Effect of Temperature, Concentration and Aggregation on the Rheological Behavior of ZrO_2 – Avocado Oil Nanolubricant

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ABSTRACT

The paper investigates the effect of dispersed ZrO_2 nanoparticles on the rheological behavior of avocado oil. ZrO_2 nanoparticles are added in three weight percentages and their effect on viscosity is measured on Anton par's MCR 102 in accordance with DIN EN ISO 3219 international standard. The shear rates and temperatures are varied from 500 - 4000 s^{-1} and 40-100 $^{\circ}C$ respectively. The effect of low temperatures (20 $^{\circ}C$ to -20 $^{\circ}C$) on the viscosity of oil is also evaluated designating the pour point and cloud point of the avocado oil. The addition of nanoparticles increases the viscosity of avocado oil and preserves the Newtonian behavior of oil at all particle fractions and temperatures. The Newtonian behavior of avocado oil and the nanolubricants are quantified by the Ostwald-e-Waale power law equation. The measured values of viscosity are correlated with the existing theoretical viscosity models and a disagreement between the two is observed.

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1. INTRODUCTION

Automotive tribology is one of the concerns in today's era and sustainable lubrication is an important part of it. Petroleum-based oils are non-replenishable sources of energy that are depleting continuously. Further, mineral oils release harmful elements in the environment resulting in ecological degradation. Hence, mineral oils need to be replaced by sustainable lubricants. Bio-oils are emerging as potential substitutes for petroleum-based lubricants. Bio-oil possesses excellent thermo-physical

(viscosity, viscosity index, and flashpoint) and biodegradable (non-toxicity) properties [1]. Fatty acid composition plays an important role in determining the effectiveness of bio-oils as a lubricant. There are two types of fatty acids present in bio-oils: Saturated fatty acids and Unsaturated fatty acids. Unsaturated fatty acids include monounsaturated fatty acids that contain a single double bond and polyunsaturated fatty acids that contain two or more double bonds in their fatty acid chain. Saturated fatty acids are associated with excellent tribological and oxidative properties. However, these fatty acids

also result in poor low-temperature properties. Polyunsaturated fatty acids possess excellent low-temperature properties like pour point but undergo oxidation easily. As a result, oils with a higher percentage of monounsaturated fatty acids are considered ideal for lubrication. The paper introduces a new biolubricant - Avocado oil, for lubrication purposes. The oil is selected owing to its high content of monounsaturated fatty acids that makes it suitable for lubrication in automobiles [2]. Avocado oil contains 65-68 % monounsaturated fatty acids, 16-20 % polyunsaturated fatty acids and 14-16 % saturated fatty acids. The major producer of avocado oil in the world is Mexico followed by Dominican Republic, Peru, Indonesia, and Colombia. Avocado oil is extracted by different chemical and mechanical methods. Various properties of avocado oil are shown in Table 1.

Table 1. Physical properties of avocado oil.

Properties	Measurements
Viscosity @ 40 °C (mPa.s)	38.5
Viscosity index	252
Density (g/cm ³)	0.902
Pour point (°C)	-3
Cloud point (°C)	-0.18

Nanolubrication has emerged as a potential remedy for the existing problems of energy conservation [3,4]. Nanoparticles dispersed in oil greatly improve the thermal and tribological properties of lubricants. The addition of nanoparticles in lubricants leads to higher cooling rates increasing the effectiveness of lubricants [5]. The increase in heat transfer of fluids is attributed to the increase in thermal conductivity, surface area, and collision between particles, thereby, accelerating the heat transfer. Further, the nanoparticles improve the friction and wear characteristics of lubricant, contributing to the resource conservation [6-9]. Tijerina et al. [10] investigated the tribological and thermal properties of natural oils (soybean oil, corn oil, and sunflower oil) mixed with metal oxide nanoparticles. It is observed that the introduction of SiO₂ nanoparticles increases the thermal conductivity of soybean oil and sunflower oil by approximately 11 %. Further, a decrease in the coefficient of friction is also

observed with all the natural oils. Diabb et al. [11] investigated the tribological properties of sunflower oil and corn oil mixed with varying concentration of SiO₂ nanoparticles for sheet forming process. It is observed that 0.025 wt.% SiO₂ concentration is most effective in improving the antiwear properties of oils. The mass loss for corn oil and sunflower oil decreases from 0.215 mg and 0.210 mg respectively to 0.015 mg and 0.035 mg respectively.

