International Journal of Refrigeration 86 (2018) 356–372

Contents lists available at ScienceDirect

International Journal of Refrigeration

journal homepage: www.elsevier.com/locate/ijrefrig

Experimental studies on thermal and rheological behaviour of TiO_2-PAG nanolubricant for refrigeration system

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ARTICLE INFO

Article history:
Received 23 September 2017
Revised 3 November 2017
Accepted 7 November 2017

Keywords:
Nanolubricant
Polyalkylene glycol
Thermal conductivity
Rheology

ABSTRACT

Thermal conductivity and rheological properties of TiO_2-PAG nanolubricant for 0.07 to 0.8% volume fractions in the temperature range 20°C to 90°C have been investigated. The nanolubricant is prepared using two step method. The results showed that the thermal conductivity and viscosity of nanolubricant increase with increase in volume fraction and decrease with increase in temperature. The measured thermal conductivity and viscosity are compared with that obtained from classical models and the classical models fail to predict these properties accurately. The highest thermal conductivity and viscosity are observed to be 1.38 and 10 times greater than that of pure lubricant for 0.8% and 0.6% volume fraction respectively. Non-Newtonian shear thinning behaviour of TiO_2-PAG nanolubricant was confirmed by computing power law and consistency indices. The optimum value of volume fraction for refrigeration application is 0.4%.

1. Introduction

The enhancement of thermal conductivity of fluids by the dispersion and stabilisation of solid particles was established by Maxwell (Levin and Miller, 1981) more than a century ago. The term nanofluid was coined by Choi (Eastman et al., 1997; Lee et al., 1999) at Argonne National Laboratory, USA. The purpose behind the development of nanofluids is to enhance the thermophysical and heat transfer performance of conventional heat transfer fluids. The nanofluids exhibit higher thermal performance compared to conventional heat transfer fluids (Rashmi et al., 2014; Mahmoudi et al., 2016; Hajmohammadi, 2017a). This leads to the best hope for lubricants based nanofluids as well. Nanolubricant is a new class of lubricant produced by dispersing nanosized particles of metals, metal oxides, carbon and its derivatives into conventional lubricating oils. Most significant current thoughts in refrigeration industry is cost reduction and energy saving. Refrigerators and air conditioners are appliances which contribute to the most significant energy consumption in the domestic sector. Lot of energy is expending in the form of frictional power in the refrigerant compressors. Trivial savings can contribute a huge impact in the world energy scenario. Modern refrigeration and air-conditioning systems are more efficient because of great design improvements; nevertheless there is still little effort to use nanolubricants in them. Dispersion of nanoparticles into base oils is a promising approach towards enhancing certain characteristics, such as thermal, rheological and tribological properties. The viscosity and rheological characteristics are probably more crucial parameters to be measured and analysed along with thermal conductivity. If the viscosity of the lubricant is reformed, the effect will reflect in the friction coefficient and frictional power loss in refrigerant compressors and ultimately result in the improvement in Coefficient of performance (COP). In a vapour compression refrigeration system when the refrigerant is circulated through the compressor it will carry traces of nanolubricant so that the other parts of the system will have nanolubricant-refrigerant mixture. Presence of nanoparticle in the refrigerant enhances the flow boiling and condensation heat transfer characteristics thereby improving the performance of the refrigeration system. The time dependent physical properties of nanofluids and the reversibility of sedimentation and adsorption on the surface of the tubes are important factors for sustainable running of nanofluids especially with refrigerants and have to be rigorously studied. The study on dynamic characteristics of ammonia- water based TiO_2 nanofluids through a circulating device was conducted by Yang et al. (2017) and the study revealed that, TiO_2 nanofluids with SDBS surfactant exhibits better dispersion for a long-term use. Kumaresan et al. (2013) explored the potential of nanofluid phase change material (NFPCM) in energy saving in a chiller integrated with the Cool Thermal Energy Storage (CTES) system and reported that the use of NFPCM reduces the energy consumption by 6–9%. Few studies are reported in literature

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https://doi.org/10.1016/j.ijrefrig.2017.11.014
0140-7007/

Nomenclature

English symbols

m	mass of nanoparticles [g]
k	thermal conductivity $[\mathrm{W(mK)}^{-1}]$
T	temperature [K]
Cp	specific heat $[\mathrm{kJ(kgK)}^{-1}]$

Greek symbols

β	ratio of nanolayer thickness to original radius
φ	volume fraction [%]
μ	dynamic viscosity [cP]
ρ	density $[\mathrm{kg.m}^{-3}]$
τ	shear stress $(\mathrm{dyne\ (cm)}^{-1})$
γ	shear rate (s^{-1})

Subscripts

bf	base fluid
eff	effective
p	particle

Abbreviations

COP	coefficient of performance
CTES	cool thermal energy storage
EER	energy efficiency ratio
NFPCM	nanofluid phase change material
PAG	polyalkylene glycol
SDBS	sodium dodecylbenzene sulfonate
SEM	scanning electron microscope
TEM	transmission electron microscope

regarding the thermophysical and rheological characteristics of nanolubricants. Extensive experimental studies are required to establish the thermal and rheological potentials of lubricants appended with nanoparticles before the commercial use of nanolubricants. Thermal conductivity and viscosity are the thermophysical characteristics of nanofluids that have been studied by many investigators and shown that thermal conductivity increases with increase in volume fraction and temperature (Duangthongsuk and Wongwises, 2009; Buonomo et al., 2015). Viscosity plays an important role in rheological behaviour of fluids (Afrand et al., 2016; Akbari et al., 2016). Nanoparticles loading and particle size can affect viscosity, thus rheological behaviour of a nanofluids. Viscosity of nanofluids increases with increase in volume fraction and particle size and a reverse trend is observed with increase in temperature (Hemmat Esfe and Saedodin, 2014; Serebryakova et al., 2015; Bobbo et al., 2012). Temperature and particle shape play a vital role in the viscosity and thermal conductivity of nanofluids (Jeong et al., 2013; Jiang et al., 2017). Rheological behaviours of nanofluids are quite different from each other and a specific behaviour cannot be established for all nanofluids. Viscosity of Ag-heat transfer oil was studied by Aberoumand et al. (2016), and their results indicated that the base fluid which exhibits Newtonian behaviour changes into non-Newtonian while adding even a small amounts of nanoparticles. Kedzierski (2001, 2014) shown that lubricant viscosity significantly influences the boiling characteristics of refrigerant/lubricant mixtures. The prospect of modern tribology has been expanded with the advent of nanomaterial-based lubricants. According to the investigations that have been conducted, presence of nanoparticles in oils may enhance their lubricating properties compared to base fluid; this would in turn result in increase in the durability of the components (Kole and Dey, 2013; Akhavan-Behabadi et al., 2015; Hemmat Esfe et al., 2015, 2014).The anti-wear and friction reduction capabilities were considerably improved when machine oil is appended with ZrO_2 nanoparticles (Ma et al., 2010). Addition of diamond and SiO_2 nanoparticles in liquid paraffin at a tiny concentration have better anti-wear and anti friction properties than the pure paraffin oil (Peng et al., 2009). Extreme pressure (EP) testing of cutting fluids modified by diamond and molybdenum disulfide (MoS_2) nanoparticles showed that nanofluids containing 2–4% MoS_2 nanoparticles increased the load carrying capacity up to 16% (Mosleh et al., 2017). It has also been reported that the nanoparticles get dragged into contact area and interact with the surface, causing an improvement in the tribological behaviour of the lubricating oil (Rasheed et al., 2016). There are also some studies in the literature reporting the performance improvement of HVAC systems that use nanolubricants (Subramani and Prakash, 2011; Kumar and Elansezhian, 2012; Sanukrishna et al., 2017). Their studies show that addition of oxide nanoparticles in compressor oil increases the freezing capacity and COP. Wang et al. (2010), showed that the Energy Efficiency

Table 1
Thermal conductivity models.

