calculate the volumetric concentration:

Formula for single nanoparticle type sample calculation:

$$\phi_{Al_2O_3/TiO_2} = \frac{\frac{m_{Al_2O_3/TiO_2}}{\rho_{Al_2O_3}}}{\frac{m_{MO}}{\rho_{MO}}}$$

$\phi_{Al_2O_3/TiO_2}$ = 0.2 vol%, 0.5 vol%, 1.0 vol%, 1.5 vol%

Formula for hybrid nanoparticles sample calculations:

$$\phi_{x_{Al_2O_3}-y_{TiO_2}} = \left(x_{Al_2O_3}\phi_{x_{Al_2O_3}-y_{TiO_2}}\right) + \left(y_{TiO_2}\,\phi_{x_{Al_2O_3}-y_{TiO_2}}\right)$$

$$x_{Al_2O_3} = \frac{\frac{m_{Al_2O_3}}{\rho_{Al_2O_3}}}{\frac{m_{Al_2O_3}}{\rho_{Al_2O_3}} + \frac{m_{TiO_2}}{\rho_{TiO_2}} + \frac{m_{MO}}{\rho_{MO}}}$$

$$y_{TiO_2} = \frac{\frac{m_{TiO_2}}{\rho_{TiO_2}}}{\frac{m_{Al_2O_3}}{\rho_{Al_2O_3}} + \frac{m_{TiO_2}}{\rho_{TiO_2}} + \frac{m_{MO}}{\rho_{MO}}}$$

$$x_{Al_2O_3}; y_{TiO_2} = 0.25,\ 0.5,\ 0.75$$

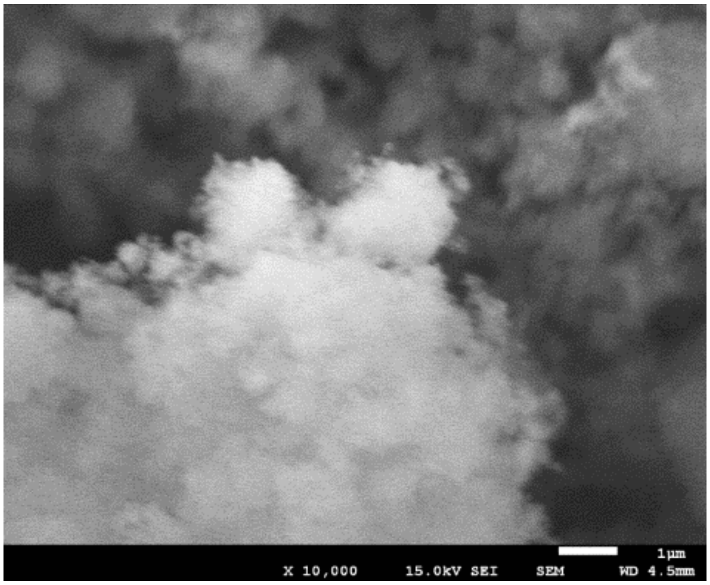

Figure 6: α -Al_2O_3 nanoparticles, 5nm

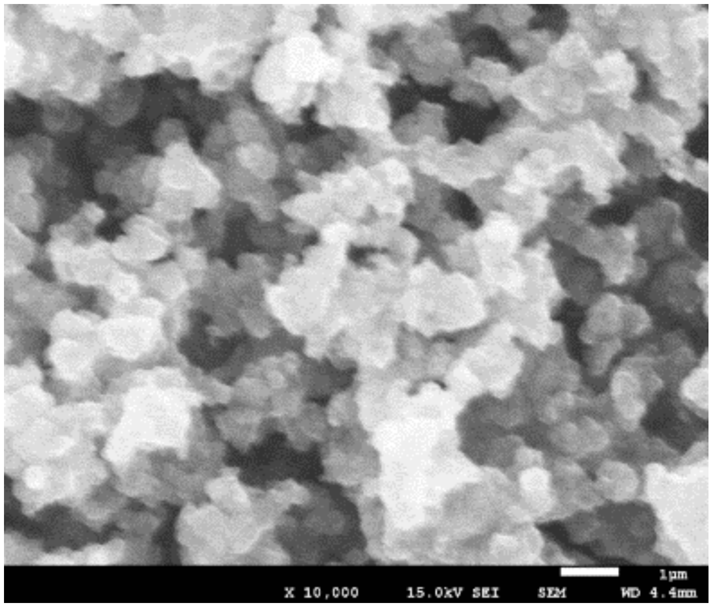

Figure 7: TiO_2 nanoparticles (anatase), 5nm

Once the nanoparticles are mixed with the paraffin oil in the desired quantity to form a nanofluid, the solution is then ultra-sonicated for 12 hours using a Branson 1800 sonicator as shown in Figure 8.

Figure 8: Branson 1800 sonicator

Experimental Setup for Viscosity Measurement

The Brookfield DV2T viscometer is used to measure the viscosity of the nanofluid; it measures the fluid viscosity at a given shear rates. Its torque ranges from 0.1-200 rpm, temperature sensing range from -100 °C to 300 °C. A cone and plate geometry was chosen for viscosity measurements as it provides a uniform shear rate throughout the cross section. Omega HCTB –1070 constant temperature circulating bath is used to maintain the sample temperature at a desired temperature, The temperature bath is connected to the viscometer sample cup through external piping.

Figure 9: Viscometer connected to the temperature bath.

Assemble and level the viscometer, switch on and auto zero the viscometer, attach the spindle and the viscometer is ready to take the viscosity values. After setting up the viscometer, it is necessary to set up a plate. Cone is first attached to the viscometer and then plate is attached using the threading provided, to set up the gap the light provided on the viscometer used. Once the cone touches the plate the viscometer displays a light this light should be turned off by setting a gap through rotation of nob provided on the viscometer by one division. Next step is to add 0.5ml sample of nanofluid to the plate using a pipette and take the viscosity values using the options provided on the touch screen by setting an rpm with respect to the shear rate. Temperature bath offers the digital temperature control of liquids. It regulates temperature ranges from ambient +10 °C - 130 °C and provides internal and external circulation. Top control housing houses electronic temperature controls for the unit and fine tuning. Main temperature control is used for setting the operating temperature. Temperature control button sets the temperature to the exact operating temperature desired after setting the main temperature control. Fine tune option control to enhance the temperature control. Digital temperature display is an LED display for set point and actual temperature readings.

CHAPTER 4

RESULTS AND DISCUSSIONS

After the experimental investigation were performed on the individual Al_2O_3, TiO_2 and the mixtures, here are the various inferences that were drawn for the same to analyze the rheology of these nanofluids.

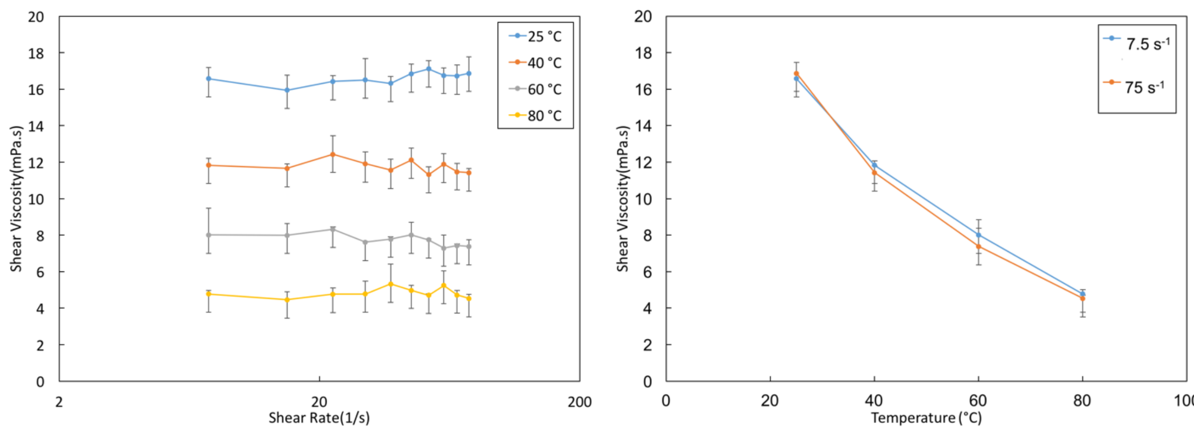

Figure 10: Rheological behavior of mineral oil

Figure 10 illustrates the rheological behavior of mineral oil basefluid. In the first plot it is observed that the mineral oil basefluid has Newtonian behavior as a function of shear rate i.e. There is a linear relationship between shear viscosity and shear rate, no matter how much the shear rate is increased the viscosity still remains constant at every shear viscosity data point. It's also observed that the shear viscosity decreases with increasing temperature while the Newtonian behavior still remaining at higher temperatures. From the second plot in the above figure it's observed that the relationship between viscosity and temperature is nonlinear, its rather exponential. Viscosity at both the shear rate is the function of temperature, so for both the shear rates the viscosities remain same at a given temperature for the basefluid.

