



RHEOLOGICAL CHARACTERISTICS OF ALUMINIUM OXIDE (AL₂O₃) BASED NANOLUBRICANT

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ABSTRACT

This paper presents the rheological measurement of aluminium oxide (Al₂O₃) nanolubricant. The nanolubricant was prepared using the two-step method from dry Al₂O₃ nanoparticles and Capella D lubricant as base fluid. The dynamic viscosity of the Al₂O₃ nanolubricant at constant shear rate was measured at atmospheric pressure in the temperature range of 278 K to 323 K for pure based lubricant along with nanolubricant mass concentration of 1%, 2% and 4% with nanoparticle size of 10 nm, 20-30 nm and 80 nm. The measured data was analysed using the linear fit and exponential function fit. The result showed that at constant particle size and concentration, the dynamic viscosity reduces with increase in temperature while at constant temperature, the viscosity increased with nanoparticle concentration. The exponential function fit regression best describe the relationship between the viscosity and temperature when compared with the linear fit regression while the polynomial function fit best describe the relationship between the viscosity and mass concentration.

Keywords: *Dynamic viscosity, nanolubricant, shear rate, regression, concentration, temperature*

1. INTRODUCTION

The introduction of nanoparticles into base fluid had led to tremendous increase in the thermal conductivity of the nanofluid when compared to the base fluid [1-3]. This discovery led to the application of nanofluid in various energy systems such as refrigeration, air conditioning, pumping systems, heat exchangers, high-power electronic components, energy conversion systems and solar energy system. The dispersion of nanoparticles into a base fluid such as compressor lubricant to form nanolubricant alters the flow properties of the base fluid. The pressure drop, convective heat transfer coefficient and pumping power are proportional to the viscosity of a lubricant used in vapour compression refrigeration system [4-5]. Hence, the viscosity of the lubricant used in the compressor affects the overall efficiency of the system. With this, the determination of the rheological properties of nanolubricant used in vapour

compression refrigeration system is needed to determine its compatibility with existing compressor or the redesign of either the compressor or modification of the nanolubricant.

Majority of the research carried out showed that the viscosity of the nanolubricant is dependent on the mass concentration of nanoparticles, temperature of the nanolubricant but few research have been conducted on the effect of nanoparticle size on the viscosity of nanolubricant. Sharif *et al* [6] investigated the viscosity of the Al₂O₃/Polyalkylene glycol (PAG) 46 nanolubricants for 0.05 to 1.0% volume concentrations at temperatures of 303.15 K to 353.15 K. The viscosity of the nanolubricant increases exponentially with the increase of volume concentration and decrease exponentially at elevated temperature. Kerdzierski [7] formulated a correlation of the viscosity of Copper oxide (CuO) nanoparticles dispersed in Polyester lubricant as a function of

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temperature and nanoparticle concentration. The temperature range considered was approximately between 288K and 318K with CuO nanoparticles size of approximately 30 nm diameter and volume fraction of 2%, 4% and 40%. The three-parameter exponential best-fit regression or estimated means was used for the normalized viscosity. A series of rheological study of diethylene glycol-based yttrium oxide (Y₂O₃) was conducted by [8]. Dynamic viscosity of Y₂O₃/DG nanofluids at constant shear rate was measured in the temperature range of 0°C to 50°C for different concentrations of nanoparticles in nanofluid. It was observed that Y₂O₃/DG nanofluid cannot be determined as shear thinned or shear thickened and that the viscosity curve is not linear and has a maximum at a shear rate of about 200s⁻¹. The work showed that dependence of the dynamic viscosity on temperature cannot be correctly approximated with exponential function for this nanofluid. The tenth degree polynomial was used to approximate the dependence of the dynamic viscosity of Y₂O₃/DG nanofluids on temperature which gave an accuracy of 2% with the experimental data, which is a significant improvement when compared to the exponential function. Esfe [9] carried out an evaluation of MWCNTs-ZnO (10%-90%)/5W50 nanolubricant at different temperatures of 55, 45, 35, 25, 15, and 5°C. and volume fractions of 1%, 0.75%, 0.5%, 0.25%, 0.1%, and 0.05%. Nanofluid viscosity was optimized in proportion to temperature, shear rate, and volume fraction in maximum and minimum modes. The ANN was applied for designing a model for accurate prediction of viscosity and the results were compared with the results of the mathematical correlations. It was concluded that the neural network outperformed the presented relation in predicting viscosity; therefore, it is more accurate.