Model	Correlation
Maxwell (Levin and Miller, 1981)	$\frac{k_{eff}}{k_{bf}} = [\frac{k_p+2k_{bf}+2(k_p-k_{bf})\varphi}{k_p+2k_{bf}-(k_p-k_{bf})\varphi}]$
Hamiton and Crosser (Hamilton and Crosser, 1962)	$\frac{k_{eff}}{k_{bf}} = \frac{k_{p+}(n-1)k_{bf}-(n-1)\varphi(k_{bf}-k_p)}{k_p+(n-1)k_{bf}+\varphi(k_{bf}-k_p)}$
Timofeeva (Timofeeva et al., 2007)	$\frac{k_{eff}}{k_{bf}} = [1+3\varphi]$
You and Choi (Yu and Choi, 2003)	$\frac{k_{eff}}{k_{bf}} = [\frac{k_p+2k_{bf}+2(k_p-k_{bf})(1+\beta)^3\varphi}{k_p+2k_{bf}-(k_p-k_{bf})(1+\beta)^3\varphi}]$

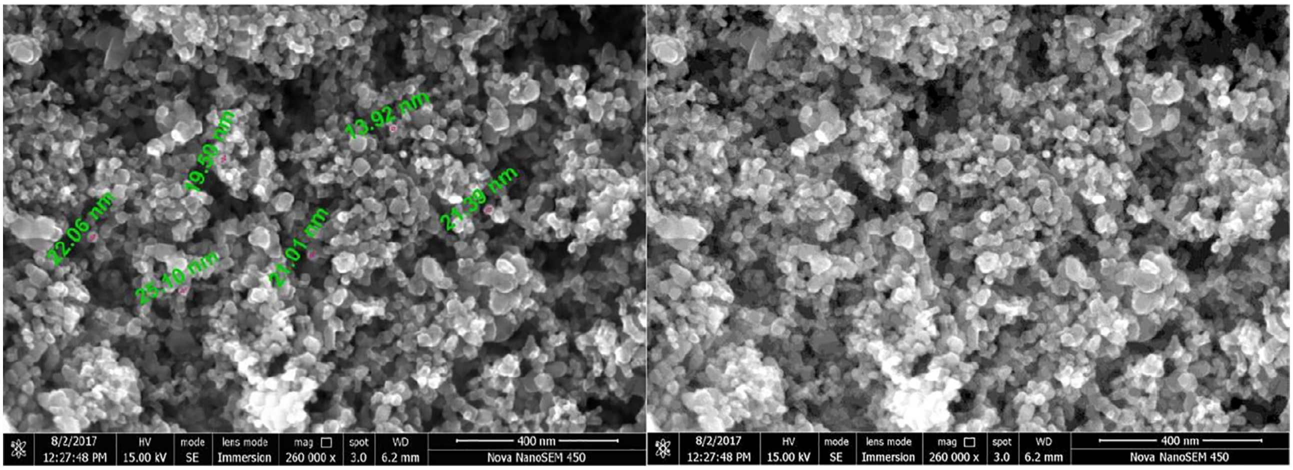

Fig. 1. SEM images of TiO_2 dry nanoparticles.

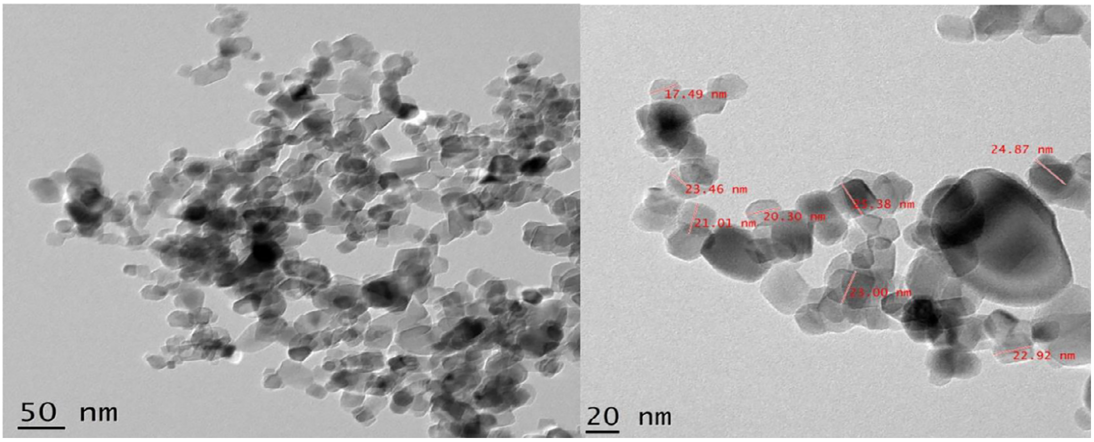

Fig. 2. TEM images of TiO_2 suspension.

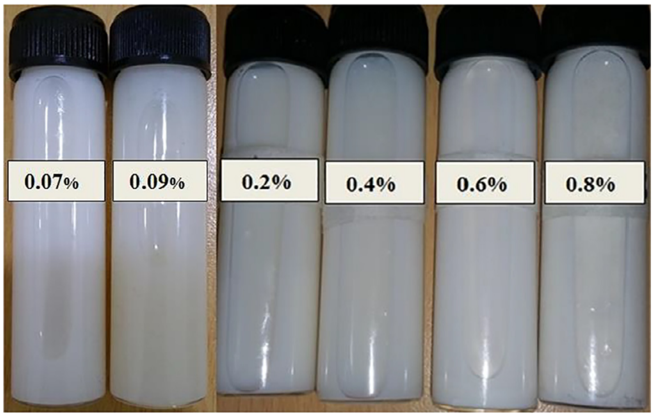

Fig. 3. Samples of TiO_2/PAG nanolubricant at different volume fractions.

Ratio (EER) of residential air conditioners can be increased by 6% if the polyolester oil is replaced with $NiFe_2O_4$-nanolubricant. In another study, Krishna Sabareesh et al. (2012), explored the effect of dispersing low concentration of TiO_2 nanoparticles in mineral oil based lubricants. They investigated the effect of nanoparticles on viscosity, lubrication qualities, and the performance of refrigeration systems utilizing R12 (Dichlorodifluoromethane) as the working fluid and reported that average heat transfer increases by 3.6%, compressor work reduces by 11% and consequently COP increases in by 17%. Sharif et al. (2016), investigated the thermal conductivity and viscosity of polyalkylene glycol (PAG) lubricant suspended with Al_2O_3 nanoparticles at different volume fractions and working temperatures and suggested to use a volume concentration of less than 0.3% for applications in automotive air condition systems. The thermal performance of a rotary system consisting of a stationary housing and a rotating cylinder has been enhanced by the addition of metallic nanoparticles into lubricant (Hajmohammadi, 2017b).

Despite the fact, the thermophysical and rheological properties of nanofluids are widely investigated by various researchers; property data related to PAG oil based nanolubricants is scarce. In the present study, nanolubricant was prepared by dispersing TiO_2 nanoparticles in Polyalkylene glycol (PAG), a synthetic refrigerant

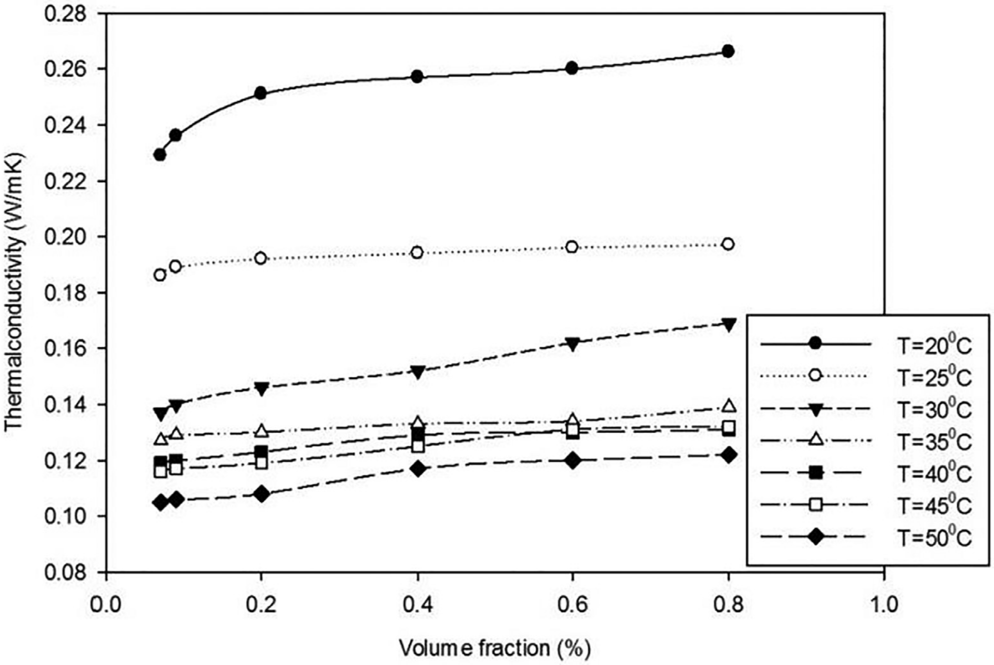

Fig. 4. Variation of thermal conductivity of TiO_2-PAG nanolubricant with volume fractions at different temperatures.