Rheological Behavior of Al_2O_3 and TiO_2 Nanofluids

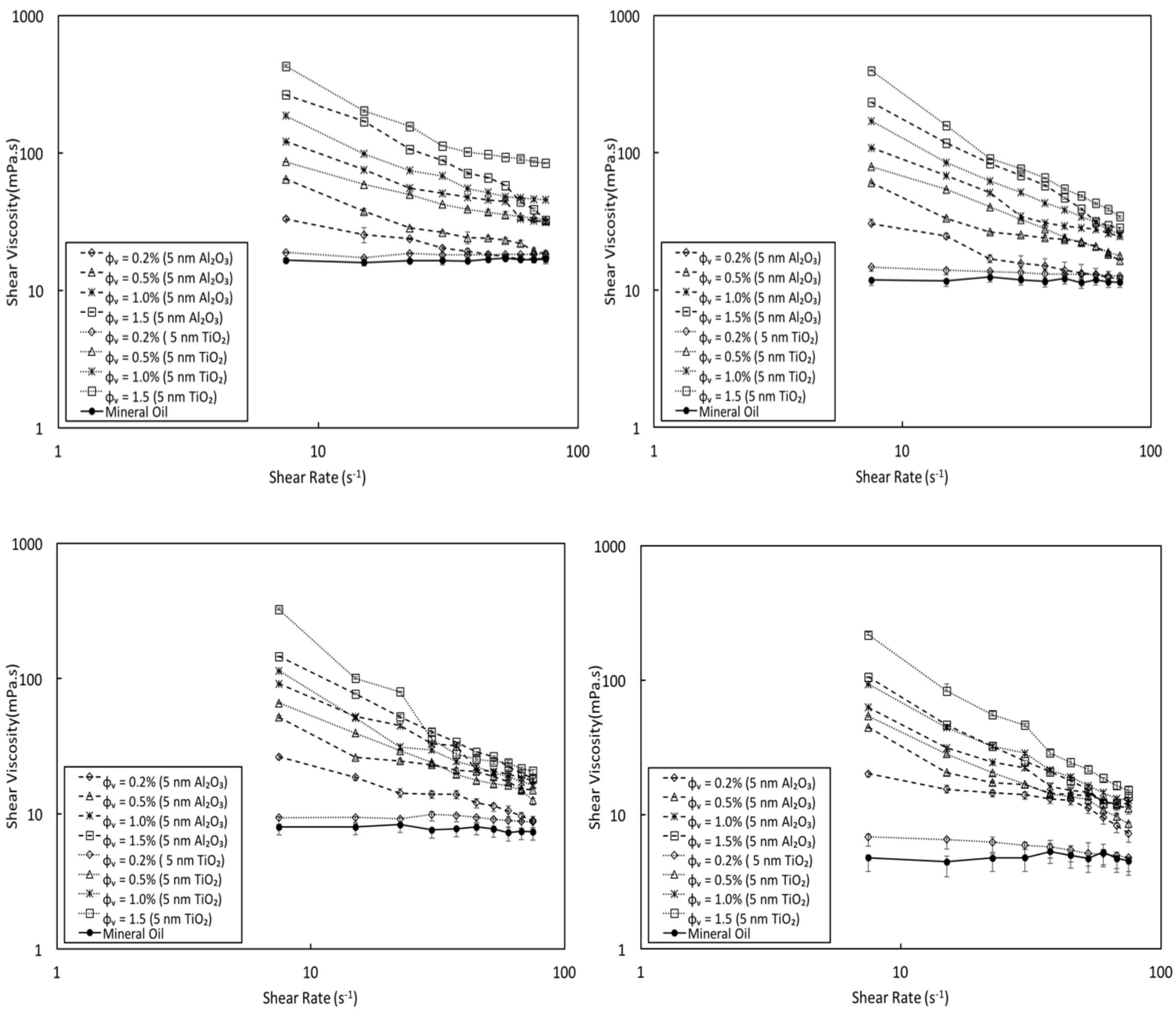

Figure 11: Shear viscosity vs shear rate of Al_2O_3 and TiO_2 nanofluids at all volumetric concentrations at 25 °C, 40 °C, 60 °C, and 80 °C

The objective of the entire results is to see if the viscosity of the Al_2O_3, TiO_2 and hybrid nanofluids coming closer to the viscosity of the basefluid. There are three approaches that were analyzed. The first approach is to see the viscosity of the Al_2O_3 and TiO_2 coming closer to the viscosity of the basefluid. So the viscosity results were measured for volumetric concentration 0.2% - 1.5% at 25 °C, 40 °C, 60°C and 80 °C from Figure 11; it can be seen that the mineral oil basefluid has a Newtonian behavior i.e., there is a linear relationship between shear viscosity and shear rate, no matter how much the shear rate is increased the viscosity still remains constant for every viscosity value. Once the nanoparticles are added into the system the fluid behavior changes from Newtonian to non-Newtonian, the amount of Al_2O_3 and TiO_2 nanoparticles added to the paraffin effect the shear thinning behavior of the fluid. The viscosity of both Al_2O_3 and TiO_2 nanofluids decreases with increasing shear rate for all the volumetric concentrations. The slope of the curve increases as we increase the volumetric concentration for both the nanofluids. For a given volumetric concentration, the viscosity of TiO_2 nanofluid is higher than Al_2O_3 nanofluid in most cases since different nanoparticle affects the viscosity of the basefluid is different. The linear relationship with a negative slope in a lol-log plot shows a steady rate of decrease in viscosity with increasing shear rate. Similar behavior is observed for all the temperatures except for the fact that the plots are shifting down a bit as the temperature is increased.

So it does not matter if the shear rate is varied, volumetric concentration is varied or the temperature is varied; the viscosity of the Al_2O_3 and TiO_2 nanofluids is always going to be higher than the viscosity of the basefluid.

Table 2

Power law parameters as a function of volumetric concentration of Al_2O_3 and TiO_2 nanofluids at 25°C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v = 0.2% (5 nm TiO_2)	18.265	0.993	0.00053
φ_v = 0.2% (5 nm Al_2O_3)	58.592	0.7	0.97711
φ_v = 0.5% (5 nm TiO_2)	186.74	0.582	0.97821
φ_v = 0.5% (5 nm Al_2O_3)	149.62	0.512	0.94752
φ_v = 1% (5 nm TiO_2)	536.63	0.399	0.95651
φ_v = 1% (5 nm Al_2O_3)	355.11	0.439	0.96708
φ_v = 1.5% (5 nm TiO_2)	1384.5	0.318	0.94025
φ_v = 1.5% (5 nm Al_2O_3)	1763.5	0.108	0.98209

'k' in Table 2 is referred to as the "flow consistency index" which is the measure of consistency of the substance and 'n' in the above is referred to as the "flow behavior index". k is like a proportionality constant, which in a log-log form gives a measure of the viscosity at a given shear rate. When the nanoparticles are present in the system, k is the measure of forces due to agglomeration of the nanoparticles, k value is different for different nanoparticle for a given concentration because the agglomeration forces are different for different nanoparticles, since there are two different nanoparticles there will be two different types of interaction with the basefluid, Hence there would be two different k's for the same volumetric concentration and because we have two different k's, the Al_2O_3 nanofluid will eventually go down to mineral oil as the shear rate is increased for all the volumetric concentrations whereas the TiO_2 nanofluid would not go to the mineral oil, it rather stays at its intrinsic viscosity as we increase the shear rate. The consistency index value increases with increasing volumetric concentration for both the nanofluids. Smaller the value the n, more shear thinning is the fluid, the shear thinning behavior is not significant at lower concentrations but as we increase the volumetric concentration the value of n goes down which means the fluid is undergoing more shear thinning, the flow behavior index decreases with increases amount of nanoparticles because the slope gets more steep as we increase the particle concentration. The R^2 value determines how close the data is to the regression model, the R^2 value is between 0 and 100%, more the value of R^2 the better the model we are considering.

Table 3

Power law parameters as a function of volumetr: concentration of Al_2O_3 and TiO_2 nanofluids at 40 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v = 0.2% (5 nm TiO_2)	16.597	0.938	0.98675
φ_v = 0.2% (5 nm Al_2O_3)	58.781	0.624	0.96535
φ_v = 0.5% (5 nm TiO_2)	315.43	0.332	0.9976
φ_v = 0.5% (5 nm Al_2O_3)	136.73	0.521	0.93114
φ_v = 1% (5 nm TiO_2)	779.99	0.206	0.99475
φ_v = 1% (5 nm Al_2O_3)	371.47	0.36	0.94564
φ_v = 1.5% (5 nm TiO_2)	2568.7	-0.01	0.98308
φ_v = 1.5% (5 nm Al_2O_3)	1508.2	0.076	0.9941

Smaller the value the n, more shear thinning is the fluid, the shear thinning behavior is not significant at 0.2% volumetric concentration but as we increase the volumetric concentration the value of n goes down which means the fluid is undergoing more shear thinning, the flow behavior index decreases with increases amount of nanoparticles because the slope gets more steep as we increase the particle concentration.