Several theoretical models and correlation are available in literatures to evaluate the viscosity of nanofluids. The foremost of the model was proposed by Einstein [10], the model was formulated considering linearly viscous fluid dilute suspension which contains spherical particles dispersed in low fraction less than 2% and the interaction between the particles was neglected. The dynamic viscosity model is given in Equation 1.

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

where μ_{nf} is the viscosity of the nanofluid, μ_{bf} is the viscosity of the base fluid and φ is the mass concentration of nanoparticle.

Brinkman [11] modified the Einstein model to predict the viscosity of spherical particles for higher volume concentration. The model is given as;

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{(1 - \varphi)^{2.5}} \quad (2)$$

The Brinkman model was used by [2] to study the relative viscosity of Al₂O₃/R-134a nanorefrigerant with respect to nanoparticles concentration. The observation from the analysis confirmed that the viscosity increased as nanoparticles concentration increased as represented by the model. [12] reported that the Brinkman's theory perfectly predicted the experimental result obtained using Cu/water nanofluid and transform oil/water nanofluid at a temperature range of 20 - 50°C.

Batchelor [13] also extended the Einstein model as

$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + C_1\varphi + C_2\varphi^2) \quad (3)$$

where C₁ and C₂ are constants from experimental results.

Batchelor's model was modified by [14] and is given as;

$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + C_1\varphi + C_2\varphi^2 + C_3\varphi^3) \quad (4)$$

C₁, C₂ and C₃ were constant from experimental studies. Furthermore, another model given in Equation 3 was proposed by [3] also determine viscosity of nanofluid.

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 7.3\varphi + 123\varphi^2 \quad (5)$$

Esfe [9] reported that at a nanoparticle size of 40nm, the Batchelor model and the Wang's model failed to accurately predict the dynamic viscosity of MgO-water nanofluid flowing through a straight circular tube. A new correlation was then proposed given as;

$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 11.61\varphi + 109\varphi^2) \quad (6)$$

Most of the theoretical formulas in existence relate the viscosity of colloidal suspensions or nanofluids to particle volume fraction without considering the effect of nanoparticle size and temperature. More investigation on the dynamic viscosity of nanolubricant at low temperatures needs to be conducted. Therefore, the aim of this paper is to investigate the effect of temperature on viscosity of Al₂O₃/Capella oil at various concentration and particle size over a range of temperatures from 278 K to 323 K.

2. METHODOLOGY

2.1 Materials characterisation of Al₂O₃ nanopowder

The Al₂O₃ was purchased from Nanostructured and Amorphous Materials, Inc. USA. The average size of

the nanoparticle was determined to be 10 nm, 20-30 nm and 80 nm. The nanoparticles were physically monitored using the scanning electron microscopy (SEM) to characterise the morphology of the nanoparticles samples while X-ray powder diffraction (XRD) was carried out on the nanoparticles powder to determine the phase identification of a crystalline material. The Scanning electron microscopy (SEM) images are shown in Figures 1. The appearance shows that an 80 nm Al₂O₃ nanoparticle is spherical when compared with 10 nm and 20-30 nm of the same Al₂O₃ nanoparticle. Most of the nanoparticles in 10 nm nanoparticle sizes are agglomerated when compared to 20-30 nm and 80 nm sizes. Figure 2 shows that the XRD of 10 nm and 80 nm Al₂O₃ are similar, a higher intensity was obtained at 37°, 46° and 68° which showed the amorphous nature of the nanoparticles. The XRD of 20 – 30 nm showed six predominant peaks at 19°, 21°, 37°, 40°, 46° and 68° which confirms the crystalline nature of 20 – 30 nm Al₂O₃ nanoparticles.

2.2 Sample preparation

The nanolubricant samples used in this study were prepared using the two-step method. A commercial

Capella D- lubricant commonly used in ammonia systems as well as some large chillers using CFCs and HCFCs was used as the based fluid to prepare the nanolubricant.

Samples were prepared with different mass concentration of 1%, 2% and 4% using Aluminium oxide (Al₂O₃) nanoparticles of nominal diameter 10 nm, 20-30 nm and 80 nm. The mass concentration of nanoparticle in the lubricant was calculated using Equation 8.

$$\varphi = \frac{m_p/\rho_p}{m_p/\rho_p + m_l/\rho_l} \quad (8)$$

where, φ is the nanoparticle mass concentration; m_p and m_l are the masses of the nanoparticle and lubricant respectively while ρ_l and ρ_p are liquid phase density of the lubricant and nanoparticle respectively. No surfactant was added during the sample preparation in order not to alter the properties of the nanolubricant. The dry Al₂O₃ was dispersed into the lubricant and mixed mechanically for 2 hours using the magnetic stirrer. The sample was later transferred to the ultrasonic bath and mixed for 180 minutes to destroy nanopowder agglomerates. Some samples of nanolubricants prepared are shown in a Figure 3.