The addition of nanoparticles also affects the viscosity of the fluids. Viscosity is an important property of a lubricant. It plays an important role in the formation of specific film thickness and also has an impact on pumping efficiency [12]. The effect of nanoparticles on the rheological properties of conventional lubricants has been investigated by various researchers [13-15]. Some studies also have been dedicated to the rheological properties of sustainable lubricants. Sajeeb and Kumar [5] investigated the effect of concentration of hybrid nanoparticles (CeO₂-CuO) on the viscosity of coconut oil. The hybrid nanoparticles in varying concentrations of 0 wt.% to 1 wt.%. The viscosity is determined for a temperature range of 30–90 °C with shear rates varying from 1-500 1/s. It is observed that the coconut oil and nanofluids depict non-Newtonian behavior at very low shear rates of 6-15 s⁻¹ whereas, the flow behavior changes to Newtonian behavior for the higher shear rates. Further, an increase in the viscosity is observed with an increase in the particle concentration with 1 wt.% depicting the highest increase in the viscosity. Padmini et al. [16] mixed MoS₂ nanoparticles with different vegetable oils viz, coconut oil, sesame oil, and canola oil and investigated the rheological and tribological properties at different particle concentrations. The nanoparticles are added in varying concentrations of 0-1 wt.%. It is observed that the viscosity of all the oils increases with an increase in concentration. However, the percentage increase in viscosity for different oils is different. The maximum viscosity for all the oils i.e. coconut oil, sesame oil, and canola oil are observed at a temperature of 30 °C and 1 wt.% concentration, and is equal to 0.592 cm²/s, 0.54 cm²/s, and 0.581 cm²/s respectively. Mechiri et al. [17] made a comparative study of rheological study between petroleum-based oils and vegetable

oil mixed with Cu-Zn nanoparticles. The hybrid nanoparticles (Cu-Zn) are prepared in three different ratios i.e. 50:50 75:25 and 25:75. The nanoparticles are added in three volume fractions (0.1, 0.3 and 0.5) and are less than 25 nm in size. It is observed that both the base oil and nanofluids depict Newtonian behavior. Further, the increase in viscosity with an increase in particle volume fraction is attributed to the aggregation of nanoparticles and material properties. The maximum increase in the viscosity is observed with Cu-Zn of 50:50 ratio as greater aggregation effects are observed at this hybrid concentration.

Metal oxide nanoparticles are the most commonly used nanoparticles in nanolubrication. About 26 % of the nanolubrication studies are based on metal oxides [18]. ZrO₂ nanoparticles possess excellent chemical stability, hardness, crystallinity, and corrosion resistance as compared to the other metal oxides. ZrO₂ nanoparticles can be synthesized by various cost-effective physical, chemical (sol-gel method, hydrothermal methods, precipitation methods, etc) and biological synthesis methods. The cost-effective synthesis of ZrO₂ nanoparticles has been reported by various researchers [19,20]. The introduction of ZrO₂ nanoparticles improves the life of machines, contributing to the energy-saving, and surpassing its expenses. The effect of ZrO₂ nanoparticles on the rheological and tribological properties of lubricating oils have been reported by various studies [21-27]. Philip et al. [28] investigated the tribological and thermophysical properties of coconut oil mixed with hybrid nanoparticles (Ce-Zr). It is observed that hybrid nanoparticles improve the tribological properties of oil by rolling and protective film mechanism. Further, an increase in the viscosity index, flash point, and fire point of the bio-oil is also observed with the addition of hybrid nanoparticles. Abdullah et al. [29] introduced surfactant modified ZrO₂-graphite nanoparticles in waste cooking oil. It is observed that ZrO₂-graphite nanoparticles in 0.1:0.3 vol.% are most effective in improving the tribological properties of oil. The minimum frictional coefficient and wear scar diameter at 0.1:0.3 vol.% is equal to 0.0507 and 576 µm respectively.