Table 4

Power law parameters as a function of volumetr[illegible] concentration of Al_2O_3 and TiO_2 nanofluids at 60 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v = 0.2% (5 nm TiO_2)	10.233	0.972	0.26167
φ_v = 0.2% (5 nm Al_2O_3)	61.595	0.565	0.9699
φ_v = 0.5% (5 nm TiO_2)	255.95	0.31	0.99194
φ_v = 0.5% (5 nm Al_2O_3)	114.29	0.531	0.92972
φ_v = 1% (5 nm TiO_2)	473.93	0.2	0.96461
φ_v = 1% (5 nm Al_2O_3)	405.4	0.263	0.9788
φ_v = 1.5% (5 nm TiO_2)	2873.4	-0.199	0.94486
φ_v = 1.5% (5 nm Al_2O_3)	868.24	0.106	0.99879

The consistency index value increases with increasing volumetric concentration for both the nanofluids. It is also observed that the k values are going down for a given volumetric concentration from 40 °C to 60 °C which shows that at 60 °C the fluid does not need as much shear thinning as 40 °C. Smaller the value the n, more shear thinning is the fluid, the shear thinning behavior is not significant at 0.2% volumetric concentration but as we increase the volumetric concentration the value of n goes down which means the fluid is undergoing more shear thinning, the flow behavior index decreases with increases amount of nanoparticles because the slope gets more steep as we increase the particle concentration.

Table 5

Power law parameters as a function of volumetr: :oncentration of Al_2O_3 and TiO_2 nanofluids at 80 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v = 0.2% (5 nm TiO_2)	9.9319	0.839	0.93743
φ_v = 0.2% (5 nm Al_2O_3)	47.542	0.612	0.85059
φ_v = 0.5% (5 nm TiO_2)	226.03	0.25	0.98754
φ_v = 0.5% (5 nm Al_2O_3)	101.96	0.478	0.91224
φ_v = 1% (5 nm TiO_2)	487.51	0.145	0.99365
φ_v = 1% (5 nm Al_2O_3)	235.99	0.289	0.97999
φ_v = 1.5% (5 nm TiO_2)	2040.5	-0.148	0.99293
φ_v = 1.5% (5 nm Al_2O_3)	614.06	0.061	0.98175

The consistency index value increases with increasing volumetric concentration for both the nanofluids. It is also observed that the k values are going down for a given volumetric concentration from 60 °C to 80 °C which shows that at 60 °C the fluid does not need as much shear thinning as 60 °C. Smaller the value the n, more shear thinning is the fluid, the shear thinning behavior is not significant at 0.2% volumetric concentration but as we increase the volumetric concentration the value of n goes down which means the fluid is undergoing more shear thinning; the flow behavior index decreases with increases amount of nanoparticles because the slope gets more steep as we increase the particle concentration.

Rheological Behavior of Al_2O_3, TiO_2 and Hybrid Nanofluids

In the previous section it has been seen if the viscosity of the Al_2O_3, TiO_2 and hybrid nanofluids coming closer to the viscosity of the basefluid. Now the second approach is to look what happens if two nanoparticles are mixed with the basefluid at certain ratios and see if these mixtures are going close to the viscosity of the basefluid.

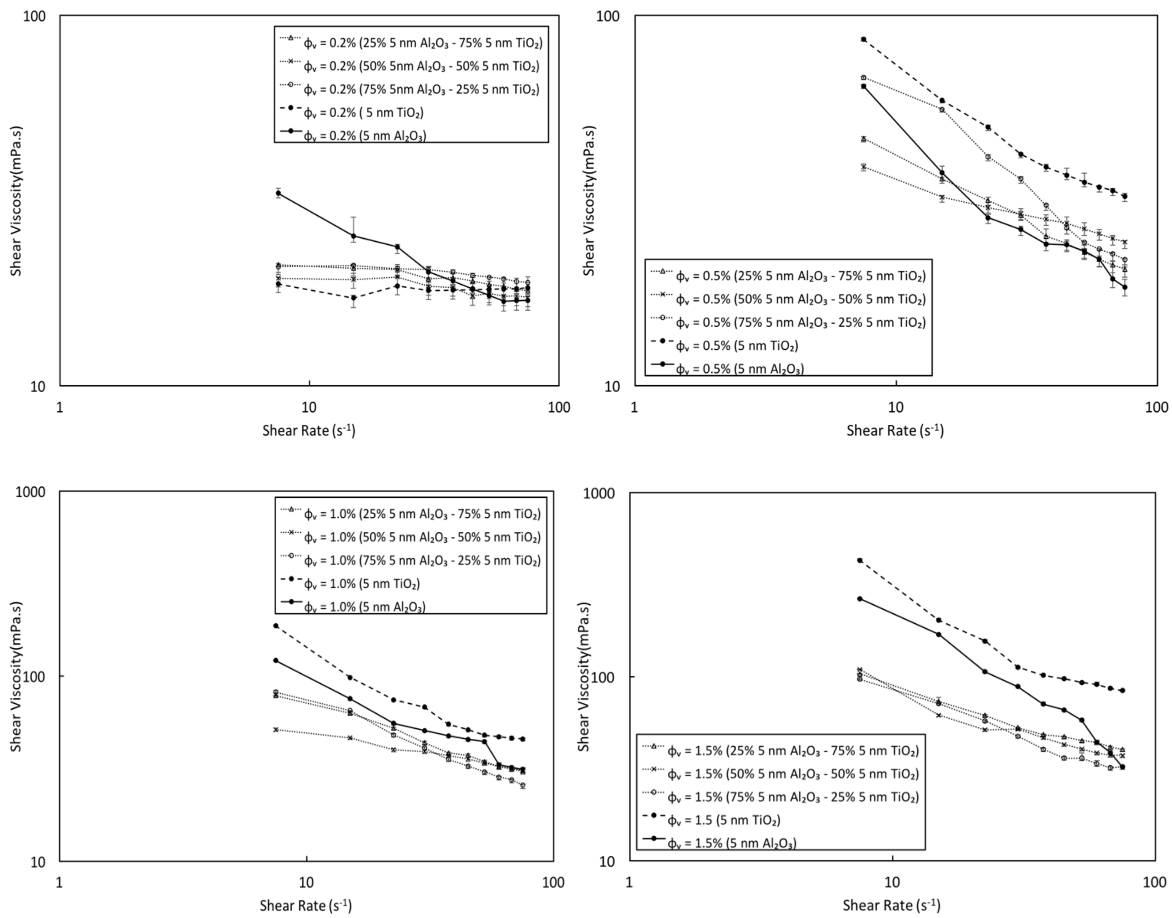

Figure 12: Shear viscosity vs shear rate of Al_2O_3, TiO_2 and hybrid nanofluids at individual volumetric concentration at 25°C

Now that how the change in shear rate and the change in volumetric concentration affects the shear viscosity of Al_2O_3 and TiO_2 nanofluids at a given temperaturehas been seen. Figure 12 shows how the shear viscosity is affected over a range of shear rate at a given volumetric concentration for Al_2O_3, TiO_2 and its hybrid systems at 25 °C.

At 0.2% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls between the single particle nanofluids, with the viscosity of Al_2O_3 nanofluid is at the top and TiO_2 nanofluid fuild at the bottom. But at higher shear rates, the shear viscosity of hybrid nanofluid (75% Al_2O_3 – 25% TiO_2) is the highest with Al_2O_3 being at the bottom.

Table 6:

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.2% at 25 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =0.2% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	25.205	0.926	0.92711
φ_v =0.2% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	22.741	0.938	0.81589
φ_v =0.2% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	23.703	0.951	0.83139
φ_v = 0.2% (5 nm TiO_2)	18.265	0.993	0.00053
φ_v = 0.2% (5 nm Al_2O_3)	58.592	0.7	0.97711

The flow consistency index k is highest for Al_2O_3 nanofluid and least for TiO_2 and the value of k for hydrid nanofluids falls between the single particle nanofluids. At the given concentration the k value is different for Al_2O_3, TiO_2 and its mixtures because the agglomeration forces are different for each one of them since the interaction of Al_2O_3, TiO_2 and its mixtures with the basefluid is different. However, the k values for TiO_2 and mixtures are close to each other which shows that it does not need as much shear thinning as Al_2O_3 to get to 75 s^{-1}. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for TiO_2 and mixtures but the value of n goes down for Al_2O_3 which means the fluid is undergoing more shear thinning to get to 75 s^{-1}.

At 0.5 % volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. At lower shear rates it's observed that the shear viscosity of (25% Al_2O_3 – 75% TiO_2) and (50% Al_2O_3 – 50% TiO_2) nanofluids falls below the single particle nanofluids, whereas the (75% Al_2O_3 – 25% TiO_2) nanofluid falls between the single particle nanofluid with the viscosity of TiO_2 nanofluid being at the top. But at higher shear rates, the shear viscosity of hybrid nanofluids falls between the single particle nanofluids with TiO_2 being at the top and Al_2O_3 being at the bottom. It's observed that the viscosity of Al_2O_3, TiO_2 and its mixtures increased with the increase in volumetric concentration from 0.2% to 0.5%.