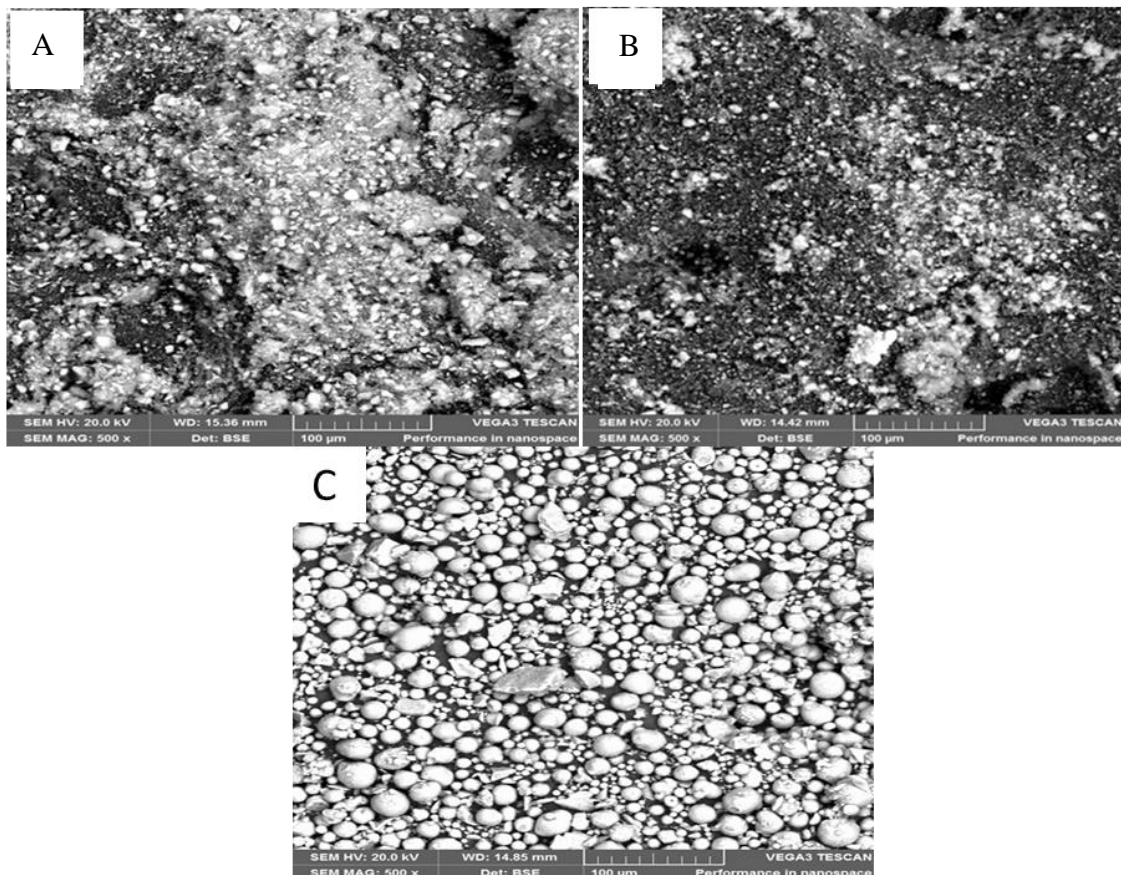


Figure 1: Scanning microscope graphs for Al₂O₃ (A) 10nm (B) 20-30 nm (C) 80 nm

2.3 Rheological measurement

The Brookfield DV –II Viscometer (DV2T) was used to measure the dynamic viscosity of the liquid nanolubricant at various temperatures of 278 K to 323 K. The torque, viscosity, shear stress and shear rate of the nanolubricant were measured at various temperatures. The selected speed was 100 rpm. The nanolubricant was poured in a beaker and the temperature was raised to 333 K and was placed in a water bath packed with ice.

The viscosity of the nanolubricant depended on the shear rate, time of test and the spindle geometry.