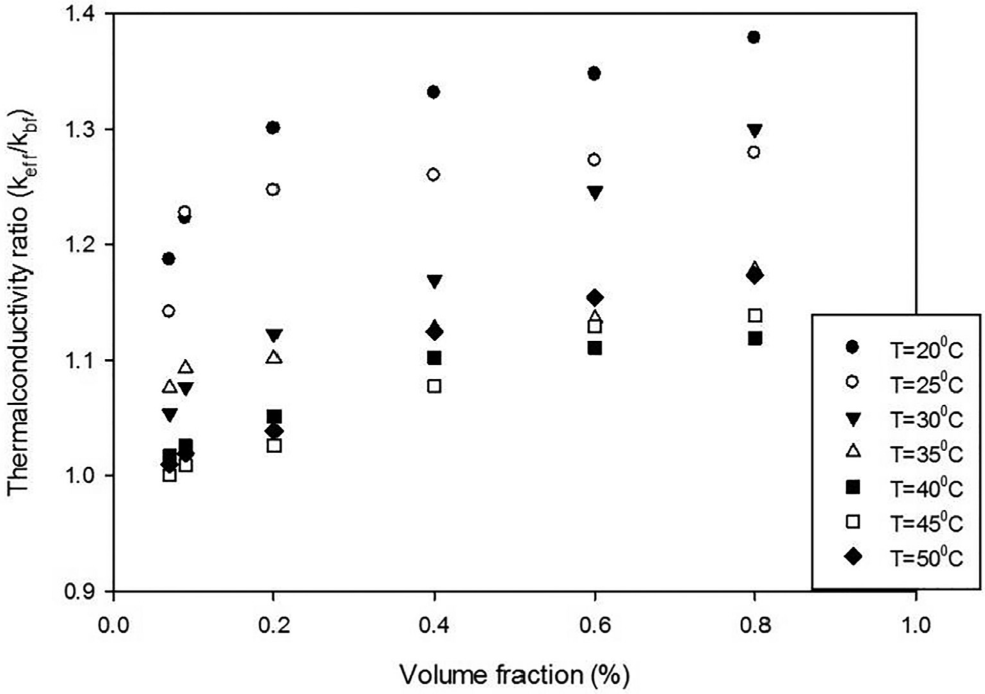

Fig. 5. Variation of thermal conductivity ratio of TiO_2 –PAG nanolubricant with volume fractions at different temperatures.

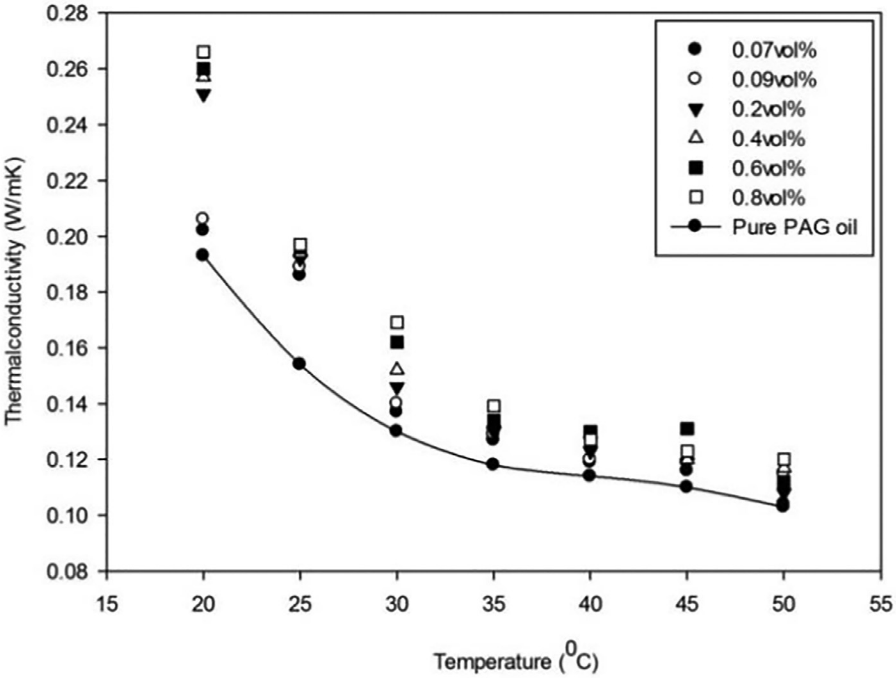

Fig. 6. Effect of temperature on thermal conductivity at different particle concentrations.

compressor oil compatible with R134a. Investigations have been carried out to study the effect of particle concentration and temperature on the thermal conductivity and viscosity. The particle volume fraction is varied from 0.07 to 0.8% and the temperature range considered is 20°C to 90°C. Studies have also been conducted at various shear rates to elucidate the rheological behaviour of the nanolubricant. The measured viscosity and thermal conductivity of nanolubricants were compared with that predicted using existing theoretical models.

2. Experimental method

2.1. Materials and characterisation

TiO_2 nanoparticle has been considered for the present study because; it can be produced in very large scale for industrial purpose and is safe, more chemically stable and relatively cheaper than other nanomaterials. TiO_2 nanoparticles (purity: 99%) spherical in shape supplied by Sigma Aldrich Limited, USA with an average size

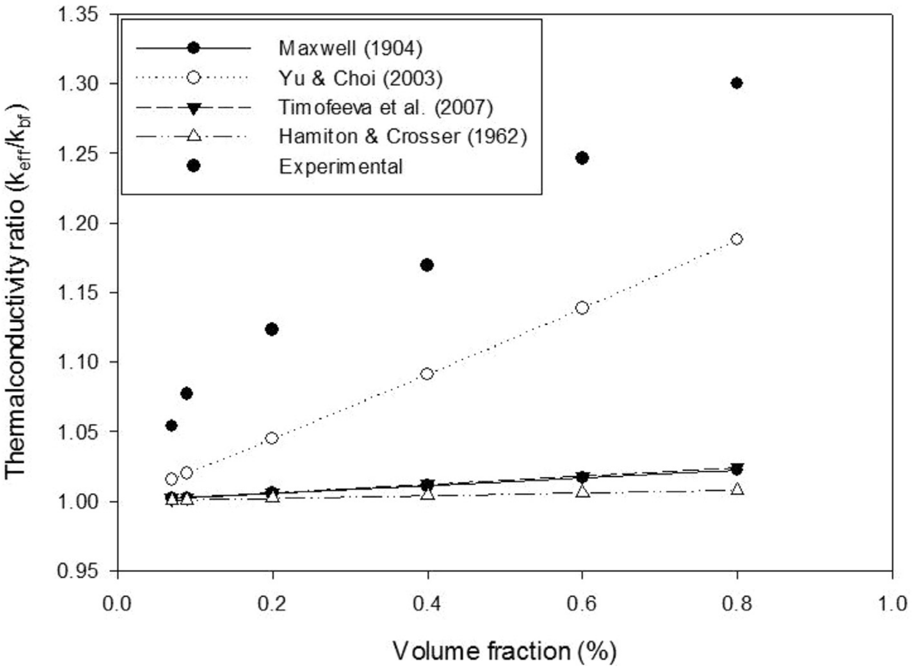

Fig. 7. Comparison between experimental thermal conductivity and model predictions at room temperature (28 °C).

of 21 nm and density 4.26 g cm^{-3} were used for the preparation of nanolubricant. The commercially available, fully synthetic, hygroscopic oil based on Polyalkylene Glycol (PAG) with a nominal liquid dynamic viscosity of 30–40 cP at 40°C, was used as the base fluid. PAG lubricants have better tribological performance than mineral oils when used together with HFCs (Matlock et al., 1999). The morphological characterisation of TiO_2 nanoparticles and nanoparticle suspension were carried out by Field Emission Scanning Electron Microscopy (FESEM) and Transmission electron Microscopy (TEM) respectively.