Table 7

Power law parameters as a function of volumetric conce....ation of Al_2O_3, TiO_2 and hybrid nanofluids at 0.5% at 25 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =0.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	96.03	0.64	0.99701
φ_v =0.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	55.704	0.81	0.98635
φ_v =0.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	217.06	0.462	0.98297
φ_v = 0.5% (5 nm TiO_2)	186.74	0.582	0.97821
φ_v = 0.5% (5 nm Al_2O_3)	149.62	0.512	0.94752

The flow consistency index k is highest for (75% Al_2O_3 – 25% TiO_2) nanofluid and least for (25% Al_2O_3 – 75% TiO_2) nanofluid. The values of k for 0.5% volumetric concentration is higher than 0.2% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 0.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for (50% Al_2O_3 – 50% TiO_2) nanofluid but the smaller value of n for the other nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. Unlike 0.2% and 0.5% volumetric concentration it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids at both lower and higher shear rates. There is a clear indication that the viscosity of Al_2O_3, TiO_2 and its mixtures increased with the increase in volumetric concentration from 0.5% to 1%.

Table 8

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1% at 25 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =1% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	192.6	0.569	0.98971
φ_v =1% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	83.545	0.771	0.98467
φ_v =1% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	247.97	0.443	0.99085
φ_v = 1% (5 nm TiO_2)	536.63	0.399	0.95651
φ_v = 1% (5 nm Al_2O_3)	355.11	0.439	0.96708

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1% volumetric concentration is higher than 0.5% volumetric concentration and it's also observed that the slope of the curves gets steep going from 0.5% - 1% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for (50% Al_2O_3 – 50% TiO_2) nanofluid but the smaller value of n for the other nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1.5% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. Unlike 0.2% and 0.5% volumetric concentration it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids at both lower and higher shear rates. Similar behavior is observed for 1% volumetric concentration as well but the difference in viscosity of hybrid nanofluids with the single particle nanofluid is not significant for 1% volumetric concentration. There is a clear indication that the viscosity of Al_2O_3, TiO_2 and its mixtures increased with the increase in volumetric concentration from 1% to 1.5%.

Table 9

Power law parameters as a function of volumetric conce[illegible]ation of Al_2O_3, TiO_2 and hybrid nanofluids at 1.5% at 25 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =1.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	220.93	0.599	0.98257
φ_v =1.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	225.03	0.568	0.93692
φ_v =1.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	272.93	0.49	0.98562
φ_v = 1.5% (5 nm TiO_2)	1384.5	0.318	0.94025
φ_v = 1.5% (5 nm Al_2O_3)	1763.5	0.108	0.98209

The flow consistency index k is highest for Al_2O_3 nanofluid followed by TiO_2 nanofluid, both single particle nanofluids, which shows that the single particle nanofluids have to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1.5% volumetric concentration is higher than 1% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 1.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is significant for all the nanofluids with smaller values of n which means the fluids is undergoing more shear thinning to get to 75 s^{-1}. Figure 13 illustrates how the shear viscosity is affected over a range of shear rate at a given volumetric concentration for Al_2O_3, TiO_2 and its hybrid systems at 40 °C.

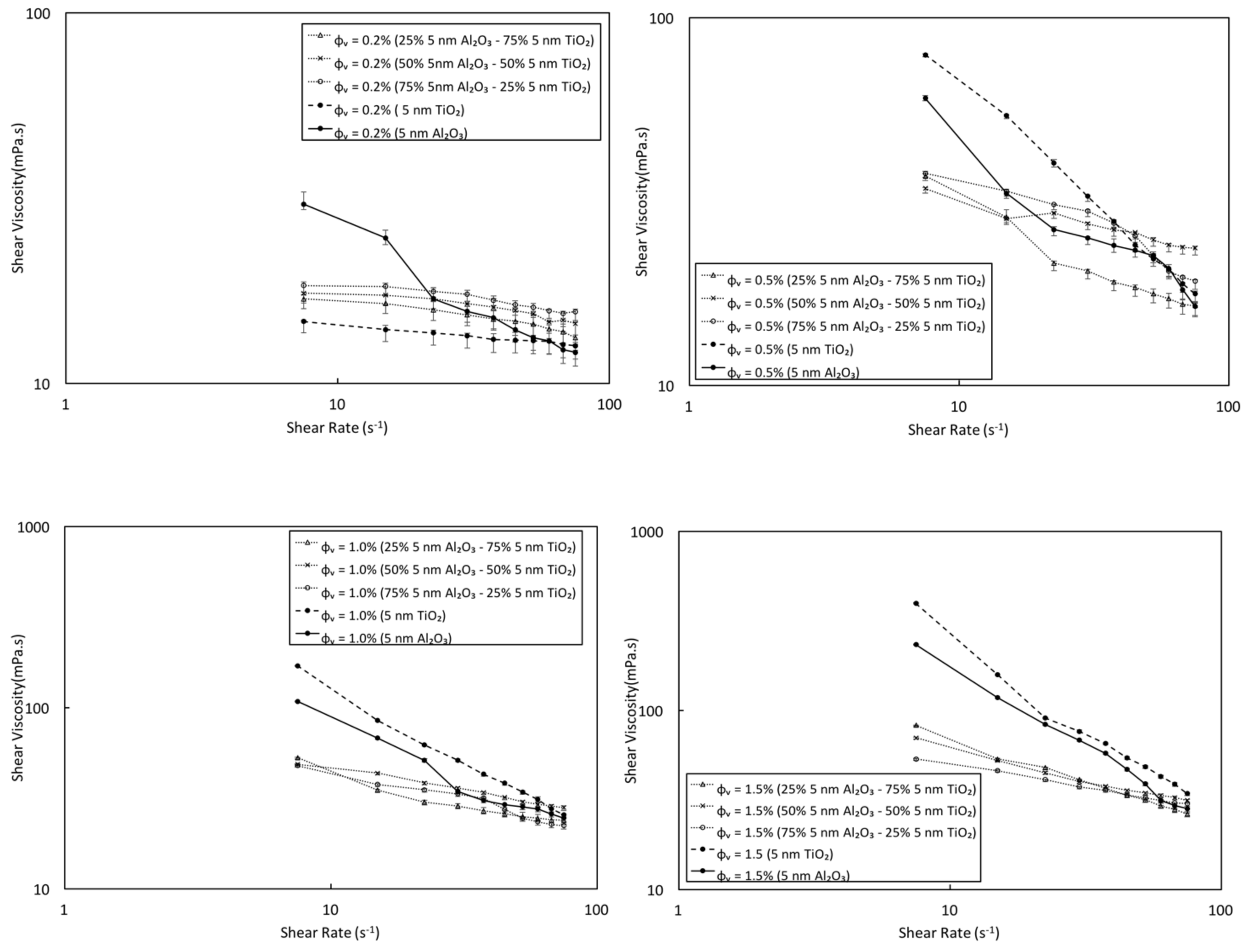

Figure 13: Shear viscosity vs shear rate of Al_2O_3, TiO_2 and hybrid nanofluids at individual volumetric concentration at 40°C

At 0.2% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 40 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 0.2% volumetric concentration at 25 °C which shows that the viscosity decreases with increasing temperature. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls between the single particle nanofluids, with the viscosity of Al_2O_3 nanofluid is at the top and TiO_2 nanofluid fuild at the bottom. But at higher shear rates, the shear viscosity of hybrid nanofluids falls above the single particle nanofluids with (50% Al_2O_3 – 50% TiO_2) being at the top and Al_2O_3 being at the bottom.

Table 10

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.2% at 40 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =0.2% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	21.369	0.898	0.94074
φ_v =0.2% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	21.679	0.912	0.88957
φ_v =0.2% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	22.557	0.915	0.9041
φ_v = 0.2% (5 nm TiO_2)	16.597	0.938	0.98675
φ_v = 0.2% (5 nm Al_2O_3)	58.781	0.624	0.96535

The flow consistency index k is highest for Al_2O_3 nanofluid and least for TiO_2 and the value of k for hydrid nanofluids falls between the single particle nanofluids. However, the k values for TiO_2 and mixtures are close to each other which shows that it does not need as much shear thinning as Al_2O_3 to get to 75 s^{-1}. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for TiO_2 and mixtures but the value of n goes down for Al_2O_3 which means the fluid is undergoing more shear thinning to get to 75 s^{-1}.

Looking at how the shear viscosity is affected over a range of shear rate at 0.5%, 1% and 1.5% volumetric concentration for Al_2O_3, TiO_2 and its hybrid systems would give a deep insight on how the shear viscosity is affected over a range of shear rate.

At 0.5 % volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 40 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 0.5% volumetric concentration at 25 °C which shows that the viscosity decreases with increasing temperature. Unlike 0.2% volumetric concentration at lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids, with the viscosity of TiO_2 nanofluid being at the top. But at higher shear rates, the shear viscosity of (50% Al_2O_3 – 50% TiO_2) & (75% Al_2O_3 – 25% TiO_2) nanofluids above the single particle nanofluids with TiO_2 being at the top. It's observed that the viscosity of Al_2O_3, TiO_2 and its mixtures increased with the increase in volumetric concentration from 0.2% to 0.5%.

