Investigation into Effective Viscosity, Electrical Conductivity and pH of γ-Al_2O_3-Glycerol Nanofluids in Einstein Concentration Regime

Saheed Adewale Adio[1], Mohsen Sharifpur[1], Josua Petrus Meyer[1]

[1] Nanofluids Research Laboratory, Thermofluid Research Group, Department of Mechanical and Aeronautical Engineering, University of Pretoria, 0002, Pretoria, South Africa.

Address correspondence to Dr. Mohsen Sharifpur,
E-mail: mohsen.sharifpur@up.ac.za
Tel: +27 12 420 2448
Fax: +27 12 420 6632

ABSTRACT

Energy sustainability is very crucial for any viable engineering solution to be achieved. In recent times, nanofluids have shown a great promise of bringing about sustainable energy development in the field of heat transfer regarding the design of heat transfer equipment. In this study, the viscosity of γ-Al_2O_3 – glycerol nanofluids; a prime factor in the design of heat tranfer equipment such as heat exchanger has been investigated in the Einstein's volume concentration regime ($\phi \leq 2\%$). This was accomplished by studying the effect of temperature, volume concentration, electrical conductivity and pH at constant shear rate on 20–30 nm γ-Al_2O_3 in glycerol. Stable γ-Al_2O_3–glycerol nanofluids samples were prepared using the famous two-step method, followed by ultrasonication at two different time period of 3 and 6 hours in a controlled temperature bath. The effect of volume concentration on the effective viscosity, electrical conductivity and pH were all monitored between the temperature range of 20–70 ^oC. In the case of 3 hours samples, the study shows no appreciable increase in the relative viscosity up to 0.5% nanoparticles volume concentration and it was observed that a critical temperature (beyond which the relative viscosity starts reducing with temperature) was reached at 55 ^oC for 2%, 60 ^oC for 1% and 65 ^oC for both 0.5% and 0.1% volume concentrations respectively. However, 6 hours sonication effect was only felt at the reduction of the relative viscosity of 2% volume concentration, with the critical temeprature observed at 55 ^oC for all volume fractions. Comparing the experimental data with the available low volume concentration classical models and emipiral model revealed that the classical models under predicted our experimental data while the empirical model anormalously over predicted the experimental data reported in this work. The electrical conductivity and pH are significantly affected by temperature and volume fraction.

INTRODUCTION

Energy sustainability is an essential part of world's developmental drive in this century and in order to achieve a sustainable development, the demand for energy efficient systems is on the increase, the likes of which has never been recorded before. This has led to more compact devices and systems being designed and built daily. However, conventional heat transfer fluids such as water, ethylene glycol, propylene glycol, mineral and engine oil, glycerol etc. cannot deliver efficient thermal management as required in these devices due to their poor thermal properties [1] compared to the high density heat energy produced in these systems. Although colloidal suspension was first introduced back in 1873 by Maxwell [2] in a bid to improve the heat transfer characteristics of the conventional heat transfer fluid, a breakthrough was not achieved until Choi's unique pioneering of nanofluids in 1995 [3]. Nanofluids are two phase suspensions containing metallic (Ag, Ni, Au, Al, Cu etc.), metallic oxides and oxides of non-metals (Al_2O_3, TiO_2, SiO_2, MgO, CuO, NiO_2, SiC, $CaCO_3$ etc.) nanoparticles dispersed in conventional heat transfer fluids. A mixture of two base fluids such as ethylene glycol–water [4–8], and mixture of two nanoparticles such as NiO–YSZ [9] has also been used in the synthesis of nanofluids and their thermal and rheological properties studied.

The dynamics of the challenges of thermal managements of new and emerging industrial equipment and/or systems are yet to be fully understood in the wake of this new heat transfer fluid (nanofluid). A number of research efforts aimed at understanding the dynamics of nanofluids thermal properties have been published such as thermal conductivity [10–13], viscosity [14–16], convective heat transfer [17, 18], electrical conductivity [19–21], specific heat capacity [22], thermal diffusivity [23] , density [24]. However, the search for a lasting explanation to the anomalous behaviours of nanofluids as depicted from different literatures continues. In one of the earliest studies on nanofluids, Wang et al. [25] experimented on

mechanical blending assisted engine oil, water, vacuum pump oil and ethylene glycol nanofluids of Al_2O_3 and CuO nanoparticles respectively to study the enhancement of their thermal conductivities as a function of nanoparticles volume concentration and methods of preparation of the nanofluids. It was established that ethylene glycol based Al_2O_3 nanofluids was the most stable of all Al_2O_3–based nanofluids at 16% volume fraction and an enhancement of about 40% was recorded at 8% volume fraction. While at volume fraction more than 10% other Al_2O_3 nanofluids exhibit agglomerations and flocculation. Other results obtained showed that thermal conductivity enhancement depend on the methods of preparation of the nanofluids. Chandrasekar et al. [26] employed microwave assisted synthesis of Al_2O_3 nanoparticles with average size of 43 nm and reported 9.7% thermal conductivity enhancement at 3% volume concentration, but the viscosity enhancement was 136%, a value that shows no promise of practicable use of the nanofluids at 5% nanoparticles volume concentration. Pastoriza-Gallego *et al*. [27] studied the nanofluids of Al_2O_3 in ethylene glycol with nanoparticles concentration up to 8.6% volume fraction. Two different samples were studied (different sizes, from different manufacturer with one in dry powdery form and the other aqueous solution) for their thermal conductivities and viscosities. The two–step method was employed to prepare both nanofluids under same conditions. It should be mentioned that nanoparticles from the samples in aqueous solution were first extracted before re-dispersion in ethylene glycol for further analyses. Their experiment shows 19% thermal conductivity enhancement for the highest volume fraction tested, while the highest viscosity enhancement for sample 1 and 2 was 46% and 96% at 6.5 % and 3% nanoparticles volume fraction respectively, primarily because of the difference in nanoparticle sizes contained in these samples. Titanium oxide in deionized water (DIW) nanofluids were investigated by Laura et al. [28], also to determine its thermal conductivity and viscosity behaviours subject to 10–70 ^{o}C temperature regime and nanoparticles volume fractions of

0.24%, 2.54% , 5.54% and 11.22% which translate to 1%, 10%, 20% and 35% weight fractions respectively. At the lowest nanoparticles volume fraction of 0.24% the enhancement of thermal conductivity was not more than 5% at all temperatures below 323.15K. However, at a higher temperature of 352.5K the enhancement was 18% while the maximum enhancement was observed at the maximum nanoparticle volume fraction of 11.22% to be 38.1%. Rheological characteristics of the samples in a rotating viscometer indicated that the nanofluids are Newtonian in nature; however, for the volume fraction of 2.54%, 5.54% and 11.22% tested the viscosity enhancements were ambiguous and unprecedentedly high.

Much of the work done in this emerging field as portrayed above and widespread in the literature is on Al_2O_3 with different base fluids. Nevertheless, there are no experimental data on thermal conductivity, electrical conductivity and viscosity of glycerol based nanofluids of alumina. Hence, this gave credence to the present research which focuses on the viscosity, electrical conductivity and pH of glycerol based alumina nanofluids. This work is carried out in the Einstein's concentration regime of $\phi \leq 2\%$, temperature range of 20–70 ^{o}C and sonication period of 3 and 6 hoursours respectively.

EXPERIMENTAL

Sample preparation and morphology

The γ-Al_2O_3 nanoparticles used in this investigations were manufactured by Nanostructured Amorphours Inc. USA. They are of 99.97% purity with true density of 3.7 g/cm^3, nearly spherical morphology and diameter between 20–30 nm as stated by the manufacturer. To further verify this, transmission electron microscopy (TEM) images were obtained on a JEOL JEM–2100F microscope operated at 200 KV, to determine the size and morphology of the nanoparticles as supplied. As shown in Figure 1, there were agglomeration of nanoparticles, but we were able to identified that the nanoparticles are nearly spherical, while their norminal

size is about 17 nm with a few aberations of as much as 50 ± 3 nm. An XPERT–PRO diffractometer (PANalytical BV, Netherlands) with theta/theta geometry, operating a cobalt tube at 35 kV and 50 mA was used to obtain the X–Ray diffraction (XRD) pattern. The XRD patterns of γ-Al_2O_3 (Figure 2a) specimen was recorded between 10°–90° range with a step size of 0.001° and a counting time of 12.705 seconds per step. The pattern corresponds to Corundum structure (Al_2O_3) from the JCPDS database and the broadening of the peaks indicates the small size of the particles (< 0.1 μm) while the pair of peaks at 2 theta > 80^o is typical of aluminium [29]. The EDX spectral analysis also depicts alumina (Figure 2b) with 50.8% oxygen and 49.2% aluminium recorded at a maximum error of ± 0.6%. Glycerol was procured from Merck Chemicals South Africa (a division of Merck Millipore, Germany), with 99.5% purity and viscosity of 1412 mPa s at 20 ^oC. The γ-Al_2O_3–glycerol was prepared using the known two–step method of preparation by direct dispersion of the nanoparticles in the base fluid. A precalculated weight of nanoparticles coresponding to a known volumetric fraction of the desired nanofluids samples were measured using a digital weighing balance (Highland HCB1002, max: 1000g, precision: 0.01g, from Adam equipment) and the base fluid is added to the corresponding desired weight. The mixture was sonicated continuously with a 24kHz UP200S Hielscher ultrasonic processor for laboratory with S14 sonotrodes to obtain an homogenized dispersion of nanoparticles in the glycerol. During this process of homogenization the sample was kept in a programmable temperature bath (LAUDA ECO RE1225 Silver temperature bath) and the temperature maintained at 15± 0.1 ^oC.

Viscosity measurement

The viscosity equipment used is a sine wave vibro-viscometer SV–10 from A&D Company Ltd. Japan with viscosity measurement limits of 0.3–10,000 mPa.s. The measuring cup of the apparatus is equiped with a water jacket connected to a programmable thermal bath for efficient temperature control of samples. The viscometer uses the turning-fork

vibration method at a constant resonating frequency of 30 Hz to determine the vicidity of fluid samples based on power differentials that maintains the resonating frequency. The fluid sample temperature is monitored with a temperature sensor fixed between the vibrating forks that ensure uniform temperature at the sampling site. Using the online windows communication tool, both the viscosity and temperature of the sample can be accurately logged in real time at every second. The viscometer was calibrated using 99.5% glycerol with manufacturer stated viscosity of 1412 mPa.s at 20 ^{o}C. After calibration, a fresh sample of glycerol was introduced into the measuring cup and the viscosity data was sampled between the temperature of 20–70 ^{o}C. The measured viscosity was compaired with the glycerol manufacturer's and published data by Oberstar and Segur [30] at 20 and 30 ^{o}C. Additional appraisal with the published work of Miner and Dalton [31] over the temperature range of our experiment shows a very good agreement (Figure 3). The percentatge (%) error was found to be within the equipment error range as shown in Figure 3, while Figure4 further stress the fact that the vibro-viscometer is repeatable in its measurement after running the device to measure from 20–70 ^{o}C and 70–20 ^{o}C respectively. The dash double dot line in Figure 4, when traced from the temperature axis to viscosity axis highlights this fact.