The FESEM images of TiO_2 nanoparticles show the distribution and shape of the nanoparticles (Fig. 1). The particles are spherical in shape and the average particle size is 21 nm. It can also be seen that, the particles are in the form of agglomerates and these agglomerates have to be broken by magnetic and ultrasonic agitation in order to produce stable nanolubricant.

TEM images show that the suspension is homogeneous and nanoparticles have been well dispersed (Fig. 2). The nanoparticles have almost similar characteristics such as physical appearance, size and shape in the suspension also.

2.2. Preparation of nanolubricant

Preparation of nanolubricant was the first significant step in the experimental studies. Nanofluids are not mere solid to fluid suspensions. In order to achieve even, stable and durable suspension with negligible aggregation of particles, special processes are necessary. Nanofluids can be prepared either by one-step or two-step methods. In the one-step method nanoparticles are synthesized in base fluid mainly by means of chemical methods (Eastman et al., 1997). In the case of two-step method nanoparticles are firstly prepared in the form of powders by physical or chemical methods, e.g. grinding, laser ablation, inert-gas-condensation, chemical vapour deposition (CVD), chemical precipitation, micro-emulsions, thermal spray, spray pyrolysis etc. and then suspended in base fluid (Paul et al., 2011). In this study, two step procedure was adopted for the preparation of nanolubricant. The required mass of TiO_2 nanoparticles corresponding to volume fractions 0.07%, 0.09%, 0.2%, 0.4%, 0.6% and 0.8% were calculated (Eq. (1)) and weighed using a high precision electronic balance.

$$\Phi = \frac{\left(\frac{m}{\rho}\right)_{TiO_2}}{\left(\frac{m}{\rho}\right)_{TiO_2} + \left(\frac{m}{\rho}\right)_{PAG}} \qquad (1)$$

The particles were dispersed directly into PAG oil without adding any dispersant. The sample was stirred using magnetic stirrer for 1 h, and then agitated for 12 h using ultrasonic agitator (BRANSON-3800) at a frequency of 40 kHz to homogenize the samples. No evidence of sedimentation or coagulation was noticed after 120 h of preparation. TiO_2-PAG nanolubricant samples at different volume fractions are illustrated in Fig. 3.

2.3. Thermal conductivity measurement

Thermal conductivity is measured using KD2 Pro thermal property analyser (Decagon devices, Inc., USA). Thermal conductivity in the range of 0.02 to 2.00 W (m K)$^{-1}$ with an accuracy of ± 0.001 could be measured by this device. The principle of operation of the device is transient hot wire and the maximum deviation is ± 5.0%. The probe of this instrument consists of a needle with a heater and temperature sensor inside. Electric current is supplied through the heater and the temperature of the probe is measured over time. Since the transient hot-wire measurement lasts for only a few seconds, the problems related with convection is eliminated. The apparatus meets the standards of both ASTM D5334 and IEEE 442 – 1981. A refrigerated and heating circulator (F-25, Julabo, Germany) was used to maintain constant temperature of the sample with an accuracy of 0.01°C. Thermal conductivity of TiO_2/PAG oil nanolubricant at six different particle volume concentrations (0.07 to 0.8 vol. %) were measured in the temperature range of 20°C to 50 °C. The thermal property analyser was calibrated with verification standard base fluid (Glycerine, CAS 56-81-5) at a controlled temperature of 28 °C and at atmospheric pressure. The measurement of thermal conductivity was performed repeatedly. Based on deviation between thermal conductivity of standard fluid and the measured thermal conductivity during the calibration, the error in

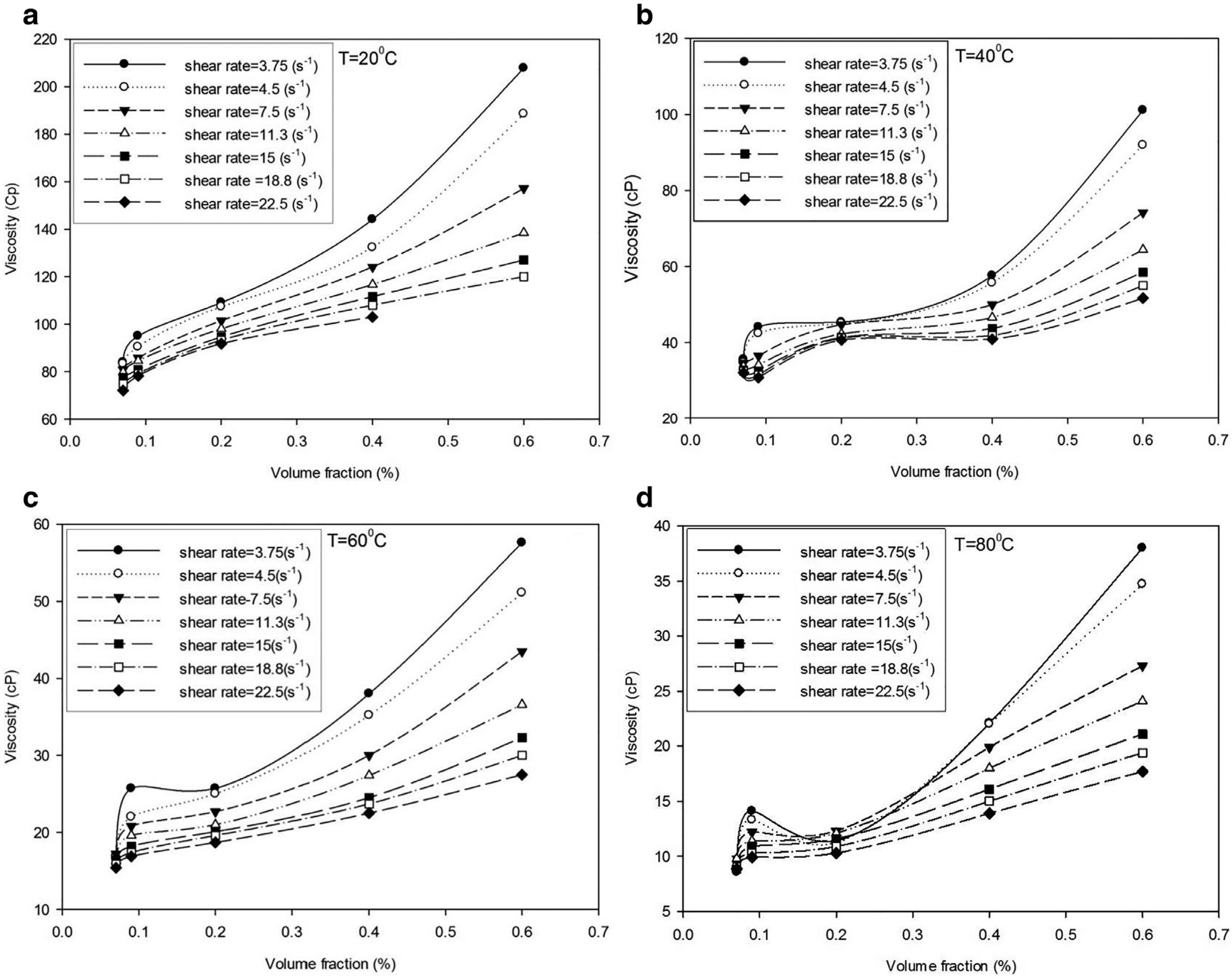

Fig. 8. Variation of viscosity of TiO_2-PAG nanolubricant with volume fractions at different shear rates at (a) Temperature = 20 °C, (b) Temperature = 40 °C, (c) Temperature = 60 °C and (d) Temperature = 80 °C.

measurement was estimated and the thermal conductivity data reported in the study represents an average of ten measurements with an estimated error of ± 1.6%. The experimental results were compared with that obtained from classical models. Table 1 shows the classical models considered.