Table 11

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.5% at 40 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =0.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	71.43	0.648	0.96152
φ_v =0.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	46.04	0.846	0.94608
φ_v =0.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	77.465	0.689	0.91017
φ_v = 0.5% (5 nm TiO_2)	315.43	0.332	0.9976
φ_v = 0.5% (5 nm Al_2O_3)	136.73	0.521	0.93114

The flow consistency index k is highest for TiO_2 nanofluid and least for (50% Al_2O_3 – 50% TiO_2) nanofluid. The values of k for 0.5% volumetric concentration is higher than 0.2% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 0.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for (50% Al_2O_3 – 50% TiO_2) nanofluid but the smaller value of n for the other nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 40 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 1% volumetric concentration at 25 °C which shows that the viscosity decreases with increasing temperature. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids but at higher shear all the nanofluids falls at the same place with very less viscosity difference.

Table 12

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1% at 40 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =1% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	90.122	0.671	0.93066
φ_v =1% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	83.966	0.747	0.98944
φ_v =1% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	98.954	0.659	0.95888
φ_v = 1% (5 nm TiO_2)	779.99	0.206	0.99475
φ_v = 1% (5 nm Al_2O_3)	371.47	0.36	0.94564

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1% volumetric concentration is higher than 0.5% volumetric concentration and it's also observed that the slope of the curves gets steep going from 0.5% - 1% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of

k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not much significant for (50% Al_2O_3 – 50% TiO_2) nanofluid but the smaller value of n for the other nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1.5% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 40 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 1.5% volumetric concentration at 25 °C which shows that the viscosity decreases with increasing temperature. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids but at higher shear all the nanofluids falls at the same place with very less viscosity difference.

Table 13

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1.5% at 40 °C

Nanoparticle Type	K(Pa s^n)	n	R^2
φ_v =1.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	210.12	0.52	0.9947
φ_v =1.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	133.87	0.658	0.98682
φ_v =1.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	91.482	0.741	0.99676
φ_v = 1.5% (5 nm TiO_2)	2568.7	-0.01	0.98308
φ_v = 1.5% (5 nm Al_2O_3)	1508.2	0.076	0.9941

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1.5% volumetric concentration is higher than 1% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 1.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is significant for all the nanofluids with smaller values of n which means the fluids is undergoing more shear thinning to get to 75 s^{-1}. Figure 14 Illustrates how the shear viscosity is affected over a range of shear rate at a given volumetric concentration for Al_2O_3, TiO_2 and its hybrid systems at 60 °C.

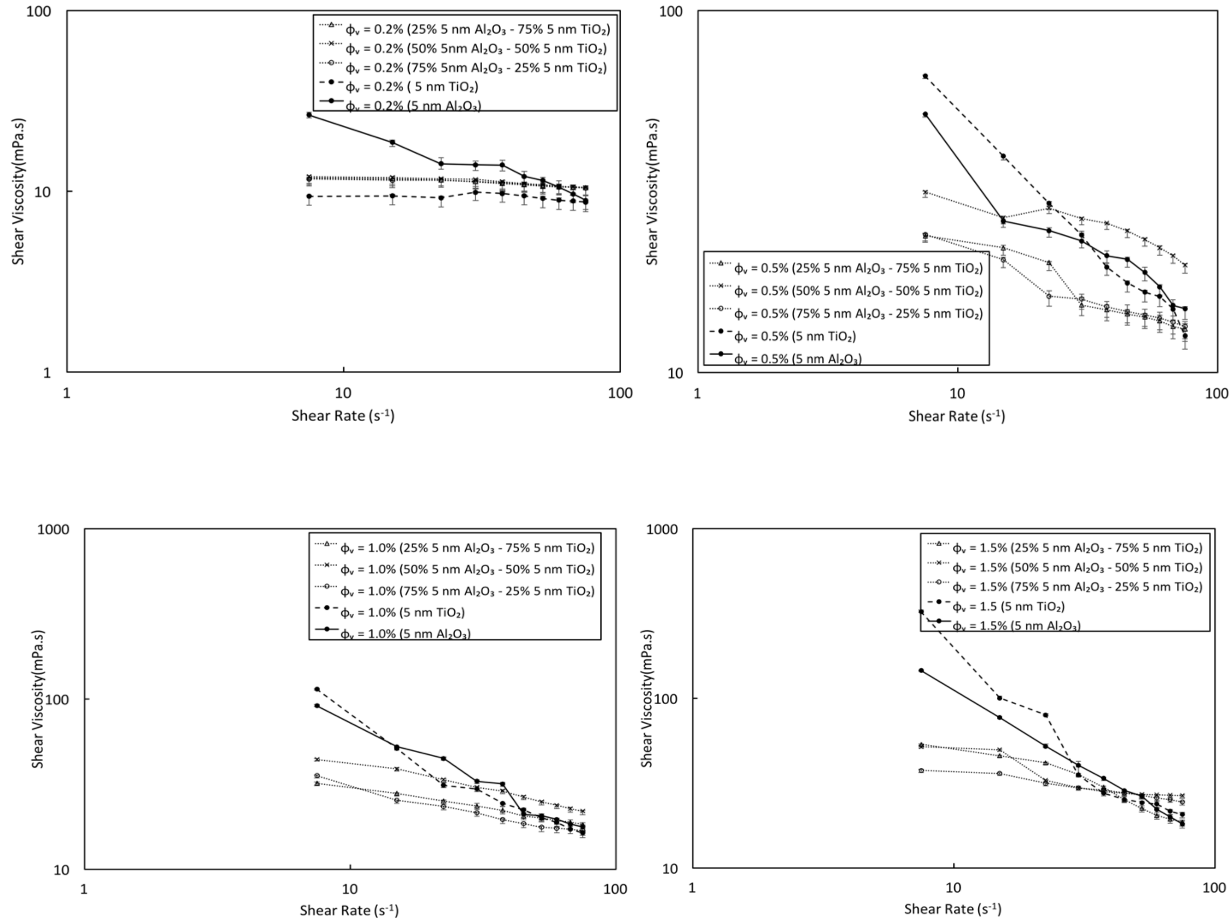

Figure 14: Shear viscosity vs shear rate of Al_2O_3, TiO_2 and hybrid nanofluids at individual volumetric concentration at 60°C

At 0.2% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 60 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 0.2% volumetric concentration at 25 °C and 40 °C which shows that the viscosity decreases with increasing temperature. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls between the single particle nanofluids, with the viscosity of Al_2O_3 nanofluid is at the top and TiO_2 nanofluid at the bottom. But at higher shear rates, the shear viscosity of hybrid nanofluids falls above the single particle nanofluids with (50% Al_2O_3 – 50% TiO_2) being at the top and TiO_2 being at the bottom.

Table 14

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.2% at 60 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =0.2% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	13.699	0.939	0.93551
φ_v =0.2% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	14.175	0.934	0.88929
φ_v =0.2% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	13.263	0.948	0.86429
φ_v = 0.2% (5 nm TiO_2)	10.233	0.972	0.26167
φ_v = 0.2% (5 nm Al_2O_3)	61.595	0.565	0.9699

The flow consistency index k is highest for Al_2O_3 nanofluid and least for TiO_2 and the value of k for hydrid nanofluids falls between the single particle nanofluids. However, the k values for mixtures are close to each other which shows that it does not need as much shear thinning as Al_2O_3 to get to 75 s^{-1}. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for TiO_2 and mixtures but the value of n goes down for Al_2O_3 which means the fluid is undergoing more shear thinning to get to 75 s^{-1}.

At 0.5 % volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 60 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 0.5% volumetric concentration at 25 °C and 40 °C which shows that the viscosity decreases with increasing temperature. Unlike 0.2% volumetric concentration at lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids, with the viscosity of TiO_2 nanofluid being at the top. But at higher shear rates, the shear viscosity of (25% Al_2O_3 – 75% TiO_2) & (75% Al_2O_3 – 25% TiO_2) falls between single particle nanofluids and (50% Al_2O_3 – 50% TiO_2) with the highest viscosity. It's observed that the viscosity of Al_2O_3, TiO_2 and its mixtures increased with the increase in volumetric concentration from 0.2% to 0.5%.

Table 15

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.5% at 60 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =0.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	44.891	0.711	0.93094
φ_v =0.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	46.04	0.846	0.94608
φ_v =0.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	46.735	0.82	0.85403
φ_v = 0.5% (5 nm TiO_2)	255.95	0.31	0.99194
φ_v = 0.5% (5 nm Al_2O_3)	114.29	0.531	0.92972

The flow consistency index k is highest for TiO_2 nanofluid and least for (25% Al_2O_3 – 75% TiO_2) nanofluid. However, the k values for mixtures are close to each other which shows that it does not need as much shear thinning as TiO_2 to get to 75 s^{-1}. The values of k for 0.5% volumetric concentration is higher than 0.2% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 0.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior shows significance for all the nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 60 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 1% volumetric concentration at 25 °C and 40 °C which shows that the viscosity decreases with increasing temperature. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids but at higher shear the (50% Al_2O_3 – 50% TiO_2) has the highest viscosity.