Electrical conductivity measurement

The electrical conductivity of the samples was carried out using CON700 from EUTECH Instruments. The device is equiped with a 2–cell electrical conductivity electrode meter with a nominal cell constant k = 1.0. The apparatus came with a built-in thermistor temperature sensor with automatic temperature compensation (ATC). It was calibrated with 1413 µS standard calibration fluid supplied by the manufacturer repeatedly at 25 ^{o}C and the measured value does not only agree with the standard value but was also repeatable (Table 1).

pH measurement

In the present investigation the pH measurements were carried out using a bench top pH/mV meter with pH measurement accuracy of 0.3% and manufactured by Jenway (model: 3510). The device is equipped with an ATC (0 – 100 ^{o}C) thermocouple and supplied with combination electrode. The high impendance meter measures the quantity of hydrogen ion activity between the range -2 to 19.999 and was calibrated using 2-points calibration with burffer 7 and 10. The pH measurement of the nanofluids samples were made between the temperature of 20–70 ^{o}C, employing an in house water jacket connected to the thermal bath in order to produce constant temperature.

EXISTING EFFECTIVE VISCOSITY, ELECTRICAL CONDUCTIVITYAND pH MODELS MODELS

Effective viscosity

Theroretical analyses of colloidal suspensions is over a century old and the inconsistent behaviour of suspensions leave researchers without choice, but to explore more in an attempt to find the causes of the atypical behaviours of colloid suspensions. As more experement is carried out daily on colloid suspensions (i.e. nanofluids) and discovery of new possible causes of enhancement discussed with the formulation of new models, it has been shown that the existing classical model can not predict in many cases the behaviour of nanofluids.

Einstein's pioneering work of 1906 [32] was established on extremely dilute suspension for rigid solid spheres with volume fraction of $\phi \leq 2\%$ and a non-interacting medium. His model (Eq. 1) predicted the viscosity as a linear function of volume fraction and it has been the basis for the derivation of many other classical models.

$$\mu_{eff} = \mu_f \left(1 + 2.5\phi\right) \tag{1}$$

Batchelor's model [33] when critically studied will be seen, in the limit of a very low particle volume fraction, to reduce to Einstein's model. The effect of interactions between particles was however, considered in the development of this model given as:

$$\mu_{eff} = \mu_f \left(1 + 2.5\phi + 6.5\phi^2\right) \tag{2}$$

Another extension of Einstein's model is the work of Brinkman [34], he modelled the viscosity of a higher suspensions concentration of a particles up to $\phi \leq 4\%$ and gave the following expression:

$$\mu_{eff} = \mu_o \left(1 - \phi\right)^{-2.5} \tag{3}$$

Many frequently cited theoretical models are either derived based on Einstein's model or for spherical micro-particles in suspension. These models fall short because there are numerous characteristic differences between micro-size and nano-size particles e.g. size to surface area ratio. Recently, Masoumi et al. [1] developed a nanoparticles characteristics conscious model for the prediction of nanofluids effective viscosity. Based on Brownian motion they considered volumetric fraction, temperature, particle diameter, nanoparticle density, base fluid physical properties and assumed a creeping flow condition in their analysis to obtain the following expression:

$$\mu_{eff} = \mu_f + \frac{\rho_p V_B d_p^2}{72 C \delta} \tag{4}$$

where ρ_p is density of the particle, d_p is the diameter of the particle, C is the correction factor for the creeping flow assumption, V_B is the Brownian velocity derived by Prasher et al. [35] and δ is the distance between the center of particles, which is given as:

$$\delta = \sqrt[3]{\frac{\pi}{6\phi}} d_p \tag{5}$$

Hosseini et al. [36] also formulated recently an analytical model for the prediction of nanofluids viscosity using dimensionless groups. Parameters considered were the viscosity of the base fluid, hydrodynamic volume fraction of nanoparticles, diameter of nanoparticles, thickness of capping layer of the nanoparticles and temperature respectively, to give the following expression:

$$\mu_{eff} = \mu_f . \exp\left[m + X\left(\frac{T}{T_0}\right) + Y\phi\left(\phi_h\right) + Z\left(\frac{d}{1+a}\right)\right] \tag{6}$$

where m is a system property constant, X, Y, Z are empirical constants obtainable from the experimental data. It should however, be noted that there are still limits to the application of the newly developed model and basically experimental data is the only reliable resource that can be worked with.

Electrical conductivity

Taking an assumption of electroneutrality (a situation where the positive ions are balanced with the negative ions) in stable base fluids is adequate. The introduction of nanoparticles at different volumetric fractions leads to a change in the ionic configuration of the initial system due to; (i) dissociation of ionic group at the particle surface, (ii) adsorption of ionic group to the particle surface, (iii) isomorphous substitution of ions etc. Nanoparticles have residual charges due to the methods of synthesis and when introduced into a presumably electroneutral base fluid, modification of the ionic strength of the suspension medium far away from the particle surface occurs because the charged particle attracts counterions firmly to its surface. Therefore, in the base fluid there exist the deficiency in the counterions and surplus of particle coions [37]. As a result the electrical conductivity of the system will be altered. In essence the electrical conductivity of nanofluids relates to the surface electro-kinetics interplay with the ionic situations in the bulk.

Based on equivalent cell model as depicted in Figure 5, Ohshima [38–41] had extensively theorized and modelled the electro-kinetics and electrical conductivity of colloids in suspensions to obtain the following equation:

$$EC^* = EC^\infty \left\{ \frac{1-\phi}{1+2\phi} \left(1 - 3\varphi \left(\frac{e\zeta}{k_b T} \right) f\left(\kappa a, \phi\right) \frac{\sum_{i=1}^{N} z_i^3 n_i^\infty / \lambda_i}{\sum_{i=1}^{N} z_i^2 n_i^\infty / \lambda_i} \right) \right\} \tag{7}$$

where EC^* is the electrical conductivity of the nanofluids, EC^∞ is the electrical conductivity of the base fluid, ζ is the zeta potential, n_i is the number density of the ions, k_b is the Boltzmann constant, T is the absolute temperature, e is the electron charge, z_i, is the particle valence and λ_i is ionic drag coefficient, and κ is the inverse of Debye length. The function $f\left(\kappa a, \varphi\right)$ in Eq. (7) is calculated using:

$$f\left(\kappa a, \varphi\right) = \frac{1}{3a^3\zeta(1+\varphi)(1+2/\varphi)} \times \int_a^b \left(\frac{a^3}{2} + r^3 \right) \left(1 - \frac{a^3}{r^3} \right) \frac{d\psi^{(0)}}{dr} dr \tag{8}$$

In the case of uncharged particles and suspension with very thin electrical double layer (EDL) formation around the particles, Eq. (8) reduces to Maxwell's equation and is presented as:

$$EC_{rel} = \frac{2(1-\phi)}{2+\phi} - 1 \tag{9}$$

Ganguly et al. [38] used Maxwell's classical model on conductivity to fit the electrical conductivity data obtained from aqueous alumina nanofluids without success and this spurs an empirical model based on their experimental data as given as:

$$\left(EC^* - EC^\infty\right) / EC^\infty = 3679.049\phi + 1.085799T - 43.6384 \tag{10}$$

Note the dependence of the relative electrical conductivity on volume fraction in Eq. (11) above. Experimentally, White et al. [20] in an investigation of Propylene glycol/ZnO

nanofluids showed that surface charge which is a measure of electrical conductivity varies with increase in particle volume concentration, and counter ion condensation (a situation whereby electrical conductivity cease to increase or reduces to plateau with further particle loading) occur due to increase in volume concentration.

Nanofluid's pH

The pH and Zeta potential of nanofluids have been investigated to determine the isoelectric point (point of zero charge) as well as the implication of their effects on the agglomeration kinetics (stability) for different nanofluids [39]. The electro-kinetic potentials of the EDL and zeta potential are two related quantities that influence the electrical-viscosity behaviour of nanofluids. Rubio-Hernández et al. [40] studied the effect of pH on nanofluids zeta potential and thickness of EDL. Timofeeva et al. [41] showed that by adjusting the pH values of nanofluids can achieve meaningful reduction in the viscosity value. They reported 34% viscosity reduction by changing the pH of SiC–water nanofluids from 5.5 to 10.3. Conversely, Zhao et al. [42] showed that viscosity increases with pH manipulation. This shows that careful manipulation needs to be carried out with respect to the zeta potentials of the nanofluids so that stability is not compromised.

An important aspect of pH of nanofluids that have not being explored is the effect of temperature variation. The pH affects stability of nanofluids as it dictates the obtainable zeta potential (mV), therefore, the effect of temperature needs to be studied. This will inform the level of modification needed for stability. For instance, if the highest mV is recorded at a particular pH at room temperature and the nanofluids working temperature is proposed to be 70 ^{o}C, then, it is pragmatic to know its pH value at 70 ^{o}C before modification is applied.

RESULTS AND DISCUSSION

The viscosity of γ-Al_2O_3 – glycerol based nanofluids is absent in the literature. In the set of on-going investigations of these nanofluids, first we have considered Einstein's concentration regime between the temperature ranges of 20–70 ^oC. The measured viscosity data of γ-Al_2O_3 – glycerol nanofluids when sonicated for 3 hours is plotted against temperature and presented in Figure 6(a). An inverse relationship exists between the effective viscosity of the nanofluids and temperature. However for volume concentration below 1.0%, the nanofluids behaves more like the base fluid throughout the temperature regime as the data points were in close proximity with the unity line (Figure 6b). The dependence of the effective viscosity of the nanofluids on volume concentration became pronounced above 0.5% volume fraction. It should be noted however, that the trend of the relative viscosity of the nanofluids with temperature for all the concentration considered are all alike, and depending on the volume concentration of the γ-Al_2O_3 critical temperature (beyond which the relative viscosity drops) falls between 55 – 65 ^oC. Sonicating the γ-Al_2O_3–glycerol nanofluids for 6 hours produced a 10% reduction in the viscosity at 2% volume concentration when compared to samples sonicated for 3 hours. Also, a critical temperature of 55 ^oC is noticed for all volume concentration loading applied. The observed trend (Figure 7) showed that this nanofluid can be engineered for application at a relatively high temperature ≥ 70 ^oC, with little or no additional pumping power requirement.