2.4. Measurement of rheological properties

In order to study the rheological behaviour, it is important to see whether TiO_2/PAG nanolubricant is categorized under Newtonian or non-Newtonian fluid. The viscosity of PAG suspensions with TiO_2 nanoparticles at different volume fractions were measured as a function of temperature and shear rate. A Brookfield LVDV-II + Pro plate-and-cone rheometer having measurement range between 1.0 and 2000 cP and spindle speeds 0–150 RPM together with the constant temperature circulator (JULABOF-25, Germany) was used for the measurements. The torque required to turn the spindle of the rheometer in a fluid is a measure viscosity of the fluid. Torque is applied through a calibrated spring to the spindle immersed in test fluid and the spring deflection measures the viscous drag of the fluid against the spindle. The amount of viscous drag is proportional to the amount of torque required to rotate the spindle, and thus to the viscosity of a fluid. Rheocalc software was used to acquire the data. Spindle used for this study was calibrated with Brookfield viscosity standard fluids. The maximum uncertainty was found to be 1.9%. All the measurements were performed under steady state conditions in the torque range of 10–100%. Measurements were carried out at nanoparticle concentrations ranging from 0.07 to 0.6 vol. %, temperature ranging from 20 °C to 90 °C and at shear rates up to 225 s^{-1}.

2.4.1. The power law model

In order to classify the nanolubricant as Newtonian or non-Newtonian fluid, Ostwald–De Waele power law model was used (Eq. (2)).

$$\tau = m\gamma^{n} \tag{2}$$

The Power Law model is described by two parameters, consistency coefficient (m) and flow behaviour index (n). Consistency index is a product's viscosity at one reciprocal second and flow behaviour index indicates the degree with which a material exhibits non-Newtonian flow behaviour, τ stands for shear stress and the shear rate. The viscosity of the fluids which follow power law is defined by following equation:

$$\mu = m\gamma^{n-1} \tag{3}$$

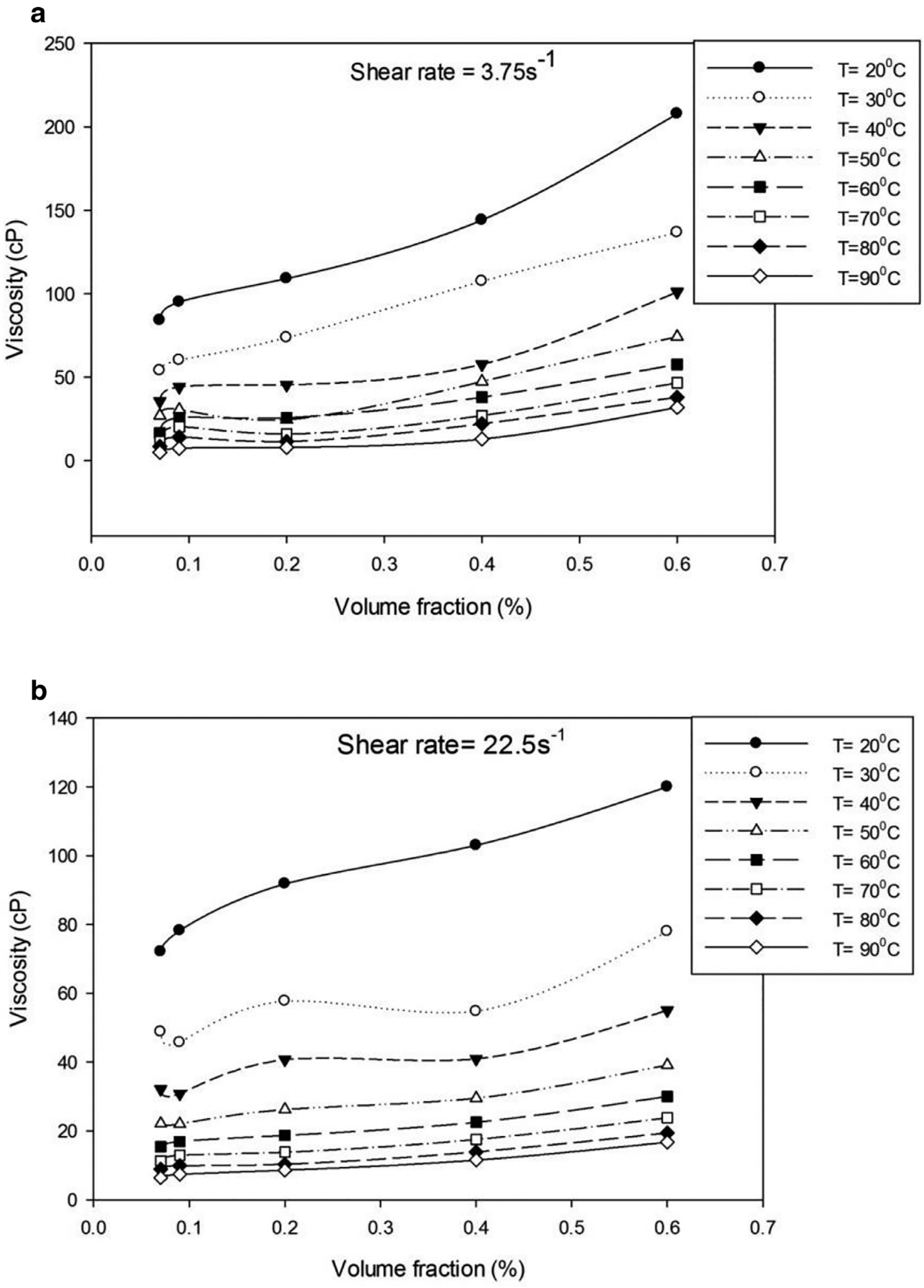

Fig. 9. Viscosity variations of TiO_2-PAG nanolubricant with volume fractions at different temperature at (a) Shear rate = 3.75 s^{-1}, (b) Shear rate = 22.5 s^{-1}.

where μ represents the apparent viscosity. Fluids which obey power law models are classified into shear-thinning and shear-thickening under increasing shear rates. If magnitude of $n<1$, the fluid is known as shear-thinning or pseudo plastic. This means that the apparent viscosity decreases as shear rate increases. When $n>1$, it is shear-thickening or dilatant behaviour i.e. their apparent viscosity increases as shear rate increases. In order to obtain these indices, logarithmic diagram of shear stress vs shear rate has been drawn and the indices are calculated by the following equation.

$$Ln(\tau) = Ln(m) + nLn(\gamma) \tag{4}$$

The viscosities obtained from experiments were compared with that calculated using theoretical models. The models considered are depicted in Table 2.