The shear rate of a given measurement is determined by the rotational speed of the spindle, the size and shape of the spindle, the size and shape of the container and the distance between the container and the spindle surface. The viscometer is guaranteed for viscosity accuracy within full scale range while the temperature accuracy is $\pm 1.0\%$ / -100°C to 148°C .

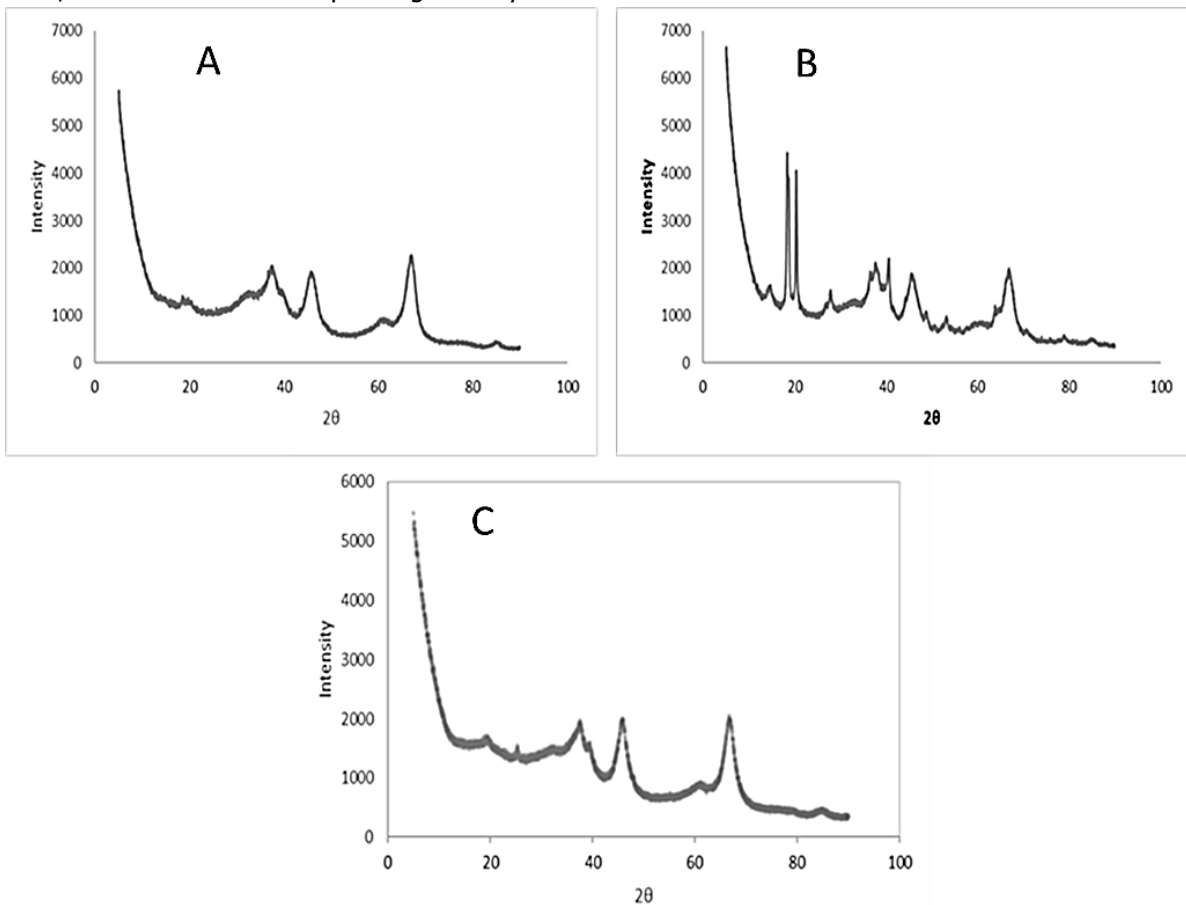


Figure 2: X-ray diffraction pattern of Al₂O₃ (A) 10 nm (B) 20-30 nm (C) 80 nm



Figure 3: Samples of nanolubricants

3. RESULTS AND DISCUSSION

3.1 Dynamic viscosity of aluminium oxide (Al₂O₃) nanolubricant

The determination of the dynamic viscosity is essential in the study of rheological behaviour of nanofluid. The measurement of the dynamic viscosity with respect to temperature at various nanoparticle concentrations, nanoparticle size was measured at constant shear rate in the temperature range from 278K to 323K at an interval of 1K.