The paper deals with the effect of different concentrations of ZrO₂ on the rheological properties of avocado oil. The variation of viscosity and shear stress with varying shear rate and temperature is measured. The effect of ZrO₂ on flow behavior is further established. Low-temperature properties of the oil are also investigated.

2. MATERIALS AND METHODS

ZrO₂ nanoparticles are procured from Nanoshel Ltd. The physical properties of nanoparticles are shown in Table 2. The shape and size of nanoparticles are characterized by X-ray diffraction (XRD) and high-resolution transmission electron microscopy (HRTEM). ZrO₂ are introduced in avocado oil in three different weight percentages i.e. 0.5, 1, and 1.5 %. Weight fractions are changed to volume fraction using equation (1). The uniform mixing of nanoparticles in avocado oil is achieved with the help of ultrasonication. Ultrasonication is carried out for 6 hours and the stability of nanoparticles is examined visually and by UV-visible spectrometer. Nanoparticles appear stable for a day after which sedimentation of particles is observed.

$$\text{Volume fraction } (\phi) = \frac{\frac{W_n}{\rho_n}}{\frac{W_n}{\rho_n} + \frac{W_o}{\rho_o}} \quad (1)$$

Where W_n, W_o represent the weight of nanoparticles and base oil, and ρ_n, ρ_o represent the density of nanoparticles and the density of oil respectively. Weight percentage fractions of 0.5 wt.%, 1 wt.% and 1.5 wt.% corresponds 0.00072, 0.0014 and 0.00201 particle volume fraction respectively.

Table 2. Material Properties.

Material Nanoparticles	Average Particle Size (nm)	Purity	True density (g/cm ³)	Melting point (°C)
ZrO ₂	45	99.9 %	5.68	2715

The rheological investigation of avocado oil is performed on Anton par's modular compact rheometer (MCR 102) as shown in Fig. 1a. The major components of the MCR 102 are: 1) EC motor with air bearings 2) Normal force sensor and 3) Optical encoder. EC motor helps in the generation of torques up to 200 mNm whereas

the minimum torque measured by the MCR 102 is equal to 5 mNm. Also, the precise measurement and control at low speeds is ensured by a linear relationship between the input stator current and electromagnetic torque. Two types of air bearings are present in the MCR 102 viz. Radial bearing and Axial bearing. The radial bearing aids in the stabilization and alignment of the geometry and the axial bearing sustains the weight of rotating components. The normal force sensor measures the normal force by converting the minute deflections in the bearing to the respective normal forces using an electric capacity method. MCR 102 can measure normal forces ranging from 0.01 N to 50 N. The optical encoder ensures the measurement of angular deflection from $0.5 \mu\text{rad}$ to ∞ , thereby, leading to accurate measurement even in weak structures. The geometry employed for viscosity measurement is cone and plate arrangement with a cone angle of 1° as shown in Fig. 1b. The diameter of the upper rotating plate is 40 mm and provides the varying shear rates to the lubricant. The lower plate is stationary and varies the temperature under different conditions. The variation in temperature at the plate surface is governed by the Peltier effect that increases the effectiveness of measurements. The cone plate geometry is in agreement with DIN EN ISO 3219 international standard. The rheological behavior of nanofluids is investigated at varying shear rates ($500\text{--}4000 \text{ s}^{-1}$) and varying temperatures of 40°C , 70°C , and 100°C . The low-temperature properties are also evaluated from 20°C to -20°C implying the flowability of lubricants at extreme temperatures. The rheological investigation of all the samples is carried out three times, and then the mean of the measurements is depicted in Fig. 1.