Figure 8 presents the comparison of the Einstein's model [32] and those built on his model by extension, to predict the viscosity of our nanofluids. The models presented by Hosseini et al. [36] was also tested with the present experimental data. However, the classical models [32–34] under predicted the present experimental data while Hosseini's model over predicted the current data with regards to it enhancement with nanoparticles volumetric loading. Conversely, an empirical model of the form presented by Namburu et al. [43] as

shown in Eq. 11 precisely described the dependence of the observed effective viscosity on temperature as shown in Figures 9 and 10. Maximum deviation of this equation with the experimental data is not more than 8.3%. This is also in line with the observation of Kole and Dey [5] and Kulkarni et al. [44] on the use of this expression. Table 2 gives the detail of the curve fitting parameters for all the volume fractions. The coefficients A and B are presented as a function of the volumetric fraction as expressed in Eq. (12) for nanofluids sonicated for 3 hours.

$$\log \mu_{eff} = A\exp(BT) \tag{11}$$

$$\left.\begin{aligned} A &= 0.605\phi^2 - 0.081\phi + 6.451 \\ B &= -0.00104\phi^2 + 0.00413\phi - 0.07857 \end{aligned}\right\} \tag{12}$$

The effect of temperature on the electrical conductivity of the γ-Al_2O_3 – glycerol nanofluids has been studied and the results show that temperature greatly influenced the electrical conductivity as presented in Figure 11. The data presented in Figure 12 reveals the effect of γ-Al_2O_3 nanoparticle loading on the electrical conductivity of glycerol. In the figure, it is convenient to say that the increase in volume fraction does not have much significant effect on the electrical conductivity. However, at 0.5% volume concentration, the highest value of electrical conductivity was recorded across all temperature which later reduced to plateau due to what is termed as counter-ion condensation [20, 45].

Figure 13 showed that, appreciable increment in viscosity occurred as the electrical conductivity reduces due to counter-ion condensation resulting from the increase in volume concentration, especially at low temperature. At temperature of 70 ^{o}C, temperature influence dominates, such that effective viscosity increase was hardly noticed. The addition of γ-Al_2O_3 nanoparticles cause the pH of the continuous phase medium (glycerol) to change from basic to acidic region at room temperature. Though there exists no single model to predict the pH of nanofluids with regards to volume fraction loading, however, at room temperature

increment in volume fraction led to increase in pH value recorded. The influence of temperature does not follow a perfect pattern, but its effect was significant and this will affect the zeta potential of the nanofluids (Figure 14).

CONCLUSIONS

Experimental investigation of γ-Al_2O_3 – Glycerol nanofluids in Einstein concentration regime has been performed for its viscosity, electrical conductivity and pH evolutions in the region of 20–70 ^{o}C. Sonicating for 3 and 6 hours, stable gamma alumina/glycerol nanofluids were prepared and investigated. Effect of 6 hours sonication on the effective viscosity of the nanofluids samples was only pronounced in sample with 2% nanoparticles loading and it was observed that at temperature above 55 ^{o}C there was reduction in the relative viscosity of the nanofluids. Therefore, it makes possible to use this nanofluids for applications above 55 ^{o}C without attracting any severe increase in pumping power. A reduction in the value of effective electrical conductivity was recorded in samples sonicated for 6 hours when compared to values obtained in the 3 hours samples. Change in pH of samples with change in temperature was well pronounced and this means the zeta potential of samples may also vary with temperature, as pH affects zeta potential a great deal. Therefore, the zeta potential of this nanofluid can be studied to determine the region of good stability and to inform which temperature the nanofluid can best be designed to function.

ACKNOWLEDGEMENT

The funding obtained from National Research Foundation of South Africa (NRF), Stellenbosch University/University of Pretoria Solar Hub, CSIR, EEDSM Hub, NAC and RDP is acknowledged and duly appreciated.

NOMENCLATURE

A	curve fitting parameter
b	curve fitting parameter
V_B	Brownian velocity
C	correction factor
d_p	nanoparticle diameter
T_0	reference temperature
m	system property constant
a	particle radius
k_b	Stephan-Boltzmann constant
z	valence
e	charge
T	suspension temperature
X	empirical constant
Y	empirical constant
Z	empirical constant
EC^*	electrical conductivity of the nanofluids
EC^∞	electrical conductivity of the base fluid
EC_{rel}	relative electrical conductivity

Greek Symbols

ζ	zeta potential
κ	inverse of debye length
ρ_p	nanoparticle density
δ	particles centre–centre distance

ϕ_h hydrodynamic volume fraction

γ nanoparticle phase

μ_{eff} effective viscosity

μ_f suspending medium viscosity

ϕ nanoparticle volume fraction

π Pi

$\psi(r)$ electric potential

n_i number density of the ion

$z_{i`}$ particle valence

λ_i drag coefficient

Subscripts

rel relative

e electron

p particle

h hydrodynamic

eff effective

f basefluids

B Brownian

0 reference

b Boltzmann

i ionic species

Superscripts

∞ basefluids

* nanofluids

REFERENCES

[1] Masoumi, N., Sohrabi, N., and Behzadmehr, A., A new model for calculating the effective viscosity of nanofluids, *Journal of Physics D: Applied Physics*, vol. 42, no. 5, pp. 0555011–0555016, 2009.

[2] Maxwell, J.C., *Electricity and Magnetism*, Oxford, Clarendon, 1873.

[3] Choi, S., and Eastman, J., Enhancing thermal conductivity of fluids with nanoparticles, ASME International Mechanical Engineering Congress and Exposition. , San Francisco, CA, 1995.

[4] Sahoo, B.C., Vajjha, R.S., Ganguli, R., Chukwu, G.A., and Das, D.K., Determination of Rheological Behaviour of Aluminium Oxide Nanofluid and Development of New Viscosity Correlations, *Petroleum Science and Technology*, vol. 27, pp. 1757–1770, 2009.

[5] Kole, M., and Dey, T.K., Viscosity of alumina nanoparticles dispersed in car engine coolant, *Experimental Thermal and Fluid Science*, vol. 34, no. 6, pp. 677–683, 2010.

[6] Kumaresan, V., and Velraj, R., Experimental investigation of the thermo-physical properties of water–ethylene glycol mixture based CNT nanofluids, *Thermochimica Acta*, vol. 545, pp. 180–186, 2012.

[7] Naik, M.T., and Sundar, L.S., Heat Transfer and Friction Factor With Water/Propylene Glycol-Based CuO Nanofluid in Circular Tube with Helical Inserts Under Transition Flow Regime, *Heat Transfer Engineering*, vol. 35, no. 1, pp. 53–62, 2014.

[8] Kulkarni, D.P., Namburu, P.K., Ed Bargar, H., and Das, D.K., Convective Heat Transfer and Fluid Dynamic Characteristics of SiO 2 Ethylene Glycol/Water Nanofluid, *Heat Transfer Engineering*, vol. 29, no. 12, pp. 1027–1035, 2008.

[9] Horri, B.A., Ranganathan, P., Selomulya, C., and Wang, H., A new empirical viscosity model for ceramic suspensions, *Chemical Engineering Science*, vol. 66, no. 12, pp. 2798–2806, 2011.

[10] Gupta, S.S., Siva, M. V, Krishnan, S., Sreeprasad, T.S., Singh, P.K., Pradeep, T., and Das, S.K., Thermal conductivity enhancement of nanofluids containing graphene nanosheets, *Journal of Heat Transfer*, vol. 110, no. 084302, pp. 1–7, 2011.

[11] Lee, S., Choi, U.S., and Li, S., Measuring thermal conductivity of fluids containing oxide nanoparticles, *Journal of Heat Transfer*, vol. 121, pp. 280–289, 1999.

[12] Hojjat, M., Etemad, S.G., Bagheri, R., and Thibault, J., Thermal conductivity of non-Newtonian nanofluids: Experimental data and modeling using neural network, *International Journal of Heat and Mass Transfer*, vol. 54, pp. 1017–1023, 2011.

[13] Choi, S.U.S., Enhancing thermal conductivity of fluid with nanoparticles, ASME. pp. 99–109. , New York, 1995.

[14] Nguyen, C.T., Desgranges, F., Galanis, N., Roy, G., Maré, T., Boucher, S., Angue Mintsa, H., Maré, T., and Mintsa, H.A., Viscosity data for Al2O3 - water nanofluid - hysteresis: is heat transfer enhancement using nanofluids reliable?, *International Journal of Thermal Sciences*, vol. 47, no. 2, pp. 103–111, 2008.

[15] Prasher, R., Song, D., and Wang, J., Measurements of nanofluid viscosity and its implication for thermal application, *Applied Physics Letters*, vol. 89, pp. 133108–1–3, 2006.

[16] Corcione, M., A Semi-Empirical Model for Predicting the Effective Dynamic Viscosity of Nanoparticle Suspensions, *Heat Transfer Engineering*, vol. 33, no. 7, pp. 575–583, 2012.

[17] Cerqueira, I.G., Mota, C.A. a., Nunes, J.S., Cotta, R.M., Balbo, A., and Achete, C. a., Experiments and Simulations of Laminar Forced Convection With Water–Alumina Nanofluids in Circular Tubes, *Heat Transfer Engineering*, vol. 34, no. 5-6, pp. 447–459, 2013.

[18] Celata, G.P., D'Annibale, F., Mariani, A., Saraceno, L., D'Amato, R., and Bubbico, R., Heat Transfer in Water-Based SiC and TiO 2 Nanofluids, *Heat Transfer Engineering*, vol. 34, no. 13, pp. 1060–1072, 2013.

[19] Sarojini, K.G.K., Manoj, S. V., Singh, P.K., Pradeep, T., and Das, S.K., Electrical conductivity of ceramic and metallic nanofluids, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 417, pp. 39–46, 2013.

[20] White, S.B., Shih, A.J., and Pipe, K.P., Investigation of the electrical conductivity of propylene glycol-based ZnO nanofluids, *Nanoscale Research Letters*, vol. 6, pp. 346–350, 2011.

[21] Wang, J.J., Zheng, R.T., Gao, J.W., and Chen, G., Heat conduction mechanisms in nanofluids and suspensions, *Nano Today*, vol. 7, no. 2, pp. 124–136, 2012.

[22] Ghazvini, M., Akhavan-Behabadi, M. a., Rasouli, E., and Raisee, M., Heat Transfer Properties of Nanodiamond–Engine Oil Nanofluid in Laminar Flow, *Heat Transfer Engineering*, vol. 33, no. 6, pp. 525–532, 2012.

[23] Murshed, S.M.S., Simultaneous Measurement of Thermal Conductivity, Thermal Diffusivity, and Specific Heat of Nanofluids, *Heat Transfer Engineering*, vol. 33, no. 8, pp. 722–731, 2012.

[24] Vajjha, R.S., Das, D.K., and Mahagaonkar, B.M., Density Measurement of Different Nanofluids and Their Comparison With Theory, *Petroleum Science and Technology*, vol. 27, no. 6, pp. 612–624, 2009.

[25] Wang, X., Xu, X., and Choi, S.U.., Thermal Conductivity of Nanoparticle - Fluid Mixture, *Journal of Thermophysics and Heat Transfer*, vol. 13, no. 4, pp. 474–480, 1999.

[26] Chandrasekar, M., Suresh, S., and Bose, A.C., Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al2O3/water nanofluid, *Experimental Thermal and Fluid Science*, vol. 34, no. 2, pp. 210–216, 2010.