A determination of the relationship between the viscosity and temperature brought about the need to carry out a regression analysis in order to determine the contribution of temperature to the variation of viscosity. Based on this, the empirical models were developed using the linear fit and exponential function fit to determine which of the regression fit gives the best explanatory changes in viscosity with respect to temperature. The fit exponential function 1 was used in the analysis. The solid lines represent the best-fit regression while the dots represent the measured data. The empirical models are given in Equations 9 and 10 while the values of the constants are shown in the summary of the Table of linear fit and exponential function fit as displayed in Table 1 – 6.

$$\mu_{nf} = U_0 + U_1 T \quad (9)$$

$$\mu_{nf} = U_0 + U_1 \exp\left(\frac{-T}{t}\right) \quad (10)$$

where μ_{nf} is the dynamic viscosity of the nanolubricant, t , U_0 and U_1 are the fitting constants and T is the temperature in Kelvin.

Figures 4 to 9 showed that the dynamic viscosity of Al₂O₃ nanolubricant significantly reduces with increase in temperature. The viscosity of a fluid is caused by cohesive force between molecules of the fluid. The increase in temperature weakens the inter-molecular and inter-particle adhesion forces thereby causes the molecules to move freely. The viscosity drops intensely from 308 K to 323 K. At elevated temperature, the increase in Brownian diffusion also reduces the dynamic viscosity. The Brownian diffusion is weak at lower temperature because of the higher base-fluid viscosity.

Further to this, the results showed that the addition of nanoparticles caused an increase in the viscosity of the base lubricant. The viscosity increased as the nanoparticle size increased but at high temperature and constant concentration, the 20-30 nm nanoparticle size tends to have the highest viscosity. This can be attributed to the structure of the

nanoparticle as corroborated by Figure 2. Figure 2(B) in the XRD shows that the 20 – 30 nm nanoparticle has more oxide crystals at different phase angles than the other oxides which suggest higher viscosity. Comparing Figures 4 to 6 it seen that at constant particle size and concentration, the viscosity reduces with increase in temperature.

At a constant low temperature of 278K, the dynamic viscosity of the nanolubricant increased as the concentration of the nanoparticles increased as shown in Figure 10-11. Nanoparticle size of 20 – 30 nm possessed the highest value of dynamic viscosity at 2% and 4% mass concentration while 80 nm sized nanoparticles showed the highest value of dynamic viscosity at 1% mass concentration. The dynamic viscosity of the nanolubricant was higher than the pure lubricant, therefore, there is the tendency that the nanolubricant will have an increasing effect on the performance of the compressor of a vapour compression refrigeration system as the nanoparticles concentration increases.

The empirical model to determine the relationship between the dynamic viscosity and nanoparticle concentration at low temperature was formulated using the linear fit and polynomial function fit.

From the regression analysis table shown in Table 7-8, it is seen that the polynomial fit gives the best relation between the dynamic viscosity and nanoparticles mass concentration. The linear fit and polynomial function fit empirical equation is given in Equation 11 and 12 respectively.

$$\mu_{nf} = U_0 + U_1 \phi \quad (11)$$

$$\mu_{nf} = U_0 + U_1 \phi + U_2 \phi^2 \quad (12)$$

where μ_{nf} is the dynamic viscosity of the nanolubricant, t , U_0 , U_1 and U_2 are the fitting constants and ϕ mass concentration shown in Tables 7-8 .

From the regression analysis, it is clear that the viscosity of nanofluid with regards to temperature is not linear but exponential while for mass concentration it is polynomial. The values obtained for standard error in all the concentration is seen to be closer to zero while the adjusted R-Square can be approximated to one for the exponential function fit which was not the case for the linear fit. These values obtained for the standard error and adjusted R-square showed that Equation 10 and 12 can be used to accurately predict the dynamic viscosity of nanolubricant with varying nanoparticle concentration, size and temperature.