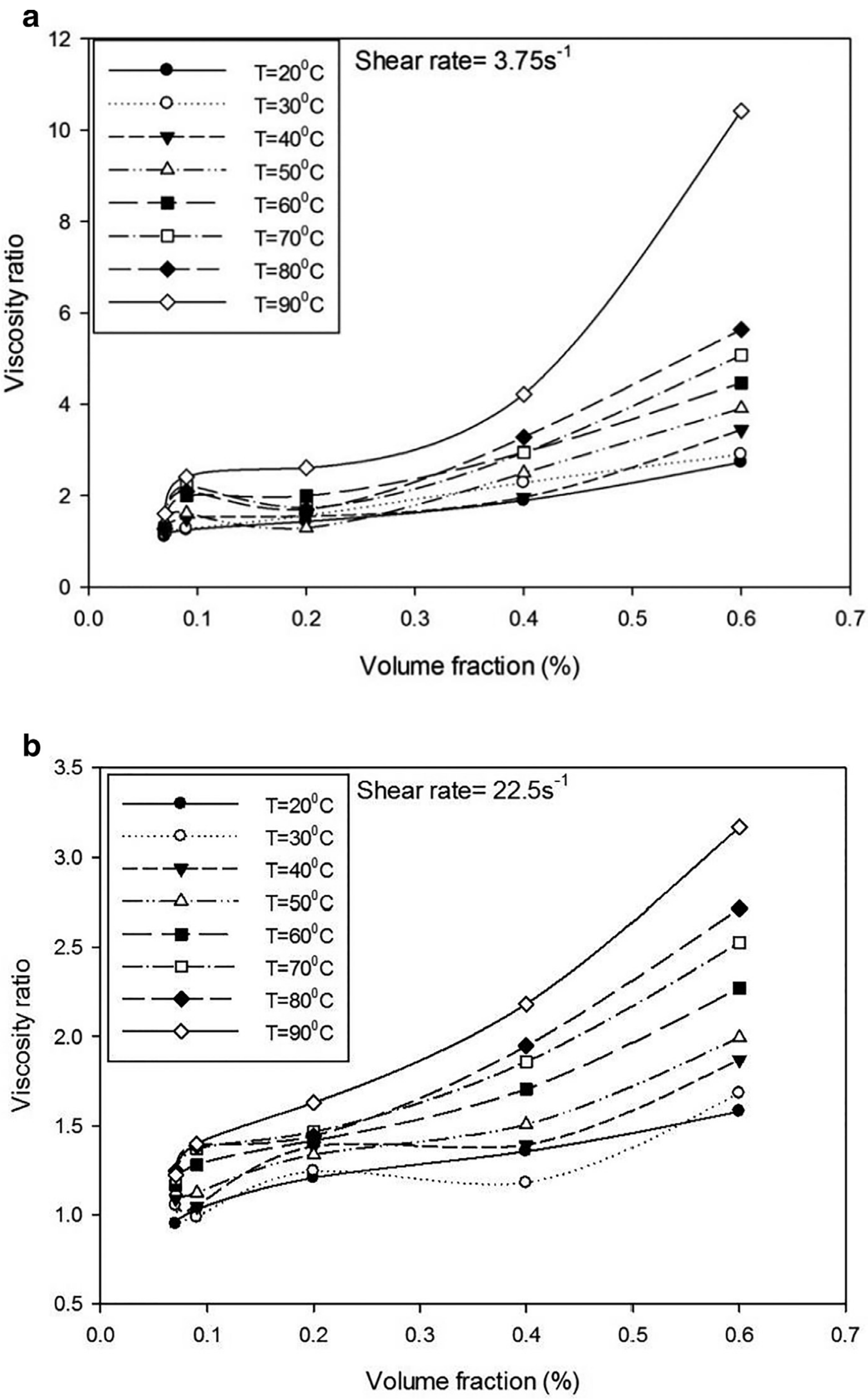

Fig. 10. Variations of viscosity ratio with volume fraction at different temperatures at (a) Shear rate = 3.75 s^{-1}, (b) Shear rate = 22.5 s^{-1}.

Table 2
Viscosity models.

Models	Correlations
Einstein (Einstein et al., 1956.)	$\frac{\mu_{eff}}{\mu_{bf}} = (1 + 2.5\varphi)$
Brinkman (Brinkman, 1952)	$\frac{\mu_{eff}}{\mu_{bf}} = \frac{1}{(1-\varphi)^{2.5}}$
Pak and Cho (Pak and Cho, 1998)	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 39.11\varphi + 533.9\varphi^2$
Wang (Wang and Xu, 1999)	$\frac{\mu_{eff}}{\mu_{bf}} = 123\varphi^2 + 7.3\varphi + 1$

3. Results and discussion

3.1. Thermal conductivity

The thermal conductivity of the TiO_2/PAG nanolubricant was measured as functions of both nanoparticle volume fraction (0.07–0.8 vol. %) and temperature (20 °C–50 °C).

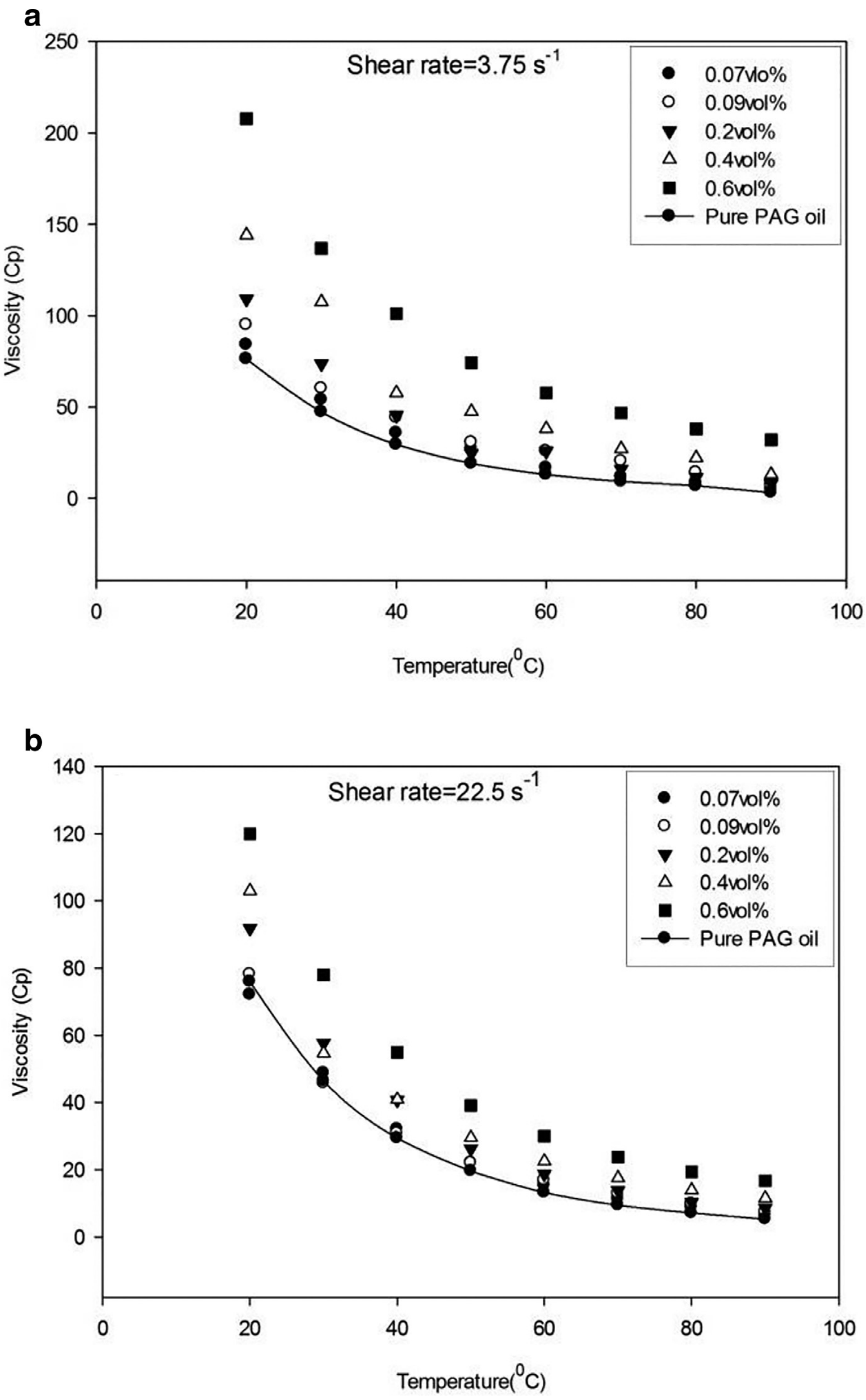

Fig. 11. Temperature dependent viscosity variation at different particle concentrations at (a) Shear rate = 3.75 s^{-1}, (b) Shear rate = 22.5 s^{-1}.

Figs. 4 and 5 show the thermal conductivity and thermal conductivity ratio (k_{nf}/k_{bf}) respectively as a function of nanoparticle volume fraction at different temperatures. The thermal conductivity of TiO_2/PAG nanolubricant increases almost linearly with particle volume fraction. The thermal conductivity enhancement of TiO_2 nanolubricants compared to pure PAG is about 37.8% at 20 °C with a volume fraction of 0.8%.