(a)

Fig 1. (a) Anton Pars Modular Compact Rheometer 102, (b) Cone and plate arrangement.

The aggregation effects of nanoparticles are observed on Anton Par's Litesizer 500. Litesizer measures the particle size of dispersed nanoparticles using a dynamic light scattering method (DLS). The measurement of average particle size by Litesizer depends on the amount of light scattered by the particles moving randomly in the oil. The small-sized particles move with greater speeds as compared to the larger particles yielding different scattering rates. The amount of light scattered by the particles is recorded for a particular period, consequently, computing the average size of the nanoparticles in oil. Further, a comparative study is performed between the measured data and the already existing viscosity models.

3. RESULTS AND DISCUSSION:

3.1 Characterization of ZrO_2 nanoparticles

The shape, size, and crystalline structure of ZrO_2 nanoparticles are obtained by XRD and HRTEM techniques shown in Figure 2. XRD results depict monoclinic structure with $\alpha=\gamma=90^\circ$ and $\beta=99.2197^\circ$. The lattice constants are given as $a = 5.1419 \text{ \AA}$, $b = 5.2057 \text{ \AA}$ and $c = 5.3096 \text{ \AA}$. The shape and size of ZrO_2 nanoparticles are further evaluated by HRTEM. It is observed that the size of the nanoparticles varies from 30-60 nm with an average particle size of around 45 nm. Nanoparticles also appear nearly spherical in shape.

Fig. 2. Characterization of ZrO_2 nanoparticles (a) XRD, (b) HRTEM.

Fig. 3. UV Visible spectroscopy of nanolubricant.

UV visible spectroscopy indicates the sedimentation of nanoparticles over a period of

time. Figure 3 indicates the absorbance of nanoparticles in avocado oil. It is observed that the absorbance of nanoparticles increases greatly indicating the presence and dispersion of nanoparticles in oil. Further, the absorbance values decrease with an increase in the time (24 hours), designating the partial sedimentation of nanoparticles. DLS measurements of nanolubricant samples indicate that the particles have agglomerated with the percentage increase in the concentration of ZrO_2 nanoparticles.

Fig. 4. DLS measurements of nanofluids at different particle concentrations.

Figure 4 shows the DLS measurements at 0.5 wt.%, 1 wt.%, and 1.5 wt.% with maximum peaks at 170 nm, 281 nm, and 497 nm respectively. The hydrodynamic diameter of aggregates at 0.5 wt.% and 1 wt.% is equal to 196 nm and 353 nm respectively.

3.2 Rheological studies

3.2.1 Effect of particle volume concentration

Figure 5 depicts the effect of ZrO_2 nanoparticles on the viscosity of avocado oil. It is observed that the increase in particle volume fraction increases the viscosity of avocado oil. The increase in viscosity is observed at all temperatures of 40 °C, 70 °C, and 100 °C. The percentage increase in the dynamic viscosity at different temperatures is shown in Table 3. It is observed that 0.2 φ% brings maximum increment in the dynamic viscosity equal to 6 %, 10.9 %, and 9.8 % at 40 °C, 70 °C, and 100 °C respectively. The increase in viscosity with increasing particle volume fraction is attributed to the increased loading of nanoparticles.

Table 3. Percentage increment in the viscosity of oils.

Oil	Temperature (°C)	0.5 wt. %	1 wt. %	1.5 wt. %
	40.00	2.08	4.2	6
Avocado	70.00	4.7	8.65	10.9
	100.00	2.8	5.8	9.8

Fig. 5. Variation of dynamic viscosity with varying particle concentration at different temperatures.