Table 1: Linear fit of dynamic viscosity with respect to temperature with standard error and Adjusted R-Square for linear fit regression for 1% mass concentration

Fitting Constant	10 nm	Error	20-30 nm	Error	80nm	Error	Pure	Error
U_0	21.16187	1.07877	23.4016	0.70121	23.02512	1.12929	21.34556	0.87266
U_1	-0.06508	0.00359	-0.07107	0.00234	-0.07123	0.00375	-0.06644	0.00292
Adj. R-Square	0.87945		0.95842		0.8886		0.92501	

Table 2: Exponential function fit of dynamic viscosity with respect to temperature with standard error and Adjusted R-Square for exponential fit regression for 1% mass concentration

Fitting Constant	10 nm	Error	20-30 nm	Error	80nm	Error	Pure	Error
U_0	0.44544	0.021	-0.61291	0.3366	0.30673	0.0229	0.09632	0.05451
U_1	1.66864E8	5.462E7	9668.44349	8894.55733	8.50698E7	2.5616E7	5.82619E6	3.32221E6
t	15.71744	0.29222	36.3445	4.66699	16.42627	0.29406	19.35272	0.78027
Adj. R-Square	0.99846		0.98395		0.99865		0.99551	

Table 3: Linear fit of dynamic viscosity with respect to temperature with standard error and Adjusted R-Square for linear fit regression for 2% mass concentration

Fitting Constant	10 nm	Error	20-30 nm	Error	80nm	Error	Pure	Error
U_0	25.0862	1.40533	27.95887	1.31658	26.11882	1.4359	19.05357	0.89918
U_1	-0.07813	0.00467	-0.0874	0.00438	-0.08181	0.00477	-0.05853	0.00299
Adj. R-Square	0.86097		0.89835		0.86675		0.89469	

Table 4: Exponential function fit of dynamic viscosity with respect to temperature with standard error and Adjusted R-Square for exponential fit regression for 2% mass concentration

Fitting Constant	10 nm	Error	20-30 nm	Error	80nm	Error	Pure	Error
U_0	0.3064	0.02286	-0.02878	0.04966	0.13163	0.03201	0.36787	0.0363
U_1	1.04249E9	3.62214E8	2.74802E7	1.25381E7	5.3047E8	2.30404E8	4.58137E7	2.54709E7
t	14.38027	0.25897	17.83726	0.52708	14.9364		16.84466	0.57147
Adj. R-Square	0.99837		0.99675		0.99738		0.99535	

Table 5: Linear fit of dynamic viscosity with respect to temperature with standard error and Adjusted R-Square for linear fit regression for 4% mass concentration

Fitting Constant	10 nm	Error	20-30 nm	Error	80nm	Error	Pure	Error
U_0	26.97485	1.3473	24.03631	1.26752	27.84014	1.56463	0.0052	-0.05853
U_1	-0.08372	0.00448	-0.07189	0.00421	-0.08759	19.05357	0.89918	0.00299
Adj. R-Square	0.8856		0.86568		0.86261		0.89469	

Table 6: Exponential function fit of dynamic viscosity with respect to temperature with standard error and Adjusted R-Square for exponential fit regression for 4% mass concentration

Fitting Constant	10 nm	Error	20-30 nm	Error	80 nm	Error	Pure	Error
U_0	0.30316	0.01973	1.15141	0.07941	0.04444	0.0393	0.36787	0.0363
U_1	1.50641E8	3.47537E7	1.76537E8	1.96955E8	8.68428E8	4.50428E8	4.58137E7	2.54709E7
t	16.03741	0.21458	15.7557	1.00093	14.60366	0.39886	16.84466	0.57147
Adj. R-Square	0.99922		0.98232		0.99633		0.99535	

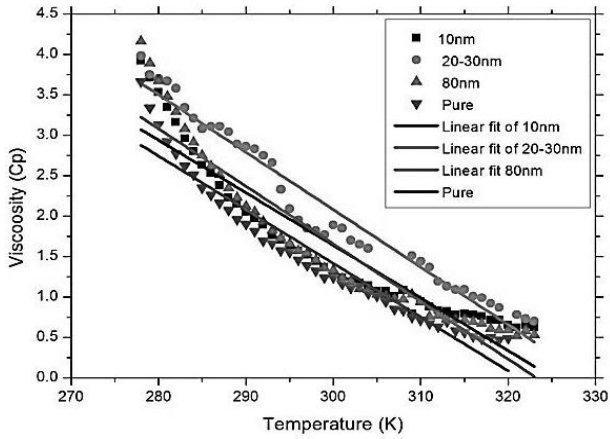


Figure 4: Dependence of dynamic viscosity on temperature for various nanoparticle sizes and mass concentration of 1% for linear function fit