There are many potential factors responsible for the anomalous enhancement in thermal conductivity of nanofluids: (i) The Brownian motion effect of nanoparticles in the base fluid is a vital factor for the observed enhancement. The heat is carried by phonons by propagating lattice vibrations in the crystalline solids suspended in fluids. Such phonons are propagating in random direction. Some ballistic phonon effects could possibly lead to an increase in thermal conductivity. If the ballistic phonons initiated in one particle can persists in the liquid, and reach nearby particle, a major increase of thermal conductivity can be expected (Shen et al., 2009). The particles may be closer enough due to the increase of particle concentration, and thus enhance coherent phonon heat flow among particles due to Brownian motion; eventually the thermal

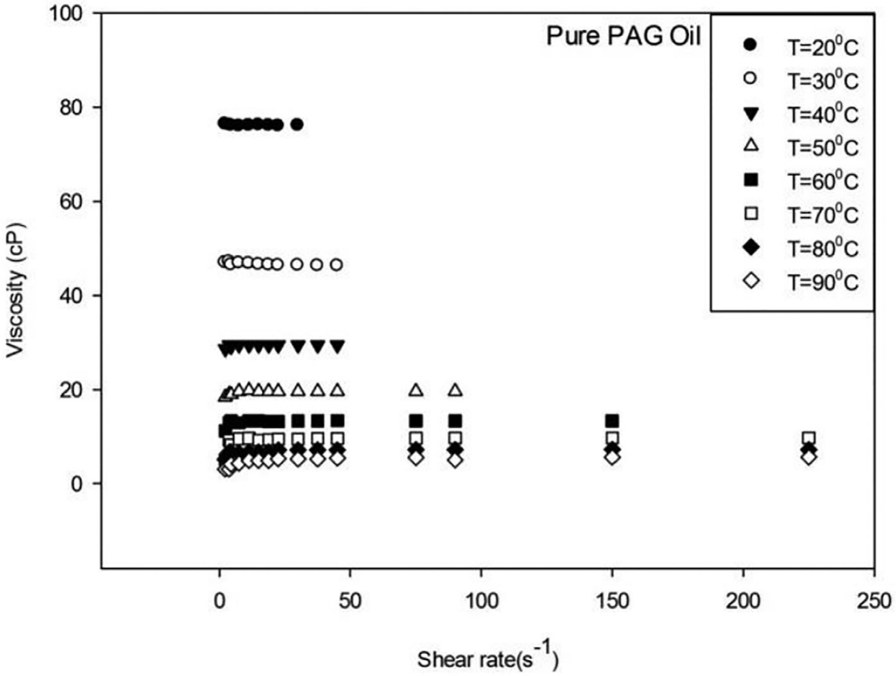

Fig. 12. Viscosity variations of Pure-PAG oil with shear rates at different temperatures.

conductivity becomes a function of nanoparticles concentration. (ii) molecular layering of the liquid: existence of a nano-layer at the solid–liquid interface and nanoparticle aggregation may constitute major contributing mechanisms for thermal conductivity enhancement in nanofluids. The liquid molecules close to particle surfaces are known to form layered structures and behave much like a solid and which will act as a thermal bridge between fluid and solid particles. (iii) the increased thermal conductivity of solid particles.

Fig. 6 shows temperature dependent variation in thermal conductivity at various particle concentrations. Thermal conductivity of pure lubricant and TiO_2-PAG nanolubricant at all particle concentrations decreases with increase in temperature. This phenomenon can be attributed to the following factors: (i) at lower concentrations and at elevated temperatures, mean path between of the nanoparticle increases and thus reduces the probability of collision (ii) the near-field radiation (Domingues et al., 2005) can also be strongly influenced by the thermal conduction within the nanofluids with increasing temperature. It can be seen that the measured thermal conductivity TiO_2-PAG nanolubricant increases with the increase in volume concentration, but in contrast, the thermal conductivity of nanolubricant shows a decreasing trend with increase of temperature.

The experimental results of thermal conductivity were compared with the results obtained from classical models and is shown in Fig. 7. It can be seen that all models underpredict the thermal conductivity and this may be due to the fact that they are based on low viscous fluids like water, ethylene glycol etc.

3.2. *Rheology of nanolubricant*

Viscosity of pure PAG oil and TiO_2/PAG nanolubricant at different volume fractions (0.07 to 0.6 vol. %), shear rate (3.75 $s^{-1}$to 225 s^{-1}) and temperatures (20 °C to 90 °C) were measured. In order to evaluate the rheological behaviour, Ostwald–de Waele power law model was used.

3.2.1. *Effect of particle concentration on viscosity of TiO_2-PAG nanolubricant*

Figs. 8 and 9 show the variation of viscosity with volume fraction at different temperatures and shear rates.

From the figures it is clear that shear rate and volume fraction play a vital role in the viscosity of nanolubricants. As the volume fraction increases, the viscosity of nanolubricant increases. However, at lower shear rates and temperatures, there is substantial increase in viscosity with volume fraction. The increase in viscosity is more significant at a particle volume fraction above 0.4%. The highest viscosity obtained is 207.8 cP at volume fraction 0.6% and at a lower shear rate of 3.75 s^{-1}. It can be seen in Fig. 9(a) and (b) that, at lower temperatures, viscosity increase is more prominent than that at higher temperature. Viscosity is a property due to the internal frictional force that develops between different layers of fluids as they move relative to each other. Actually, it happens due to the Vander Waals forces between the liquid molecules. The suspended nanoparticles in the PAG oil would raise its viscosity as a result of the collisions between nanoparticles and the base fluid. By intensifying the amount of solid nanoparticles in a fixed volume of a liquid, greater nano-racemes arise due to Van der Waals forces. In other words, as the concentration of nanoparticle increases, the particles make agglomerations within the suspension. This consequently results in the increase of internal shear stress in nanolubricant and hence an increase in viscosity.

Fig. 10 shows the variation of viscosity ratio (μ_{eff}/μ_{bf}) with volume fraction and temperature at two shear rates. There is an abrupt increase in relative viscosity at volume fraction above 0.4%. The maximum relative viscosity is found as 10.42, which is obtained at a lower shear rate of 3.75 s^{-1} and volume fraction of 0.6%.

The reason for the anomalous increase in relative viscosity may be related to the fact that at higher volume fraction the nanoparticle clustering is more and the applied lower shear rate (3.75 s^{-1}) is not sufficient enough to break the nano-clusters. As the shear rate increases, the relative viscosity is found to be decreasing. The relative viscosity of nanolubricant ranges between 1.05 to 2.18 for vol-