Table 16

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1% at 60 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =1% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	54.241	0.75	0.99409
φ_v =1% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	88.231	0.683	0.98527
φ_v =1% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	63.476	0.681	0.97797
φ_v = 1% (5 nm TiO_2)	473.93	0.2	0.96461
φ_v = 1% (5 nm Al_2O_3)	405.4	0.263	0.9788

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1% volumetric concentration is higher than 0.5% volumetric concentration and it's also observed that the slope of the curves gets steep going from 0.5% - 1% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not much significant for (50% Al_2O_3 – 50% TiO_2) nanofluid but the smaller value of n for the other nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1.5% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 60 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 1.5% volumetric concentration at 25 °C and 40 °C which shows that the viscosity decreases with increasing temperature. At lower shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids but at higher shear but at higher shear the (50% Al_2O_3 – 50% TiO_2) nanofluid has the highest viscosity.

Table 17

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1.5% at 60 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =1.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	174.46	0.494	0.93514
φ_v =1.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	100.19	0.674	0.87147
φ_v =1.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	58.162	0.804	0.97358
φ_v = 1.5% (5 nm TiO_2)	2873.4	-0.199	0.94486
φ_v = 1.5% (5 nm Al_2O_3)	868.24	0.106	0.99879

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1.5% volumetric concentration is higher than 1% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 1.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is significant for all the nanofluids with smaller values of n which means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

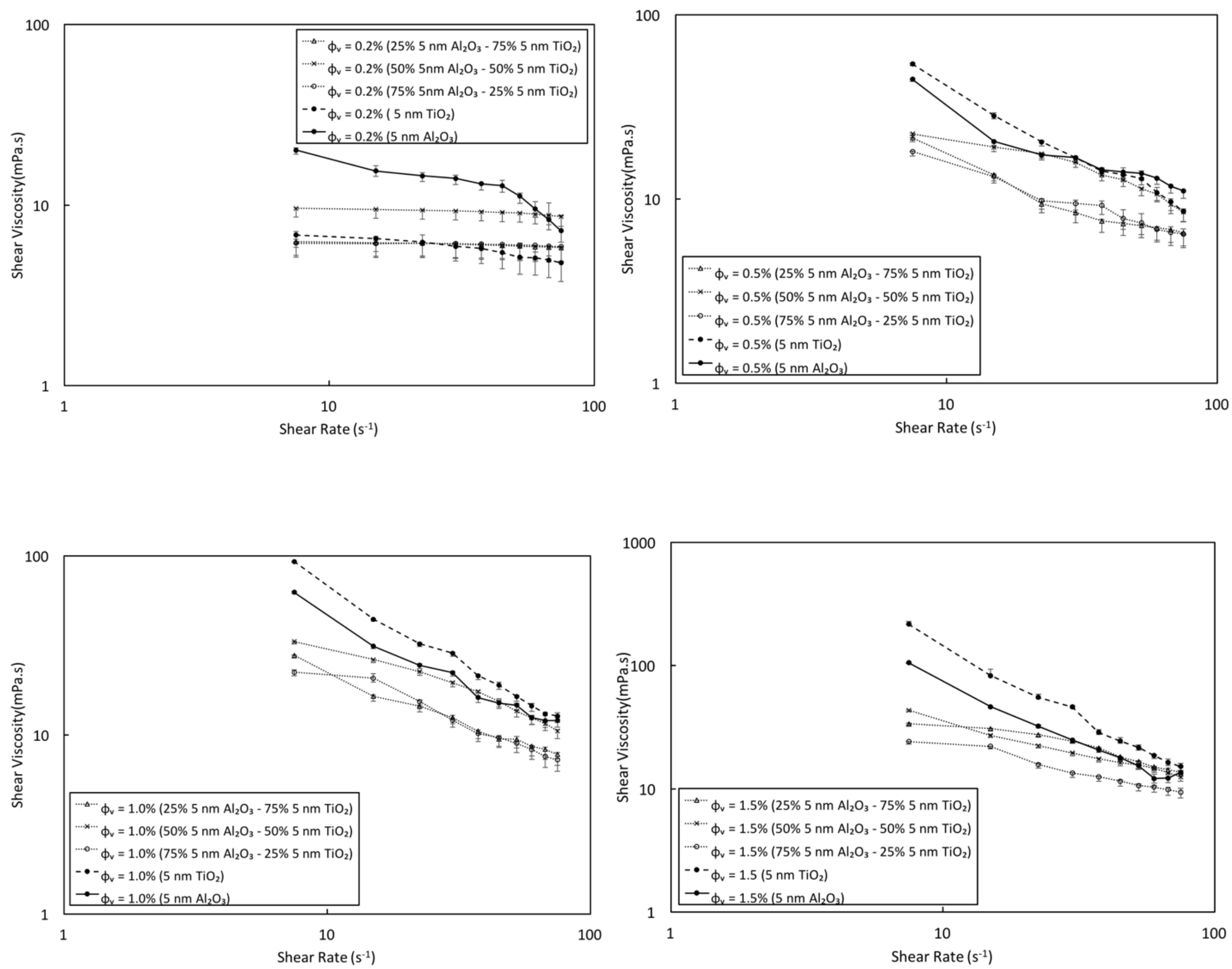

Figure 15: Shear viscosity vs shear rate of Al_2O_3, TiO_2 and hybrid nanofluids at individual volumetric concentration at 80°C

Now that we have seen how the change in shear rate and the change in volumetric concentration affects the shear viscosity of Al_2O_3 and TiO_2 nanofluids at a given temperature. Let's look at how the shear viscosity is affected over a range of shear rate at a given volumetric concentration for Al_2O_3, TiO_2 and its hybrid systems at 80 °C. Figure 15 illustrates the rheological behavior of single particle nanofluids and hybrid nanofluids at individual concentration at 80 °C.

At 0.2% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 80 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 0.2% volumetric concentration at 25 °C, 40 °C and 60 °C which shows that the viscosity decreases with increasing temperature. From the plots it's clear that the Al_2O_3 nanofluid has the highest viscosity.

Table 18

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.2% at 80 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =0.2% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	6.7901	0.965	0.9456
φ_v =0.2% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	10.625	0.957	0.88106
φ_v =0.2% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	6.4412	0.982	0.70459
φ_v = 0.2% (5 nm TiO_2)	9.9319	0.839	0.93743
φ_v = 0.2% (5 nm Al_2O_3)	47.542	0.612	0.85059

The flow consistency index k is highest for Al_2O_3 nanofluid and least for (75% Al_2O_3 – 25% TiO_2). However, the k values for TiO_2 and mixtures are close to each other which shows that it does not need as much shear thinning as Al_2O_3 to get to 75 s^{-1}. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is not significant for TiO_2 and mixtures but the value of n goes down for Al_2O_3 which means the fluid is undergoing more shear thinning to get to 75 s^{-1}.

At 0.5 % volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 80 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 0.5% volumetric concentration at 25 °C, 40 °C and 60 °C which shows that the viscosity decreases with increasing temperature. Unlike 0.2% volumetric concentration at both lower and higher shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids, with the viscosity of TiO_2 nanofluid being at the top at lower shear rate and Al_2O_3 nanofluid being at top at higher shear rate. It's observed that the viscosity of Al_2O_3, TiO_2 and its mixtures increased with the increase in volumetric concentration from 0.2% to 0.5%.

Table 19

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 0.5% at 80 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =0.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	51.403	0.501	0.93665
φ_v =0.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	59.399	0.52	0.93152
φ_v =0.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	43.549	0.553	0.98283
φ_v = 0.5% (5 nm TiO_2)	226.03	0.25	0.98754
φ_v = 0.5% (5 nm Al_2O_3)	101.96	0.478	0.91224

The flow consistency index k is highest for TiO_2 nanofluid and least for (75% Al_2O_3 – 25% TiO_2) nanofluid. However, the k values for mixtures are close to each other which shows that it does not need as much shear thinning as TiO_2 to get to 75 s^{-1}. The values of k for 0.5% volumetric concentration is higher than 0.2% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 0.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior shows significance for all the nanofluids means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 80 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 1% volumetric concentration at 25 °C, 40 °C and 60 °C which shows that the viscosity decreases with increasing temperature. At both lower and higher shear rates it's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids with TiO_2 nanofluid being at top.