[27] Pastoriza-Gallego, M.J., Lugo, L., Legido, J.L., and Piñeiro, M.M., Thermal conductivity and viscosity measurements of ethylene glycol-based Al2O3 nanofluids., *Nanoscale research letters*, vol. 6, no. 1, pp. 221, 2011.

[28] Fedele, L., Colla, L., and Bobbo, S., Viscosity and thermal conductivity measurements of water-based nanofluids containing titanium oxide nanoparticles, *International Journal of Refrigeration*, vol. 35, no. 5, pp. 1359–1366, 2012.

[29] Suryanarayana, C., and Norton, M.G., *X- Ray Diffraction A Practica 1 Approach*, Plenum Press, New York, 1998.

[30] Segur, J., and Oberstar, H., Viscosity of glycerol and its aqueous solutions, *Industrial & Engineering Chemistry*, no. september, pp. 5–8, 1951.

[31] Miner, C.S., and Dalton, N.N., Glycerine : an overview, *Chemical Society Monograph*, vol. 117, 1953.

[32] Einstein, A., A New Determination of Molecular Dimensions, *Annalen der Physik*, vol. 4, no. 19, pp. 37–62, 1906.

[33] Batchelor, G., The effect of Brownian motion on the bulk stress in the suspension of sphrerical particles, *Journal of Fluid Mechanics*, vol. 83, no. 01, pp. 97–117, 1977.

[34] Brinkman, H.C., The viscosity of concentrated suspensions and solutions, *Journal of Chemical Physics*, vol. 20, no. 4, pp. 571, 1952.

[35] Prasher, R., Bhattacharya, P., and Phelan, P.E., Brownian-Motion-Based Convective-Conductive Model for the Effective Thermal Conductivity of Nanofluids, *Journal of Heat Transfer*, vol. 128, no. 6, pp. 588–595, 2006.

[36] Hosseini, S., Moghadassi, A., and Henneke, D.E., A new dimensionless group model for determining the viscosity of nanofluids, *J. Therm Anal calorim*, vol. 100, pp. 873–877, 2010.

[37] Delgado, A. V, González-caballero, F., Hunter, R.J., and Koopal, L.K., Measurement and interpretation of electrokinetic phenomena ☆, *Journal of colloid and interface science*, vol. 309, pp. 194–224, 2007.

[38] Ganguly, S., Sikdar, S., and Basu, S., Experimental investigation of the effective electrical conductivity of aluminum oxide nanofluids, *Powder Technology*, vol. 196, no. 3, pp. 326–330, 2009.

[39] Chandrasekar, M., and Suresh, S., A Review on the Mechanisms of Heat Transport in Nanofluids, *Heat Transfer Engineering*, vol. 30, no. 14, pp. 1136–1150, 2009.

[40] Rubio-Hernández, F.J., Ayúcar-Rubio, M.F., Vlaázquez-Navarro, J.F., and Galindo-Rosales, F.J., Intrinsic viscosity of SiO2, Al2O3 and TiO2 aqueous suspensions, *Journal of Colloid and Interface Science*, vol. 298, pp. 967–972, 2006.

[41] Timofeeva, E. V., Routbort, J.L., and Singh, D., Particle shape effects on thermophysical properties of alumina nanofluids, *Journal of Applied Physics*, vol. 106, no. 1, pp. 014304–1 – 10, 2009.

[42] Zhao, J., Luo, Z., Ni, M., and Cen, K., Dependence of nanofluid viscosity on particle size and pH value, *Chin. Phys. Lett*, vol. 26, no. 066202, pp. 1–3, 2009.

[43] Namburu, P.K., Kulkarni, D.P., Misra, D., and Das, D.K., Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture, *Experimental Thermal and Fluid Science*, vol. 32, pp. 397–402, 2007.

[44] Kulkarni, D.P., Namburu, P.K., Ed Bargar, H., and Das, D.K., Convective Heat Transfer and Fluid Dynamic Characteristics of SiO 2 Ethylene Glycol/Water Nanofluid, *Heat Transfer Engineering*, vol. 29, no. 12, pp. 1027–1035, 2008.

[45] Ohshima, H., Electrokinetic phenomena in a dilute suspension of spherical colloidal particles in a salt-free medium, *Colloids and Surfaces A: Physicochem. Eng. Aspects*, vol. 222, pp. 207–211, 2003.

Table 1 Electrical conductivity calibration values

Measurements	Temperature (^{o}C)	Electrical conductivity (µS/cm)
1st Measurement	25.0	1412
	24.9	1415
	24.8	1414
2nd Measurement	25.0	1413
	24.9	1412
	24.8	1415
3rd Measurement	25.0	1412
	24.9	1415
	24.8	1415

Table 2: Curve fitting parameters A and B (R^2 values = 0.99517)

%Volume fraction	0%	0.1%	0.5%	1%	2%
A	6.68601	6.19592	6.51088	7.06113	8.691
B	-0.07844	-0.07808	-0.07734	-0.07508	-0.07456

LIST OF FIGURE CAPTIONS

Figure 1 TEM image of γ-Al_2O_3 (a) nominal diameter of 17 nm (b) 50 nm diameter taken at Image Laboratory, University of Pretoria South Africa

Figure 2: γ-Al_2O_3 characterization spectra (a) X-Ray diffraction pattern (b) EDX spectrum (inset is SEM showing analysis spot)

Figure 3 Viscosity – temperature curve of 99.5% Glycerol after calibration

Figure 4 Viscosity-temperature-time monitor of the viscometer

Figure 5 Equivalent cell model.

Figure 6 Viscosity – temperature curve of γ- Al_2O_3 – glycerol nanofluids for various volume fractions with 3 hours sonication time. (a) apparent viscosity, (b) relative viscosity

Figure 7 Viscosity – temperature curve of γ- Al_2O_3 – glycerol nanofluids with 6 hours sonication time. (a) apparent viscosity, (b) relative viscosity

Figure 8: Relative viscosity of γ-Al_2O_3 – glycerol experimental data at 20 ^oC, Einstein [32], Batchelor [33], Brinkman [34], Hosseini et al. [36] models and polynomial curve fitting model ($R^2 = 0.9953$)

Figure 9 γ-Al_2O_3 –glycerol nanofluids effective viscosity temperature dependence fit of Eq. (9) on 3 hours sonication data. (a) log-linear scale (b) linear-linear scale. CF – Curve-fit

Figure 10 γ-Al_2O_3 –glycerol nanofluids effective viscosity temperature dependence fit of Eq. (9) on 6 hours sonication data. (a) log-linear scale (b) linear-linear scale. CF – Curve-fit

Figure 11 γ-Al_2O_3 –glycerol nanofluids electrical conductivity-temperature plot (a) 3 hours sonicated samples (b) 6 hours sonicated samples. Note the effect of counter-ion condensation above 0.5% and 1.0% for 3 and 6 hours samples respectively

Figure 12 Electrical conductivity behaviour to increase in particle volume fration of γ-Al_2O_3 – glycerol nanofluids

Figure 13 Effect of Electrical conductivity variations on apparent viscosity of γ-Al_2O_3 glycerol nanofluids. AV – Apparent viscosity, EC – Electrical conductivity.

Figure 14 Trends of pH variation with temperature increment

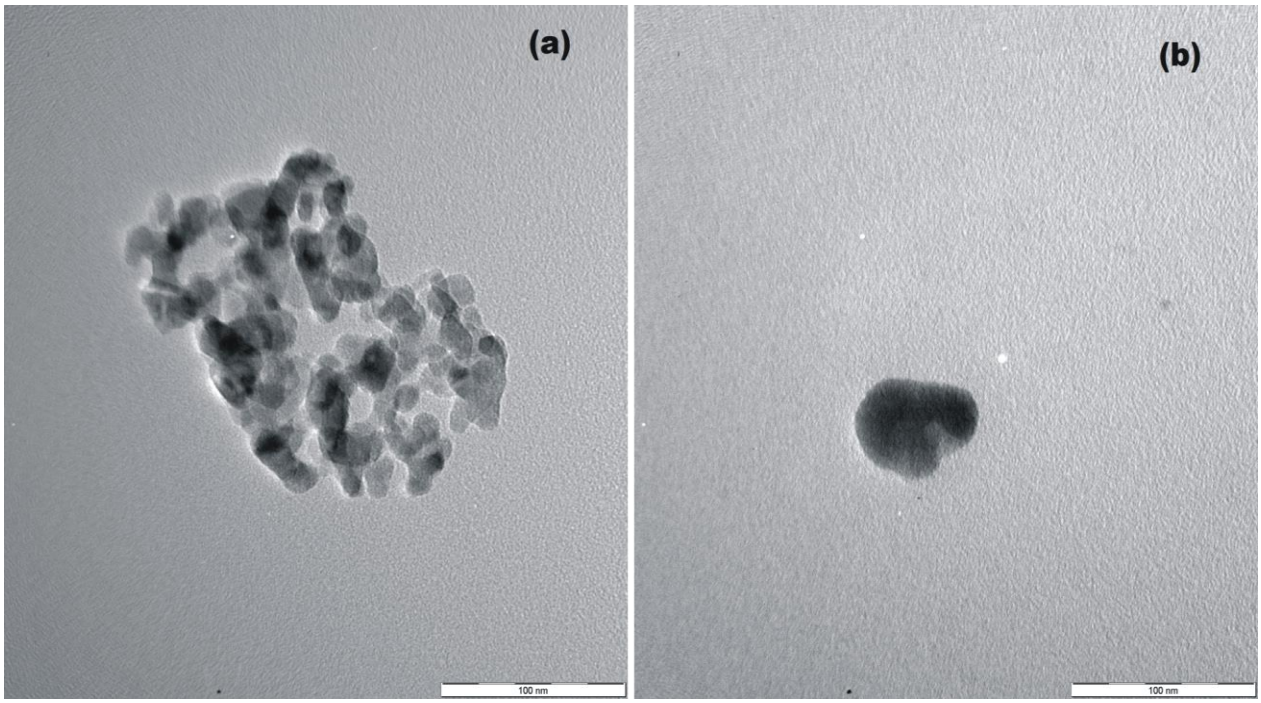

Figure 1 TEM image of γ-Al_2O_3 (a) nominal diameter of 17 nm (b) 50 nm diameter taken at Image Laboratory, University of Pretoria South Africa.