The ZrO_2 nanoadditives rest in between the oil layers and prevent the movement of oil layers. This phenomenon is further enhanced by substantial aggregation of nanoparticles due to the greater number of solid particles. The movement of the particles in the oil is governed by the Brownian motion. Brownian motion brings the random surrounding nanoparticles close to each other. As a result, nanoparticles get attracted to their surrounding nanoparticles by intermolecular forces (Van der Waal) and result in the formation of aggregates. Consequently, a higher concentration of particles leads to larger aggregates as greater number of particles collide with each other due to the Brownian motion. The increase in the aggregate size of nanoparticles at various concentrations is observed in Fig. 4. The aggregation leads to the augmentation of shear resistance, thereby, increasing the dynamic viscosity of the oil. Similar aggregation effects are reported by various investigations [22,30,31] and it is concluded that an increase in particle concentration increases the viscosity of the oil.

3.2.2 Flow behavior – variation of viscosity and shear stress with shear rate

The variation of viscosity with varying shear rates at different temperatures is depicted in Fig. 6. It is observed that the dynamic viscosity of avocado oil and avocado oil mixed with nanoadditives at all particle volume fractions remains fairly constant with an increase in shear rate. The independent relationship between the shear rate - viscosity signifies the Newtonian flow behavior. The reason for the constant shear rate - viscosity is that there is no chance of shear restructuring of fluid molecules at higher shear rates, consequently, no impact of shear rate on the dynamic viscosity is observed [5].

Figure 7 depicts the variation of shear stress with the shear rate at a temperature of 70 °C. It is observed that shear stress increases linearly with shear rate and maximum shear stress is observed at higher particle volume fractions. Also, the linear relationship between the shear stress and the shear rate is maintained with the addition of nanoparticles. Similar trends are observed at temperatures of 40 °C and 100 °C. This linear relationship indicates the Newtonian behavior of the base oil and nanolubricant. Further, the flow behavior of the base oil and nanolubricant is quantified using Ostwald-e-Waale power law equation as given by equation (2):

$$\tau = k \cdot \dot{\gamma}^n \quad (2)$$

where τ represents shear stress (Pa.), n represents power law index, $\dot{\gamma}$ represents shear strain (s^{-1}), and k = consistency index. The value of n determines the Newtonian and non-Newtonian behavior of lubricants where $n < 1$ indicates shear thinning, $n = 1$ represents Newtonian behavior, and $n > 1$, represents shear thickening of lubricant. It is observed from Table 4 that the power law index for base oil and nanolubricants at all concentrations and temperatures is very close to 1 confirming the Newtonian behavior of avocado oil. It is concluded that the addition of nanoparticles does not impact the flow behavior of oil which is highly desirable for the lubrication of tribo-pairs. The Newtonian behavior of lubricants is an important factor governing the effectiveness of lubricants as shear thinning can affect the lubrication regime at the tribopairs and shear thickening implies the decrease in pumping efficiency.

Fig. 6. Variation of dynamic viscosity with shear rate at different temperatures.

Fig. 7. Variation of shear stress with the shear rate at 70 °C with varying particle concentration.

Table 4. Power law index calculations.

Type of oil	Temperature (°C)	Consistency index (k)	Power law index (n)
Avocado oil	40	0.0396	0.996
	70	0.0181	0.983
	100	0.0088	1.005
Avocado oil + 0.07 φ % ZrO ₂	40	0.04	0.9975
	70	0.0152	1.013
	100	0.00908	1.005
Avocado oil + 0.14 φ % ZrO ₂	40	0.0412	0.996
	70	0.0192	0.987
	100	0.00913	1.008
Avocado oil + 0.201 φ % ZrO ₂	40	0.0444	0.9902
	70	0.01967	0.987
	100	0.0111	0.9895

3.2.3 Relationship between viscosity and temperature

Figure 8 depicts a decrease in the viscosity of avocado oil with an increase in the temperature for avocado oil. Also, it is observed that the dynamic viscosity of all the nanolubricants follows a similar trend i.e. maximum viscosity is observed at 40 °C and minimum at 100 °C.

Fig. 8. Variation of dynamic viscosity with the temperature at 2250 S⁻¹.