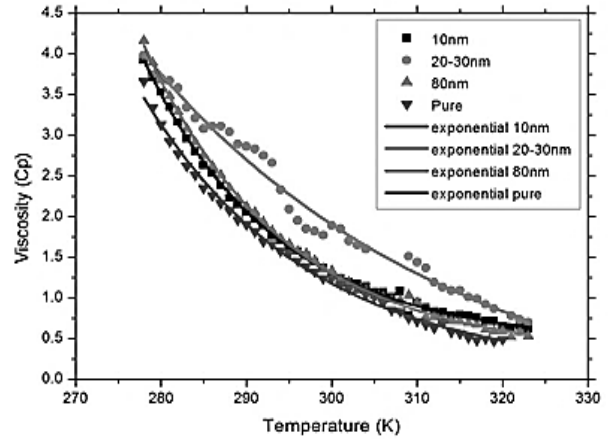


Figure 5: Dependence of dynamic viscosity on temperature for various nanoparticle sizes and mass concentration of 1% for exponential function fit

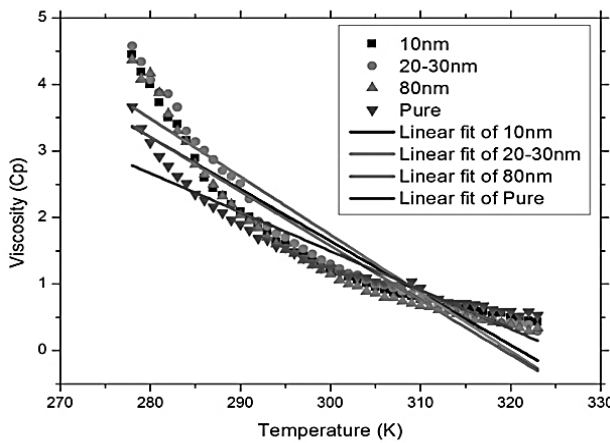


Figure 6: Dependence of dynamic viscosity on temperature for various nanoparticle sizes and mass concentration of 2% for linear function fit

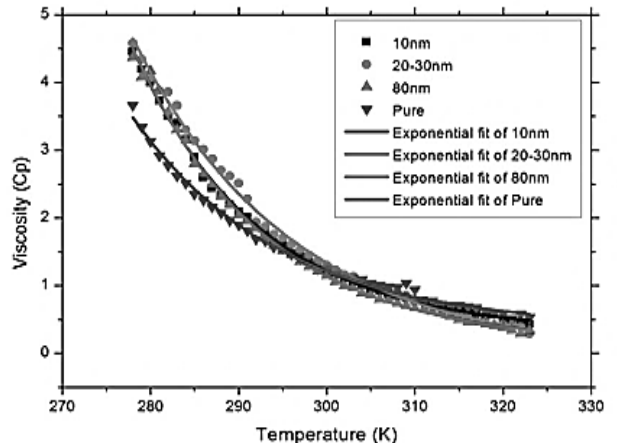


Figure 7: Dependence of dynamic viscosity on temperature for various nanoparticle sizes and mass concentration of 2% for exponential function fit

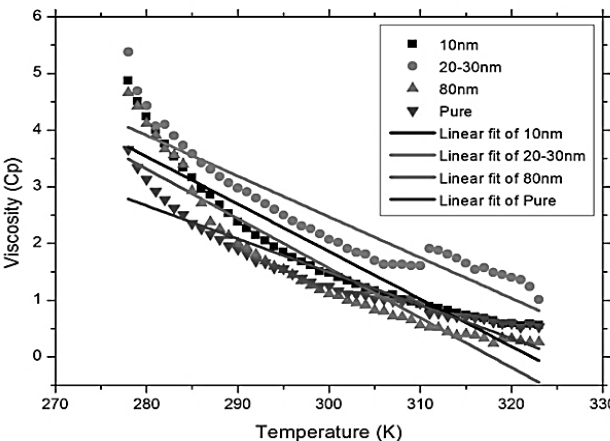


Figure 8: Dependence of dynamic viscosity on temperature for various nanoparticle sizes and mass concentration of 4% for linear function fit

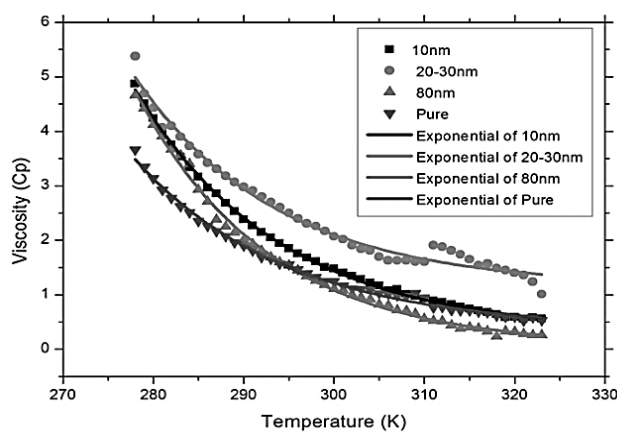


Figure 9: Dependence of dynamic viscosity on temperature for various nanoparticle sizes and mass concentration of 4% for exponential function fit