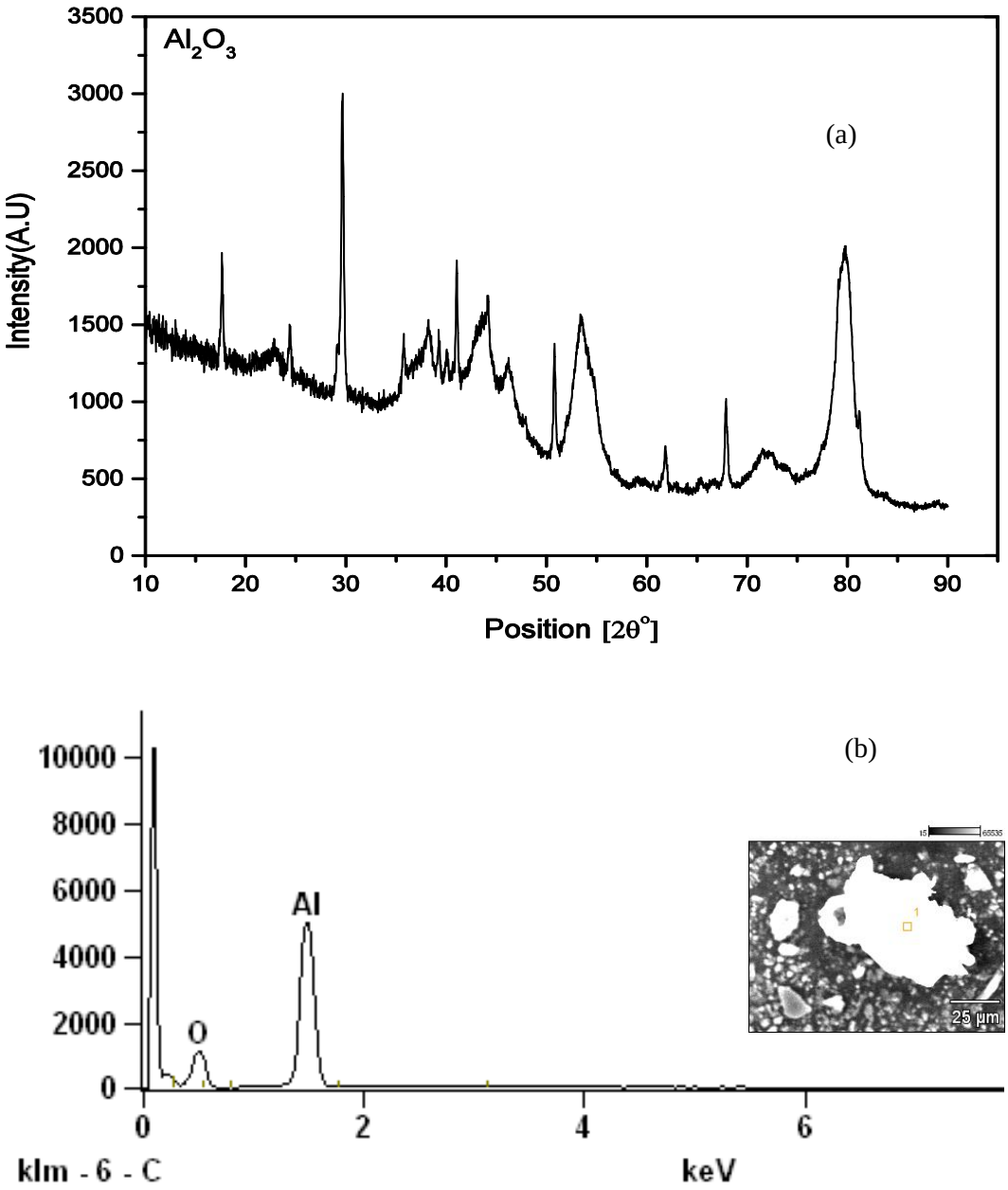

Figure 2: γ-Al_2O_3 characterization spectra (a) X-Ray diffraction pattern (b) EDS spectrum (inset is SEM showing analysis spot)