The viscosity decreases by 76 %, 75.9 %, 75.7 % and 75.3 % with avocado oil, avocado oil + 0.07 φ %, avocado oil + 0.14 φ % and avocado oil + 0.201 φ % respectively from 40 °C to 100 °C. The viscosity of a liquid is a property that arises due to the intermolecular forces (Van der Waals) between the oil molecules. The reduction in the viscosity from 40 °C to 100 °C is attributed to the decrease in Van der Waal forces between the oil molecules at higher temperatures [13]. The measurement of viscosity at 40 °C and 100 °C designates the viscosity index of the oil. The viscosity index of avocado oil is calculated as per ASTM 2270 standard and emerges to be 252 which is much greater than the petroleum-based mineral oils. This indicates better resistance of avocado oil to the rise in temperature and is a confirmation to the better rheological properties of avocado oil.

4. CORRELATION BETWEEN EXPERIMENTAL AND THEORETICAL VISCOSITY MODELS

Numerous theoretical viscosity models have been reported in the literature for determining the effect of suspended particles in a fluid. The

earliest theoretical viscosity model of suspensions is given by Einstein as shown in equation (3):

$$\eta_r = 1 + 2.5\phi \quad (3)$$

where, η_r represents the relative viscosity. Relative viscosity is defined as the ratio between the dynamic viscosity of nanofluid (μ_{nf}) to dynamic viscosity of base oil (μ_{bf}) specifying the increase in viscosity by the addition of particles. It was observed that Einstein's model is acceptable for fluids suspended with low particle volume fractions ($\phi < 0.02$). As a result, Brinkman [32] modified Einstein's model to make it applicable for fluids with medium particle volume fractions and is given by equation (4):

$$\eta_r = \frac{1}{(1 - \phi)^{2.5}} \quad (4)$$

Batchelor [33] introduced the viscosity model for higher particle fractions where the particle volume fraction is greater than 0.01 but less than 0.1. The theoretical model is valid for suspensions where interaction between particles are immense and is given by equation (5):

$$\eta_r = 1 + 2.5\phi + 6.5\phi^2 \quad (5)$$

Chong et al., [34] also developed a viscosity model for uniformly sized spherical particles and is given by equation (6):

$$\eta_r = \left[1 + \frac{0.75 \frac{\phi}{\phi_m}}{1 - \frac{\phi}{\phi_m}} \right]^2 \quad (6)$$

Other viscosity models for calculating the effect of particles are:

Cheng et al.

$$\eta_r = 1 + 2.5\phi + (2.5\phi)^2 + (2.5\phi)^3 \quad (7)$$

Wang et al., [35]

$$\eta_r = 1 + 7.3\phi + 123\phi^2 \quad (8)$$

Kitano et al., [36]

$$\eta_r = \left[1 - \left[\frac{\phi}{\phi_m} \right] \right]^{-2} \quad (9)$$

ϕ_m represents the maximum packing volume fraction and is taken as 0.605 for higher shear rates. No significant model has been yet developed for particle volume fraction greater 0.1 as the complexity is increased by the multi-particle

collisions. Table 5 represents the correlation between the measured and theoretical viscosity values. It is observed that the measured relative viscosity values are not in agreement with the theoretical models at all temperatures and concentrations as deviation keeps increasing at higher concentrations. This can be attributed to the dependence of viscosity on various parameters like operating temperature, agglomeration, shape, and size of nanoparticles.

Table 5. Correlation of viscosity between theoretical models and measured values at different temperatures and particle concentrations.

Nano fluids	Theoretical Relative viscosity						Experimental relative viscosity		
	Einstein	Brinkman	Batchelor	Kitano	Cheng	Chong	40 °C	70 °C	100 °C
Avocado oil + 0.07 ϕ %	1.0018	1.0018	1.0018	1.002	1.0018	1.0017	1.0208	1.047	1.028
Avocado oil + 0.14 ϕ %	1.0035	1.0035	1.0035	1.005	1.0035	1.0035	1.042	1.086	1.058
Avocado oil + 0.201 ϕ %	1.005	1.005	1.0053	1.007	1.005	1.005	1.06	1.109	1.098