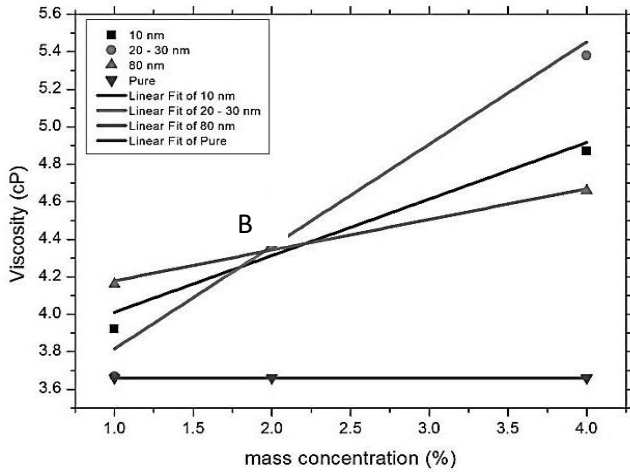


Figure 10: Dependence of dynamic viscosity on nanoparticles concentration for various nanoparticle sizes at low temperature of 278K for linear function fit

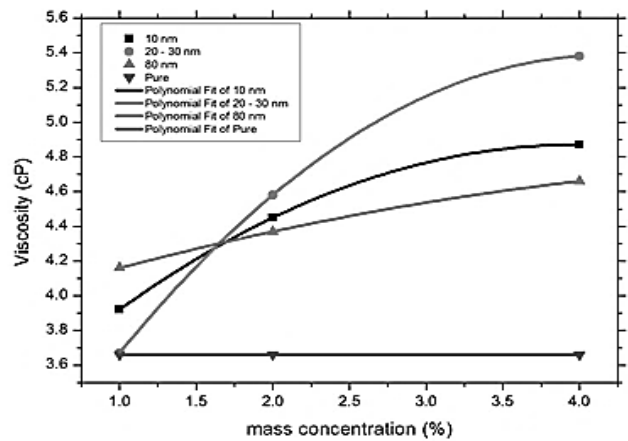


Figure 11: Dependence of dynamic viscosity on nanoparticles concentration for various nanoparticle sizes at low temperature of 278K for polynomial function fit

Table 7: Polynomial function fit of dynamic viscosity with respect to mass concentration with standard error and Adjusted R-Square for linear fit regression at low temperature

Fitting Constant	10 nm	Error	20-30 nm	Error	80nm	Error	Pure	Error
U_0	3.71	0.20949	3.27	0.33387	4.015	0.04255	3.66	5.0355E-16
U_1	0.30143	0.07918	0.54571	0.33387	0.16357	0.01608	2.19767E-16	1.90324E-16
Adj. R-Square	0.87091		0.95842		0.89848		--	

Table 8: Dynamic viscosity with respect to mass concentration with standard error and Adjusted R-Square for linear fit regression at low temperature

Fitting Constant	10 nm	Error	20-30 nm	Error	80 nm	Error	Pure	Error
U_0	3.17667	-	2.42	-	3.90667	-	3.66	-
U_1	0.85	-	1.42	-	0.275	-	-1.53837E-15	-
U_2	-0.10667	-	-0.17	-	-0.02167	-	2.56395E-16	-
Adj. R-Square	-		-		-		-	

4. CONCLUSION

The dynamic viscosity of Al₂O₃ based nanolubricant at temperature range of 276K – 323K, nanoparticle concentration of 1%, 2% and 4% and nanoparticles sizes of 10 nm , 20 – 30 nm and 80 nm was studied in the paper. The dynamic viscosity of nanolubricant was found to increase as the nanoparticles concentration and size but decreases with temperature. From the regression analysis the linear fit does not perfectly describe the relationship between the dynamic viscosity and the temperature. The result showed that the dynamic viscosity varied exponentially with temperature and polynomial function relationship with mass concentration and not linearly as proposed in most of the existing empirical models. The need to further study the effect of nanoparticles concentration and size concurrently is eminent for proper analysis of

the effect of nanolubricant on the performance of vapour compression refrigeration system.

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