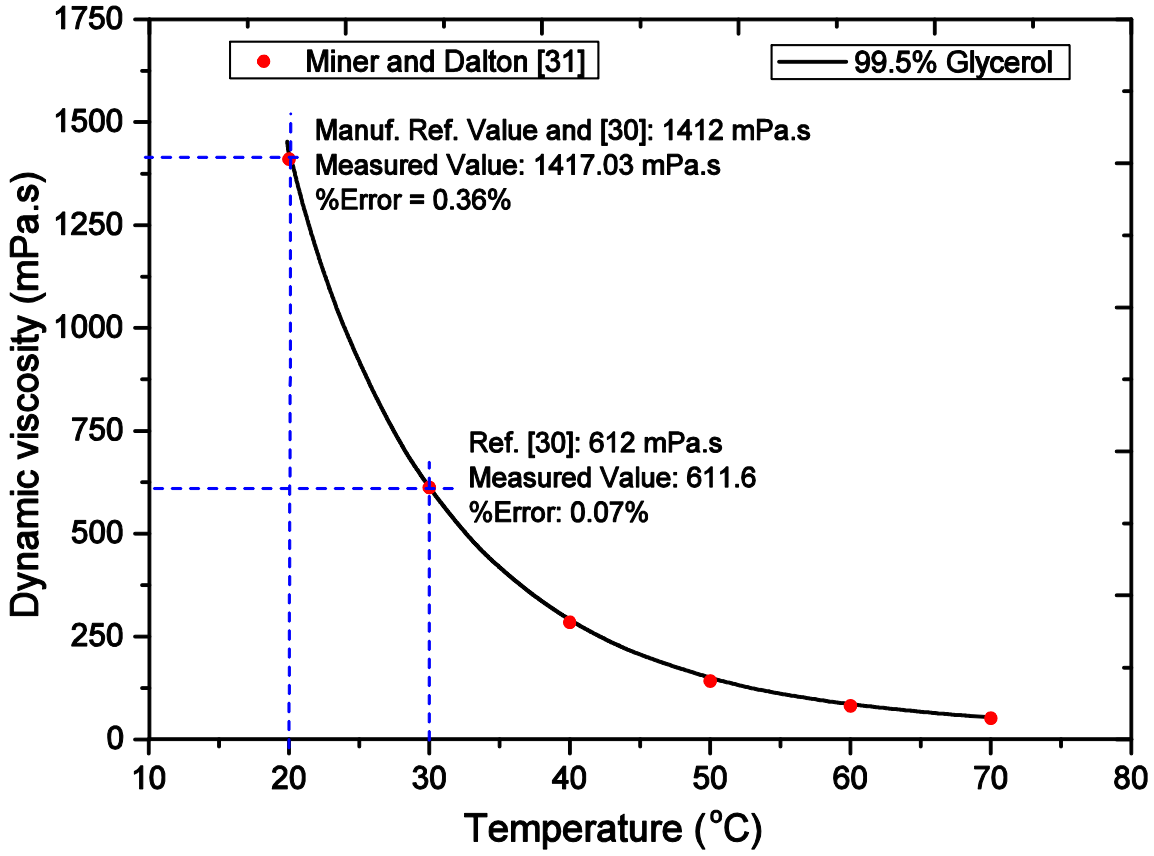

Figure 3: Viscosity – temperature curve of 99.5% Glycerol after calibration

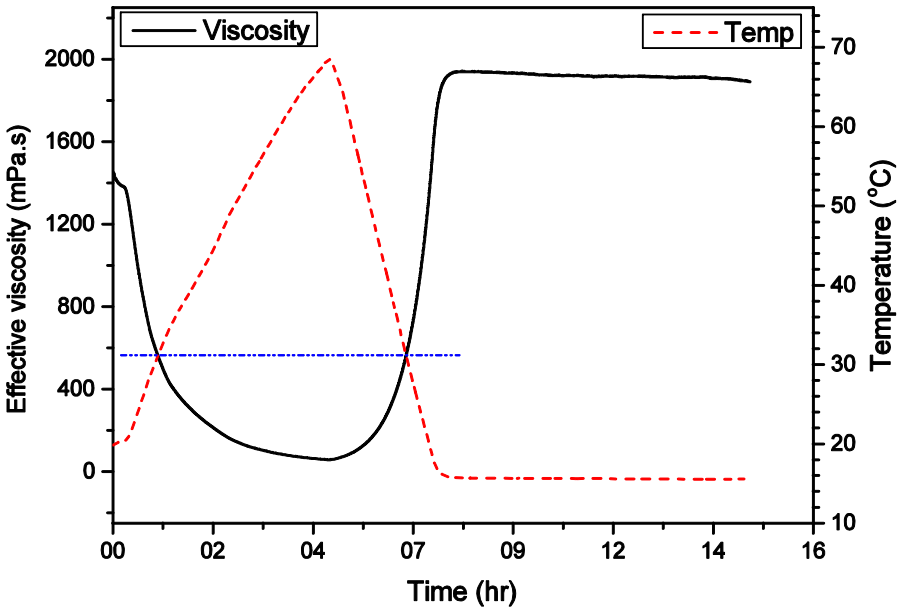

Figure 4: Viscosity-temperature-time monitor of the viscometer

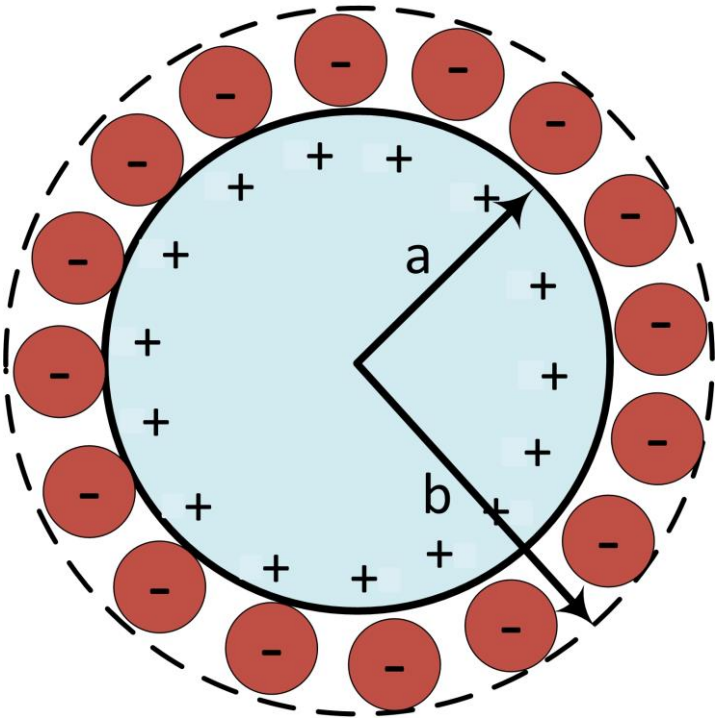

Figure 5 Equivalent cell model

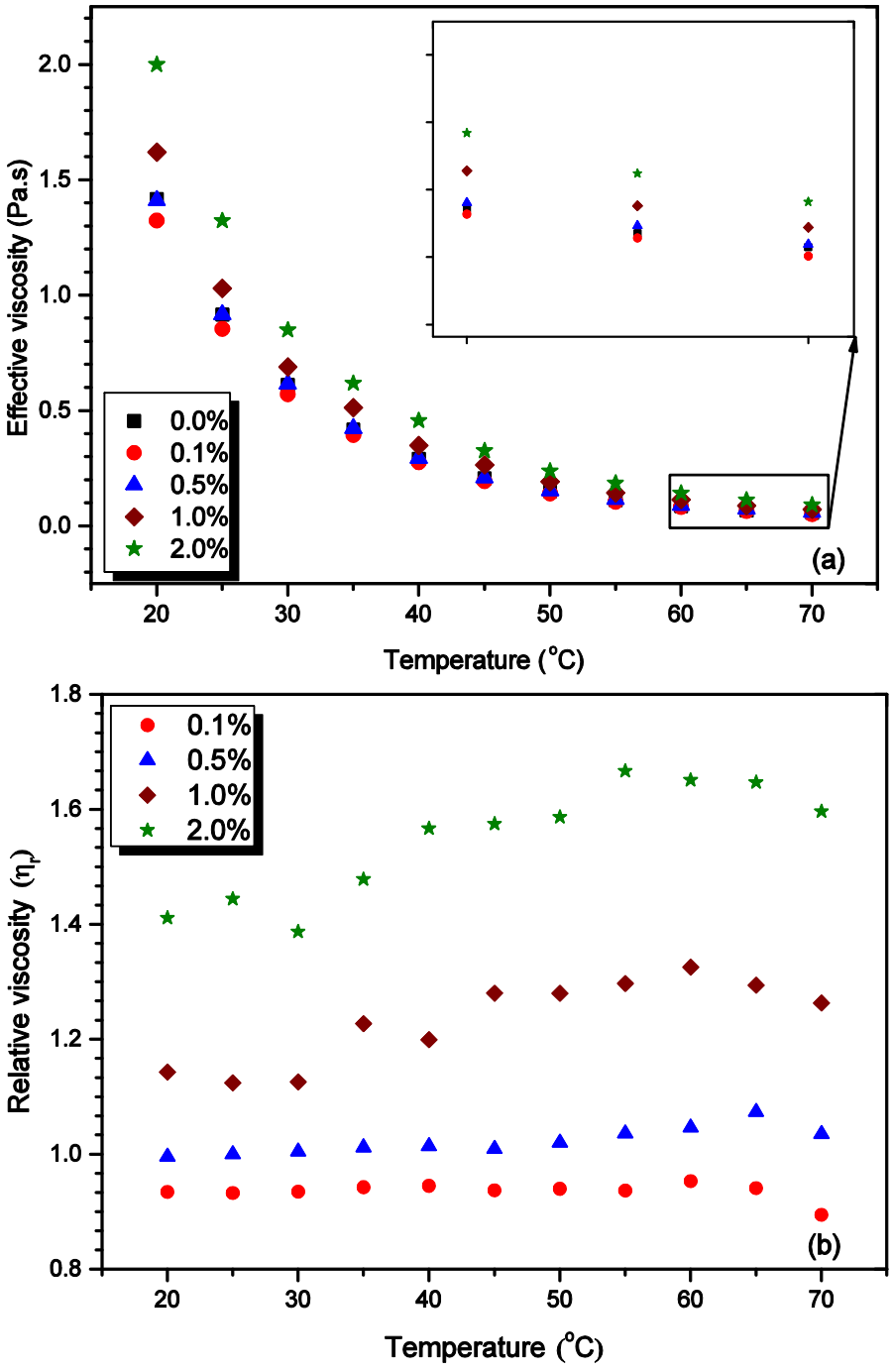

Figure 6: Viscosity – temperature curve of γ- Al_2O_3 – glycerol nanofluids for various volume fractions with 3 hours sonication time. (a) effective viscosity, (b) relative viscosity.

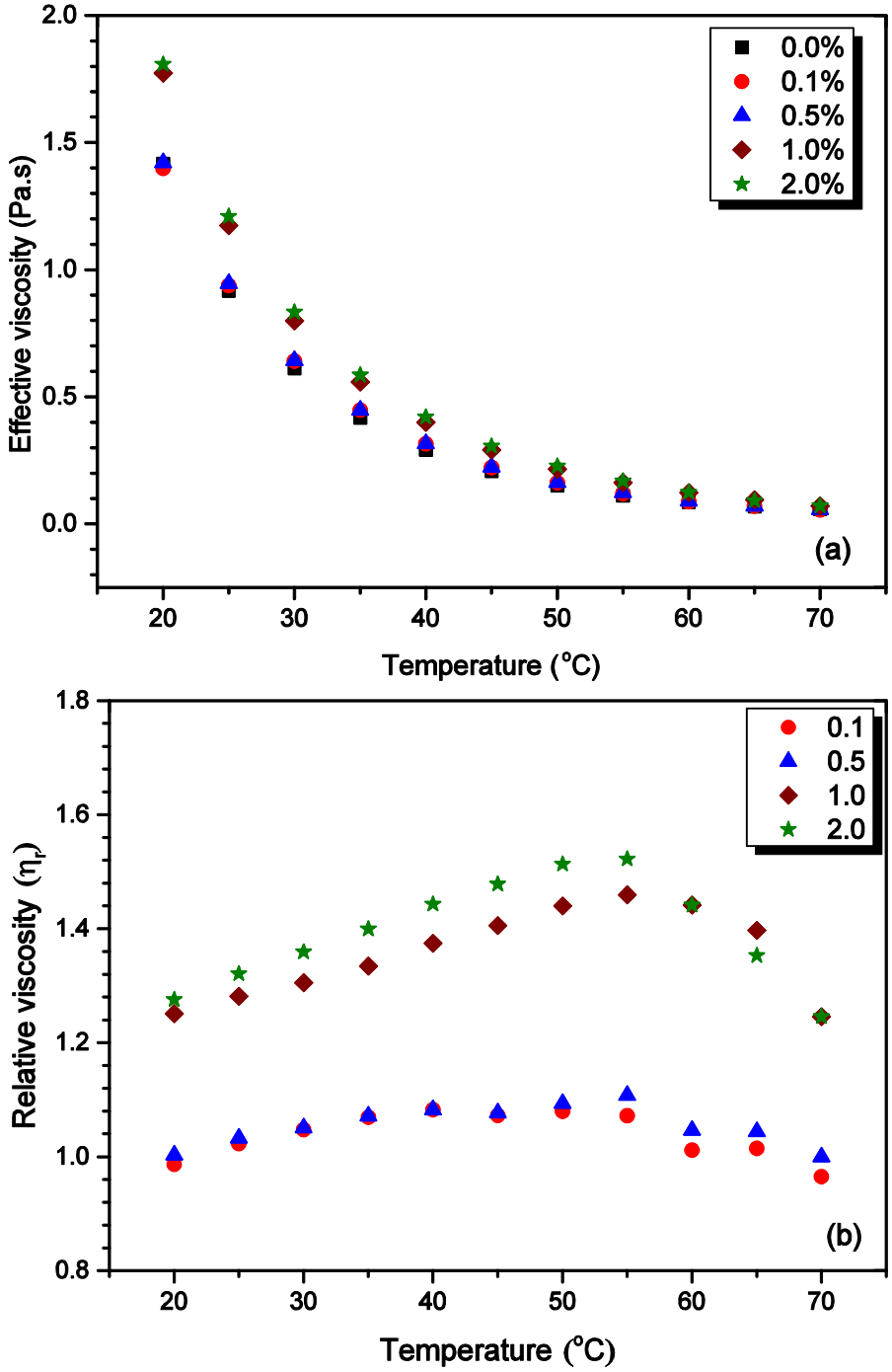

Figure 7: Viscosity – temperature curve of γ- Al_2O_3 – glycerol nanofluids with 6 hours sonication time. (a) effective viscosity, (b) relative viscosity.

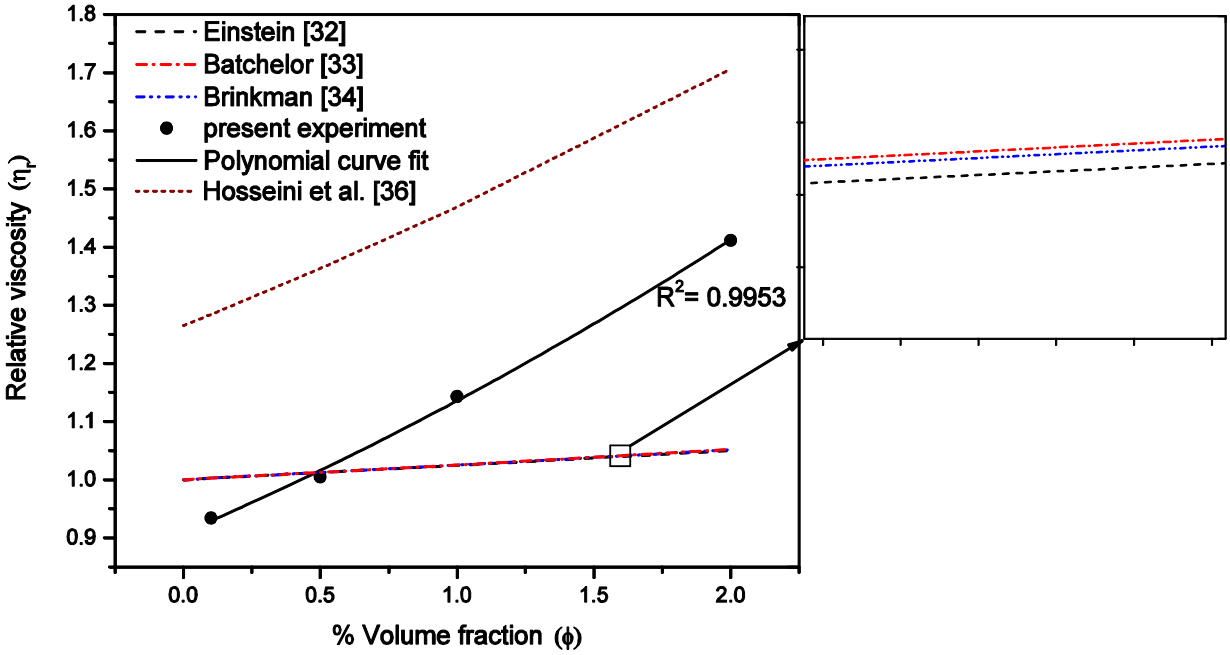

Figure 8: Relative viscosity of γ-Al_2O_3 – glycerol experimental data at 20 ^oC, Einstein [32], Batchelor [33], Brinkman [34], Hosseini et al. [36] models and polynomial curve fitting model (R^2 = 0.9953).