The effect of agglomeration of nanoparticles on the viscosity of oil is correlated and studied by modified Krieger-Dougherty equation [30] and is given by equation 10:

$$\eta_r = \left[1 - \frac{\phi}{0.5} \left(\frac{a_a}{a} \right)^{3-D} \right]^{-[\eta]\phi_m} \quad (10)$$

Where, a_a represents aggregate radii, a represent radii of primary nanoparticles and D represents fractal index and is taken as 1.8 for spherical particles. The aggregate size observed from the DLS measurement is equal to $a_a = 4.3 a$, $a_a = 7.8 a$ and $a_a = 14.6 a$ at 0.5 wt.%, 1 wt.%, and 1.5 wt.% respectively. It is observed that the theoretical measurements from the modified Krieger-Dougherty model are in good agreement with the DLS measurements at lower concentrations of 0.5 wt.% and 1 wt.% as shown in Table 6. This implies that aggregation is an important contributing factor in the increase of viscosity.

Table 6. Correlation coefficient between modified Krieger-Dougherty model and experimental values.

S.no	Concentration (ϕ)	Modified Krieger-Dougherty	Relative error (%)		
			40 °C	70 °C	100 °C
1.	0.00072	1.012	0.87	3.4	1.6
2.	0.0014	1.052	0.95	3.2	0.57

Sajeeb and Rajendrakumar [5] proposed a relation for biolubricant mixed with oxide nanoparticles given by:

$$\mu_{nf} = \mu_{bf}(1 + A * \phi - B * \phi^2) \quad (11)$$

It is observed that avocado mixed with ZrO_2 nanoparticles follows a quadratic polynomial equation with different empirical constants. The difference in the empirical constants is due to differences in nature, size, density, and agglomeration of oxide nanoparticles. The empirical constants 'A' and 'B' with correlation coefficient (R^2) for the avocado oil mixed with ZrO_2 nanoparticles are depicted in Table 7.

Table 7. Empirical constants and correlation coefficient for the newly developed model.

Temperature (°C)	A	B	R^2
40	28.57	-808.9	0.999
70	77.42	11463	0.997
100	28.54	-9912.2	0.996

5. LOW-TEMPERATURE PROPERTIES

The variation of viscosity at low temperatures governs the pour point of lubricants. Pour point governs the flowability, thereby affecting the pumpability of oil at low temperatures [37].

Fig. 9. Effect of low temperatures (20 °C to -20 °C) on the dynamic viscosity of oil at varying particle concentrations.

Fig. 10. Variation of low-temperature properties at varying particle concentrations.

Figure 9 depicts the variation of viscosity from varying temperatures of 20 °C to -20 °C. It is observed that the viscosity of oil increases gradually up to -3 °C and then rises rapidly afterward. This marks the pour point of avocado oil after which the oil starts losing its flow characteristics. The addition of nanoparticles has a minimal effect on pour point, decreasing the pour point to -2.8 °C at 0.07 ϕ %. A similar pour point is observed for the rest particle volume

fractions as observed from Fig. 10. Further, the effect of nanoparticles on the cloud point of the oil is also shown in Fig. 10. It is observed that the cloud point of oil slightly decreases with the addition of nanoparticles. The cloud of base oil decreases from -0.18 °C to 1.28 °C at 0.07 ϕ % after which the cloud point remains nearly constant. It is concluded that the addition of nanoparticles has a minimal effect on the pour point and cloud point of the oil.

6. CONCLUSION

The paper reports the effect of ZrO₂ nanoparticles on the dynamic viscosity of avocado oil. The base oil and the nanolubricants exhibit Newtonian behavior at varying shear rates and temperatures. Further, the addition of nanoparticles increases the dynamic viscosity of oil with 1.5 wt.% exhibiting a maximal increase in viscosity. DLS measurements indicate that the nanoparticles agglomerate with an increase in the particle concentration and play an important role in increasing the viscosity. The low-temperature measurements indicate that the oil starts losing its flowing characteristics at a temperature of -3 °C.

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