Table 20

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1% at 80 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =1% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	75.756	0.468	0.9859
φ_v =1% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	101.77	0.494	0.97155
φ_v =1% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	76.413	0.459	0.96267
φ_v = 1% (5 nm TiO_2)	487.51	0.145	0.99365
φ_v = 1% (5 nm Al_2O_3)	235.99	0.289	0.97999

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1% volumetric concentration is higher than 0.5% volumetric concentration and it's also observed that the slope of the curves gets steep going from 0.5% - 1% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is significant for all the nanofluid with smaller value of n means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

At 1.5% volumetric concentration, a non-Newtonian shear thinning behavior is observed for Al_2O_3, TiO_2 and hybrid nanofluids. For 80 °C the plots shift down for Al_2O_3 and TiO_2 and its hybrid systems when compared with 1.5% volumetric concentration at 25 °C, 40 °C and 60 °C which shows that the viscosity decreases with increasing temperature. It's observed that the shear viscosity of hybrid nanofluids falls below the single particle nanofluids at both higher and lower

Table 21

Power law parameters as a function of volumetric concentration of Al_2O_3, TiO_2 and hybrid nanofluids at 1.5% at 80 °C

Nanoparticle type	K(Pa s^n)	n	R^2
φ_v =1.5% (25% 5nm Al_2O_3 - 75% 5nm TiO_2)	94.452	0.567	0.92282
φ_v =1.5% (50% 5nm Al_2O_3 - 50% 5nm TiO_2)	113.71	0.49	0.99039
φ_v =1.5% (75% 5nm Al_2O_3 - 25% 5nm TiO_2)	63.713	0.555	0.96917
φ_v = 1.5% (5 nm TiO_2)	2040.5	-0.148	0.99293
φ_v = 1.5% (5 nm Al_2O_3)	614.06	0.061	0.98175

The flow consistency index k is highest for TiO_2 nanofluid followed by Al_2O_3 nanofluid, both single particle nanofluids which shows that the single particle nanofluids has to undergo more shear thinning behavior than the hybrid nanofluids with the relatively small k value. The values of k for 1.5% volumetric concentration is higher than 1% volumetric concentration and it's also observed that the slope of the curves gets steep when compared to 1.5% volumetric concentration. Hence the nanofluids has to undergo more shear thinning, hence the high value of k. Smaller the value the n more shear thinning is the fluid, the shear thinning behavior is significant for all the nanofluids with smaller values of n which means the fluids is undergoing more shear thinning to get to 75 s^{-1}.

The viscosity of Al_2O_3 nanofluid is known, the viscosity of TiO_2 is known. Intuitively the viscosities of hybrid nanofluids should fall between the single particle nanofluids, but in each one of the above cases the viscosities of hybrid nanofluids are lying outside of the single particle nanofluids.

Power Law Analysis

Figure 16 illustrates the consistency index of single particle nanofluids and hybrid nanofluids as a function of temperature. Qualitatively the flow consistency index means the agglomeration forces between the nanoparticles and the basefluid. Results indicate that the consistency index of the nanofluids increases with increasing volumetric concertation, the reason may be due to increasing agglomeration forces and forming nanoclusters between the nanoparticles and the basefluid with increasing volumetric concentration. For the given volumetric concentration, the flow consistency index decreases with increasing temperature due to weakening of those forces as the temperature is increased. But the significance is not that important as it has been seen for the previous studies.

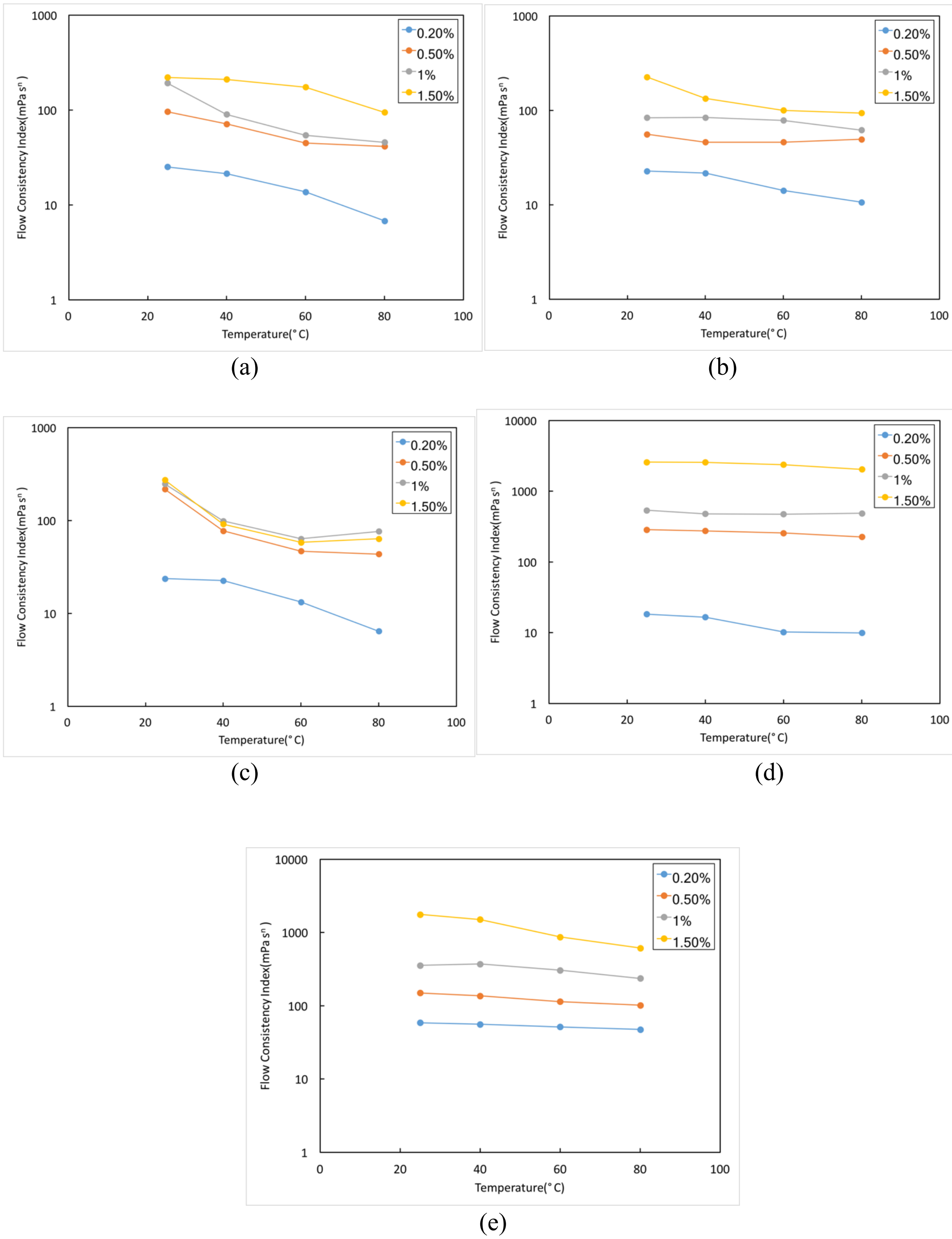

Figure 16: Consistency index as a function of temperature for (a) Al_2O_3, (b)TiO_2, (c) 25% Al_2O_3 - 75% TiO_2 (d) 50% Al_2O_3 - 75% TiO_2 and (e) 75% Al_2O_3 - 25% TiO_2 nanofluids

Comparison of Rheological Behavior of Al_2O_3, TiO_2 and Hybrid Nanofluids with Basefluid

The third approach is to see the viscosities of the single particle nanofluids and hybrid nanofluids are coming closer to the viscosity of the basefluid all together. Here the shear rate and the volumetric concentration are confined allowing the temperature to vary.