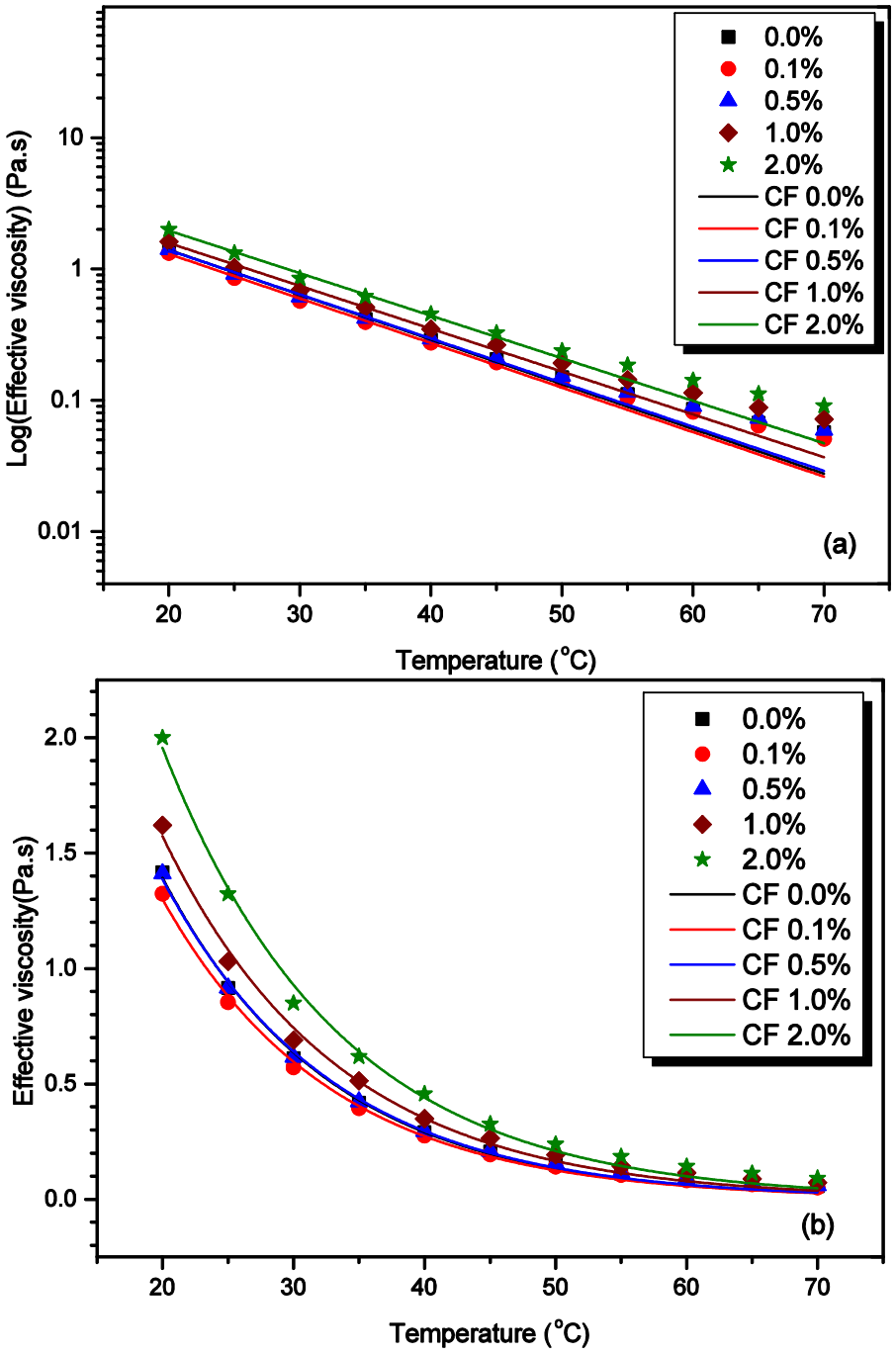

Figure 9: γ-Al_2O_3 –glycerol nanofluids effective viscosity temperature dependence fit of Eq. (9) on 3 hours sonication data. (a) log-linear scale (b) linear-linear scale. CF – Curve-fit.

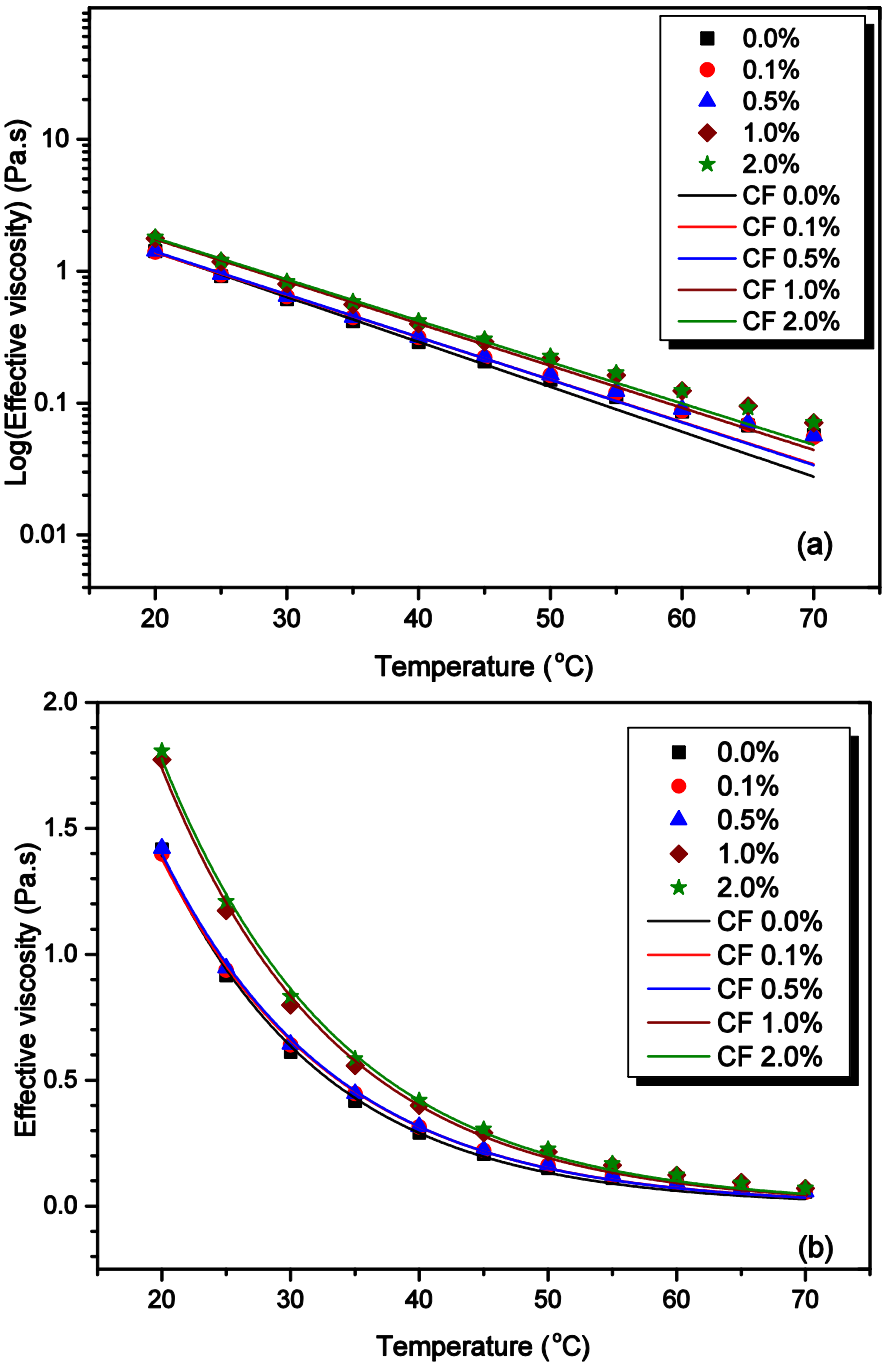

Figure 10: γ-Al_2O_3 –glycerol nanofluids effective viscosity temperature dependence fit of Eq. (9) on 6 hours sonication data. (a) log-linear scale (b) linear-linear scale. CF – Curve-fit.

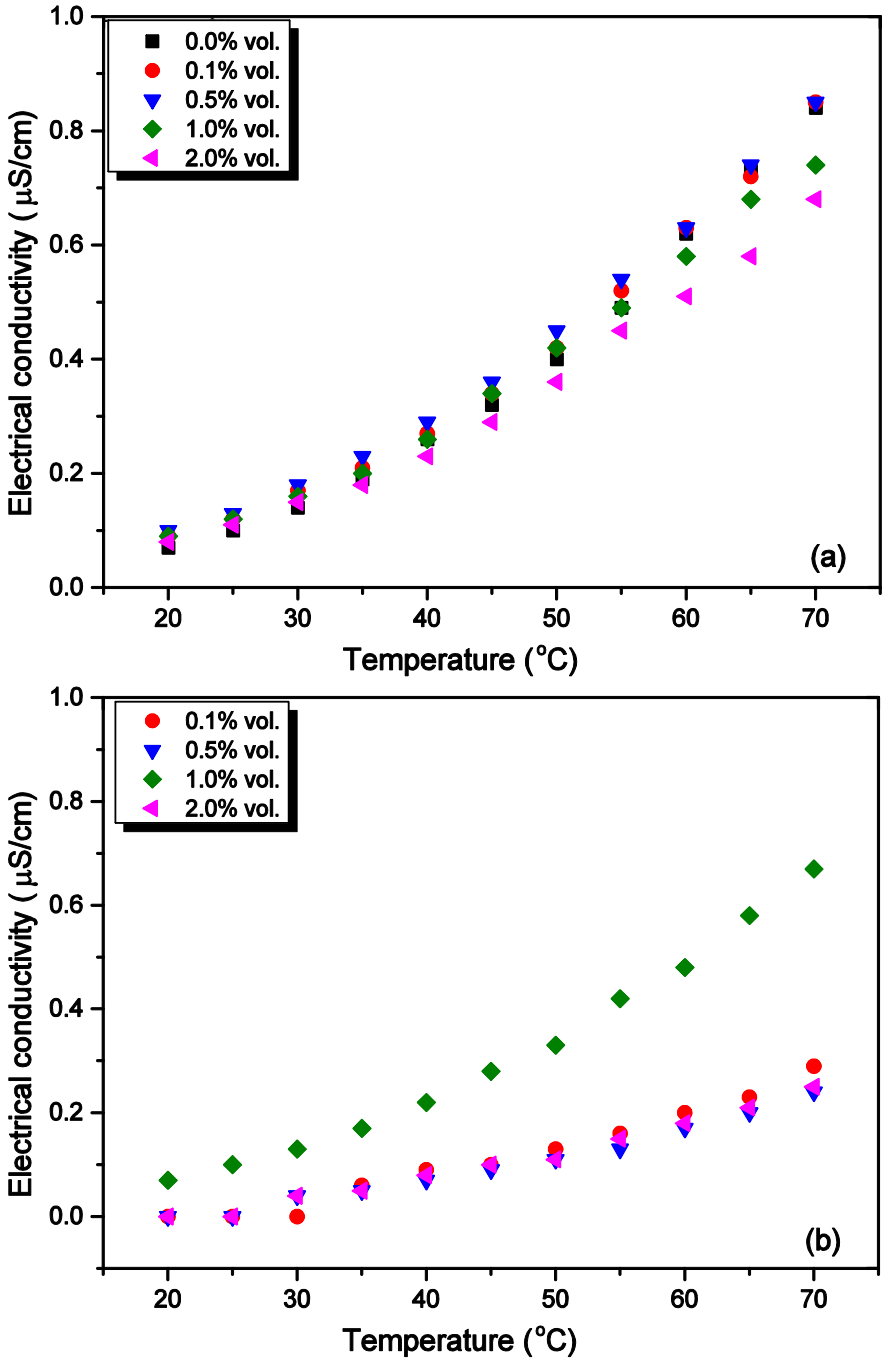

Figure 11: γ-Al_2O_3–glycerol nanofluids electrical conductivity-temperature plot (a) 3 hours sonicated samples (b) 6 hours sonicated samples. Note the effect of counter-ion condensation above 0.5% and 1.0% for 3 and 6 hours samples respectively.

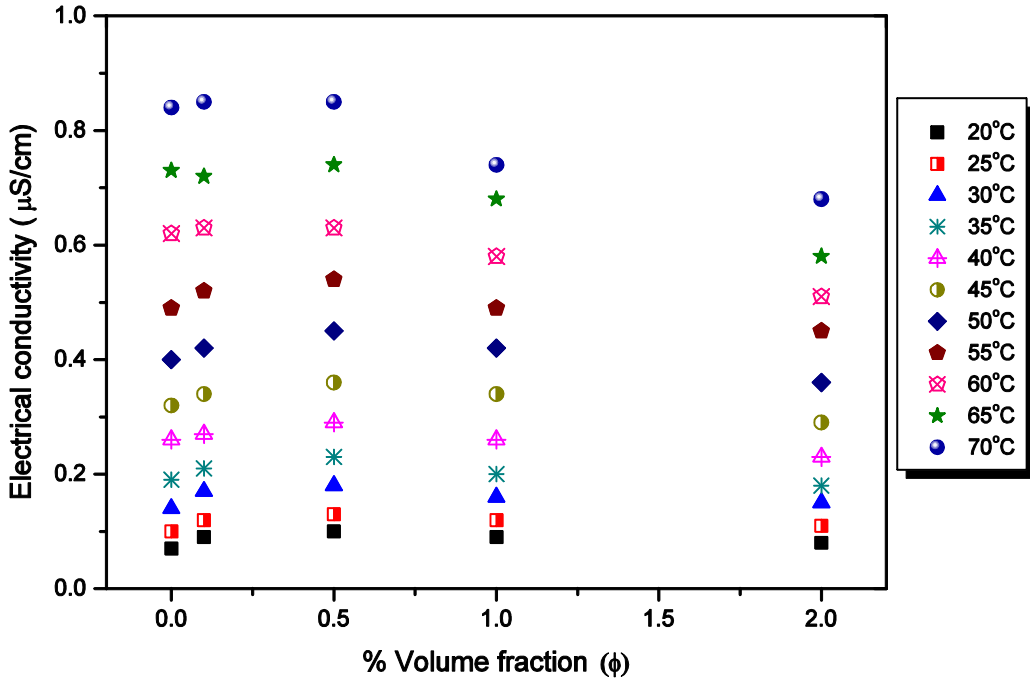

Figure 12: Electrical conductivity behaviour to increase in particle volume fration of γ-Al_2O_3 –glycerol nanofluids.

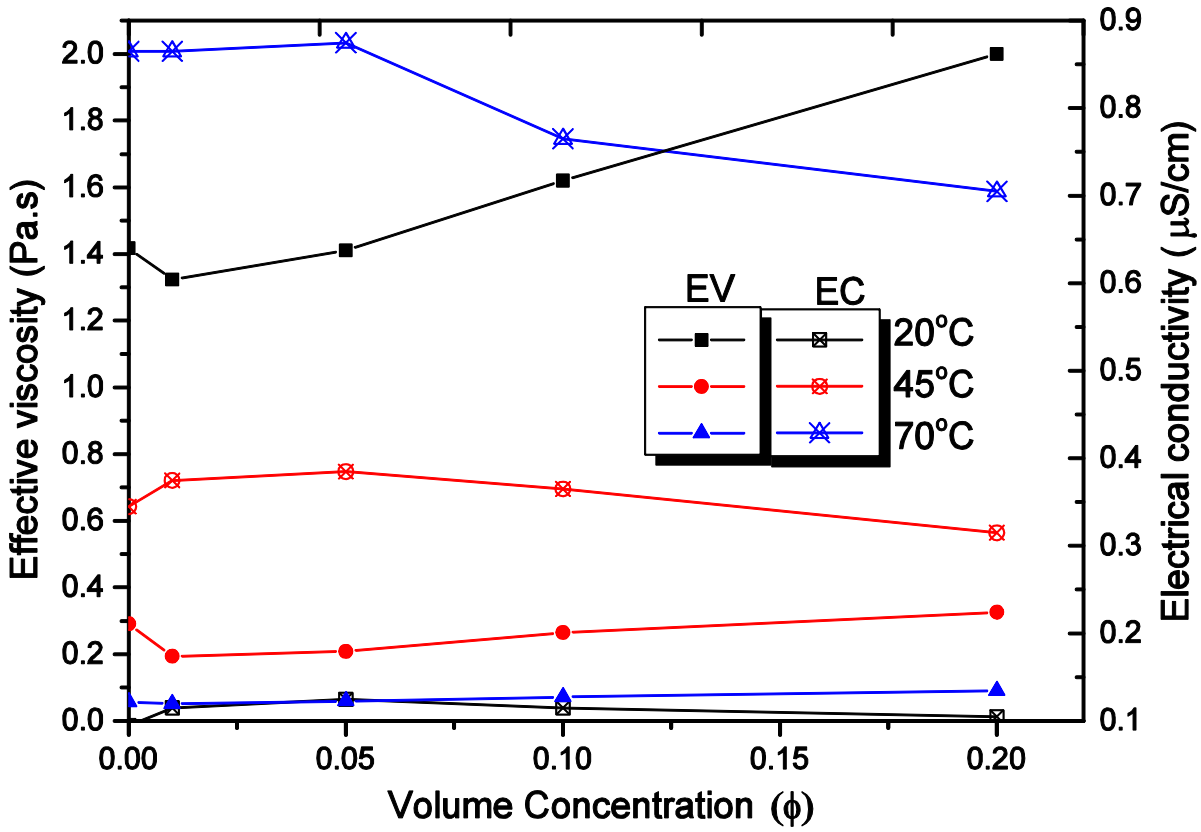

Figure 13: Effect of Electrical conductivity variation on effective viscosity of γ-Al_2O_3 –glycerol nanofluids. EV – Apparent viscosity, EC – Electrical conductivity.

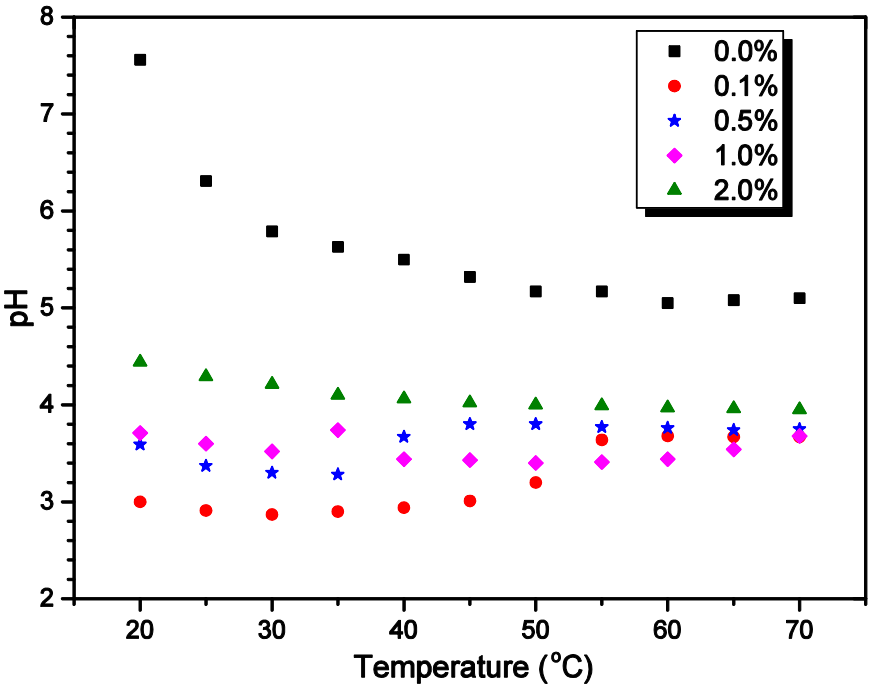

Figure 14: Trends of pH variation with temperature increment.

Saheed A. Adio is currently a PhD student at the Department of Mechanical and Aeronautical Engineering, University of Pretoria, South Africa. He obtained his B.Sc. degrees in Mechanical Engineering at the Obafemi Awolowo University, Ile-Ife, Nigeria in 2005 with Second Class Upper and after few years of working obtained his M.Sc. in 2010 with distinction from the same university. He is currently working on the mathematical modeling and experimental investigation into the effective viscosity of nanofluids under the supervision of Dr. M. Sharifpur and Prof. J. P. Meyer.

Mohsen Sharifpur is a senior lecturer and also responsible for nanofluid research laboratory in the Department of Mechanical and Aeronautical Engineering at the University of Pretoria. He received his BSc in Mechanical Engineering from Shiraz University, Iran. He completed his MSc in Nuclear Engineering, and then he received a full scholarship for PhD study in Mechanical Engineering (thermal-fluid) from Eastern Mediterranean University. He was the only one among all the postgraduate students who received four out of four for the CGPA when he received his PhD. He is the author and co-author of more than 40 articles and conference papers. His research interests include convective multiphase flow, thermal-fluid behaviour of nanofluids, porous media and waste heat to work in thermal systems. He is also a reviewer for notable accredited journals.

Josua Meyer obtained his BEng (cum laude) in 1984, MEng (cum laude) in 1986, and his PhD in 1988, all in mechanical engineering from the University of Pretoria and is registered as a professional engineer. After his military service (1988 – 1989), he accepted a position as Associate Professor in the Department of Mechanical Engineering at the Potchefstroom University in 1990. He was Acting Head and Professor in Mechanical Engineering before accepting a position as Professor in the Department of Mechanical and Manufacturing Engineering at the Rand Afrikaans University in 1994. He was Chairman of Mechanical Engineering from 1999 until the end of June 2002, after which he was appointed Professor and Head of the Department of Mechanical and Aeronautical Engineering at the University of Pretoria from 1 July 2002. At present he is the Chair of the School of Engineering. He specialises in heat transfer, fluid mechanics and thermodynamic aspects of heating, ventilation and air-conditioning. He is the author and co-author of more than 450 articles, conference papers and patents and has received various prestigious awards for his research. He is also a fellow or member of various professional institutes and societies such as the South African Institute for Mechanical Engineers, South African Institute for Refrigeration and Air-Conditioning, American Society for Mechanical Engineers, American Society for Air-Conditioning, Refrigeration and Air-Conditioning, and is regularly invited to be a keynote speaker at local and international conferences. He has also received various teaching and exceptional achiever awards. He is an associate editor of *Heat Transfer Engineering* and Editor of the *Journal of Porous Media*.