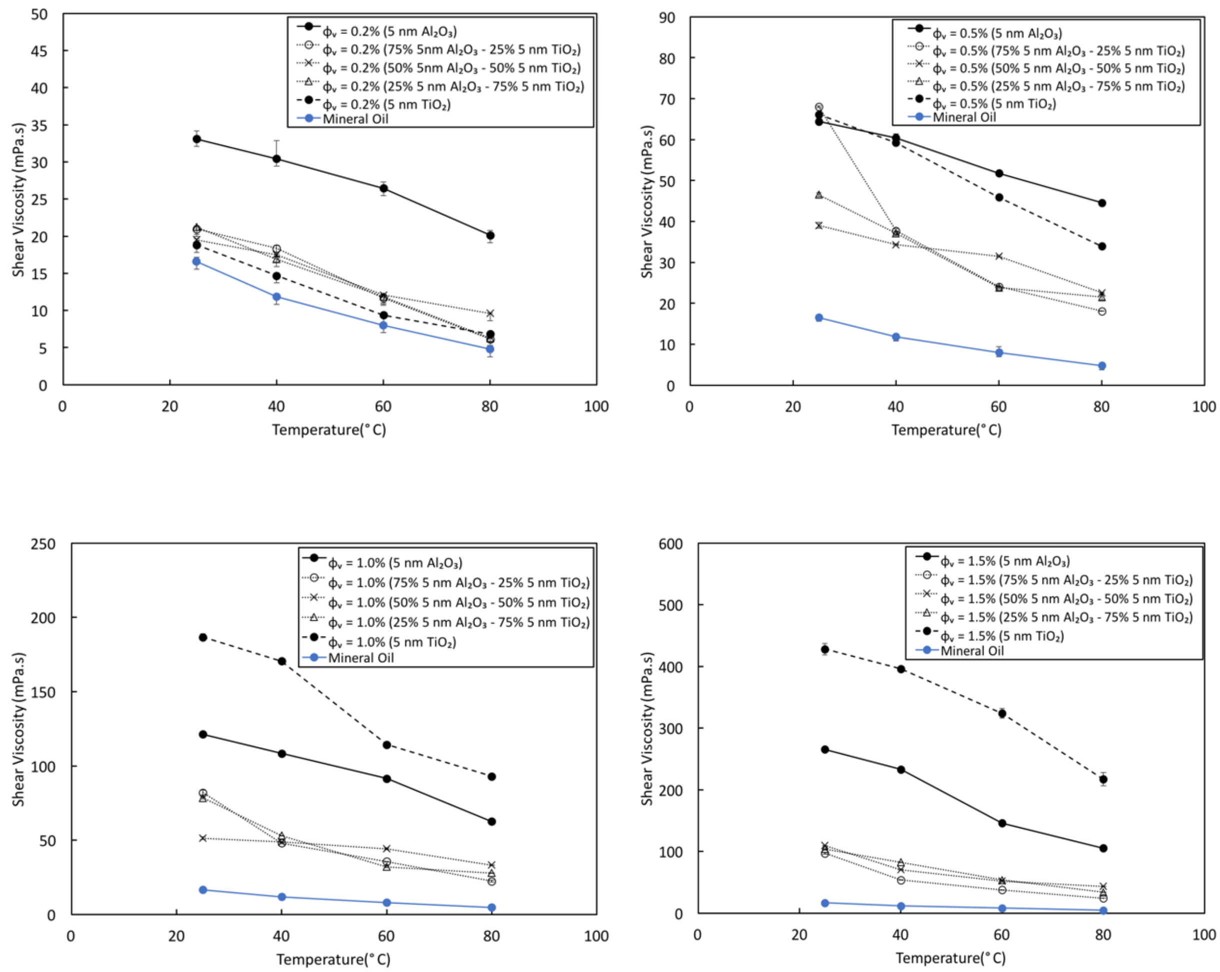

Figure 17: Shear viscosity vs temperature of Al_2O_3, TiO_2 and hybrid nanofluids at individual

For the matter of fact, it’s already known that the viscosity of the basefluid decreases with increasing temperature. A similar behavior is expected for the single particle nanofluids and hybrid nanofluids. At 7.5 s^{-1} shear rate there is a decrease in viscosity with increasing temperature for both the single particle nanofluids and hybrid nanofluids along with basefluid mineral oil at all the volumetric concentrations. As the volumetric concentration is increased its observed that the viscosity of the hybrid nanofluids coming closer to the viscosity of the basefluid at all the temperatures which very well convinces the initial assumption the viscosities of either the single particle nanofluids or the hybrid nanofluids going closer to the viscosity of basefluid.

At 75 s^{-1} shear rate, a similar trend is observed where the viscosity of single particle nanofluids and hybrid nanofluids along with the basefluid going down with temperature for all volumetric concentrations. As the volumetric concentration is increased its observed from Figure18 that the viscosity of the hybrid nanofluids coming closer to the viscosity of the basefluid only at higher temperatures and the behavior is not as consistent as it was seen for 7.5 s^{-1}.

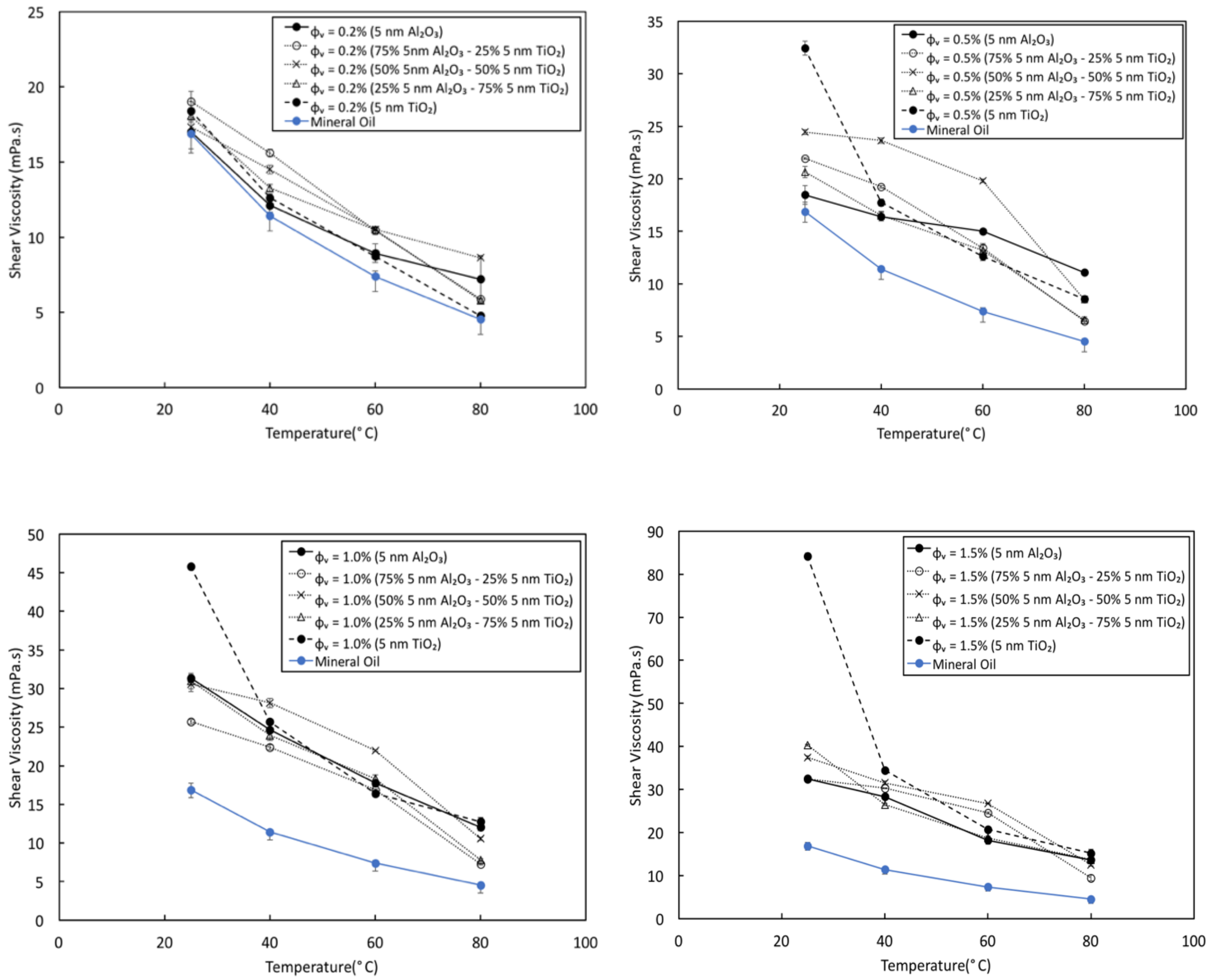

Figure 18: Shear viscosity vs temperature of Al_2O_3, TiO_2 and hybrid nanofluids at individual volumetric concentration at shear rate 75 s^{-1}

CHAPTER 5

CONCLUSIONS

- There are some cases where the viscosity of hybrids is closer to the viscosity of basefluid. 0.5%(25% 5 nm Al_2O_3 – 75% 5nm TiO_2), 0.5%(50% 5 nm Al_2O_3 – 50% 5nm TiO_2), 0.5%(75% 5 nm Al_2O_3 – 25% 5nm TiO_2), 1%(25% 5 nm Al_2O_3 – 75% 5nm TiO_2), 1%(50% 5 nm Al_2O_3 – 50% 5nm TiO_2), 1%(75% 5 nm Al_2O_3 – 25% 5nm TiO_2), 1.5%(25% 5 nm Al_2O_3 – 75% 5nm TiO_2), 1.5%(50% 5 nm Al_2O_3 – 50% 5nm TiO_2), and 1.5%(75% 5 nm Al_2O_3 – 25% 5nm TiO_2) at 7.5 s^{-1} shear rate has viscosity closer to the viscosity of basefluid.
- There are some mixtures of the hybrids that maintained the Newtonian characteristics at a particular concentration. 0.2%(25% 5 nm Al_2O_3 – 75% 5nm TiO_2), 0.2%(50% 5 nm Al_2O_3 – 50% 5nm TiO_2), and 0.2%(75% 5 nm Al_2O_3 – 25% 5nm TiO_2) at 25 °C, 40 °C, 60 °C and 80 °C exhibits Newtonian behavior, which is desirable.
- High viscosity of nanofluid is due to the formation of nano-clusters, these nano-clusters resist the flow of one layer of the fluid over another thereby increasing the viscosity of the basefluid.

CHAPTER 6

FUTURE WORK

- Nanoparticles with different sizes can be considered for the interaction. The interaction between nanoparticles of different sizes and the overall interaction with the basefluid can change the rheological behavior of the nanofluid.
- Zeta potential and size of the nanoparticles estimation through Zetasizer. The size of particles in suspension is not essentially the size of the particles used to make up the suspension. Determining the size of particles in the suspension helps to detect any tendency towards aggregation under in-use conditions. Zeta potential is directly related to electrostatic stability which provides the information that is needed to optimize the effect of charge in a suspension (Malvern Panalytical).

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