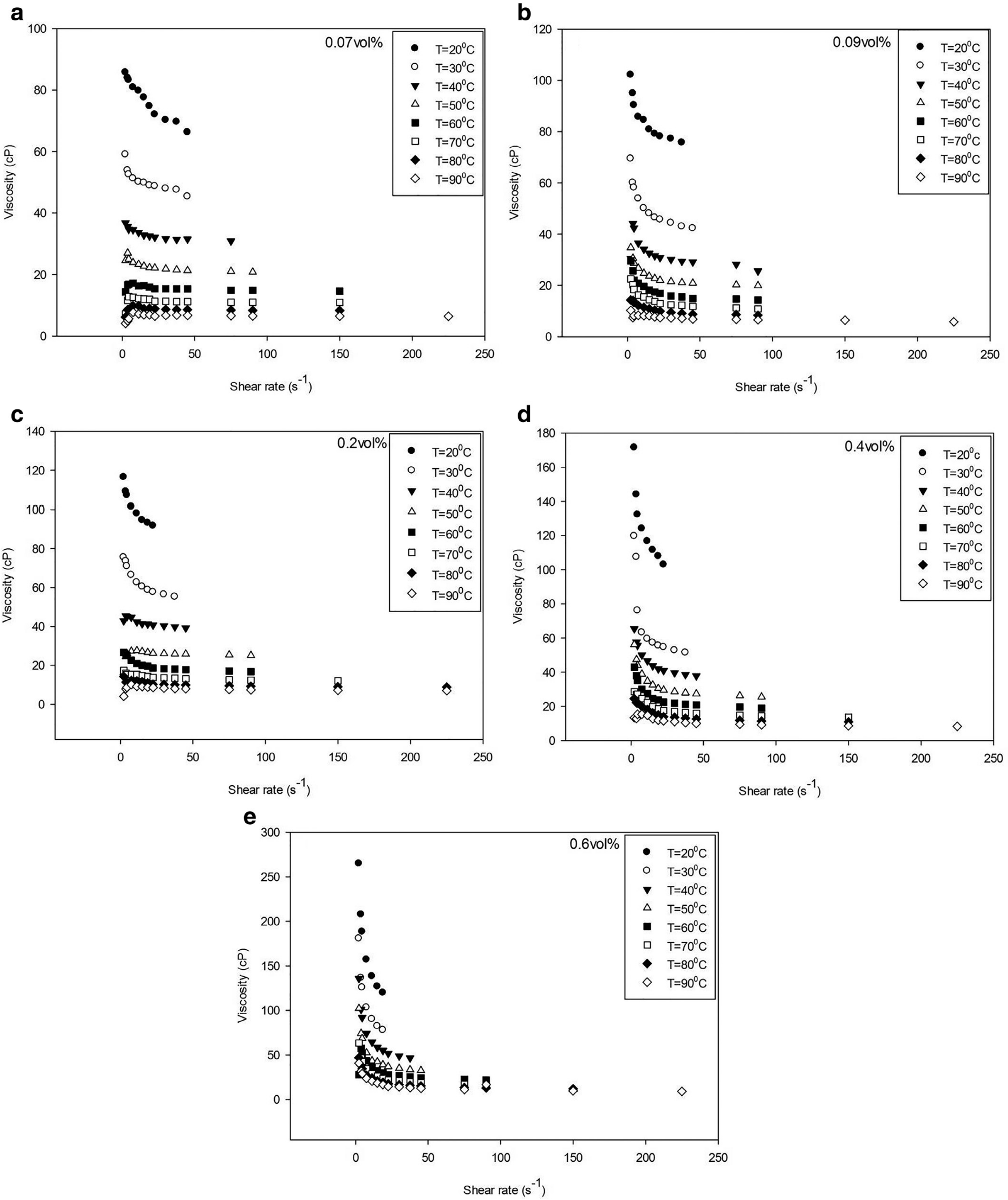

Fig. 13. Variations of viscosity with shear rates at different temperatures, at (a) Volume fraction = 0.07%, (b) Volume fraction = 0.09%, (c) Volume fraction = 0.2%, (d) Volume fraction = 0.4%, (e) Volume fraction = 0.6%.

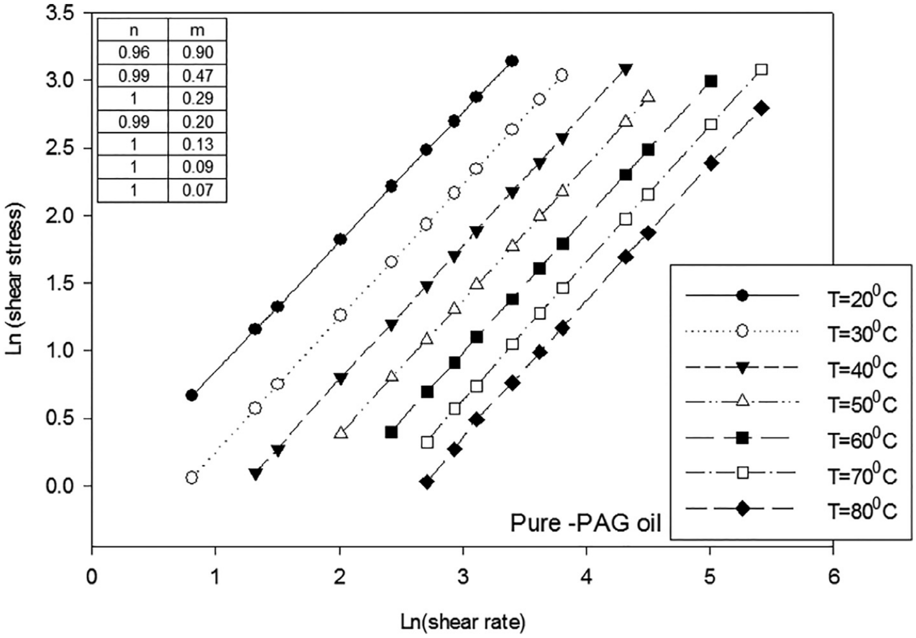

Fig. 14. Logarithmic diagram of shear stress-shear rate of pure PAG oil at different temperatures.

ume fractions range of 0.07–0.4% at elevated shear rates (22.5 s^{-1}). From this it is clear that TiO_2-PAG nanolubricant is more suitable to use at a volume fraction up to 0.4% and at moderate shear rates.

3.2.2. *Effect of temperature on viscosity*

For the understanding of viscosity variation with temperature, the dynamic viscosity versus temperature at different volume fractions are plotted in Fig. 11(a) and (b). The results reveal that irrespective of the shear rate, the viscosity of the nanolubricant diminishes with increase in temperature, similar to that of pure lubricant.

The reasons behind this phenomenon can be explained as follows: At lower temperatures, the nano racemes hinder the motion of lubricating oil layers on each other. Increasing the temperature helps the particles to overcome Van der Waals attractive forces and which may disintegrate the clusters of nanoparticles suspended in base fluid and hence the intermolecular interactions between the molecules become weak and this phenomenon leads to decrease in viscosity. Specifically, due to temperature rise, the Brownian motion will be enhanced which may cause increase in chaos and this will decrease the viscosity of nanolubricant.

3.2.3. *Rheological behaviour of base lubricant and nanolubricant*

In order to study the rheological behaviour of pure lubricant and nanolubricant, the relation between viscosity and shear rate at different temperatures are plotted. The rheological studies were performed up to shear rate of 225 s^{-1} in the temperature range 20 °C to 90 °C. Fig. 12 shows the variation of viscosity with shear rate for pure lubricant. It is evident from the figure that, over the temperature range considered, the viscosity of the pure lubricant does not depend on the shear strain rate and shows the Newtonian behaviour.

The viscosity of the nanolubricant samples were measured over the same range of shear rate and temperature and the same is shown in Fig. 13.

Obviously, the changes in viscosity with shear rate are different for nanolubricant compared to pure lubricant. At a given temperature, shear rate increment leads to apparent reduction in viscosity and it is non-linear as well. The viscosity decreases exponentially at lower temperatures and shear rates. i.e. the nanolubricant exhibit Non-Newtonian behaviour with shear thinning characteristics (pseudo plastic). The most intense non-Newtonian behaviour was recorded at a temperature of 20 °C. At higher temperatures and shear rates, shear thinning characteristics disappears and behaves as Newtonian fluid.

Figs. 14 and 15 show the logarithmic diagram of shear stress vs shear rate of pure lubricant and nanolubricant. The volume fraction is varied from 0.07 to 0.6%. The curves are fitted with *R*-squared value higher than 0.99. Here, n and m are the power law and consistency indices respectively. From figures it is clear that, regardless of temperature and volume fraction TiO_2-PAG nanolubricant is a non-Newtonian fluid. Meanwhile the pure PAG oil behaves like Newtonian fluid with power law index $n \approx 1$ at all temperatures.

Fig. 16 depicts the variation of power law index with particle dosing level and temperature. According to power law index, shear thinning is confirmed for nanolubricant at all temperatures and particle concentrations. Significant shear thinning behaviour is manifested at volume fractions above 0.4%.

Addition of TiO_2 nanoparticles to the host lubricant alters the structure of the base oil by initiating a disturbance in the molecular links. The nanoparticles act as interfaces to connect base oil layers to each other. Conversely, the difference between the Brownian nature of nanoparticles and the base fluid leads to breaking the molecular links and creating new links; eventually the nanolubricant exhibit shear thinning behaviour. With respect to Fig. 17, at low temperatures, intensification of particle concentration results in considerable increase in consistency index, which means substantial variation in viscosity. But at elevated temperatures, significant variation in consistency index has not been observed. The consistency index varied marginally and which is an indication of consistency of apparent viscosity.

3.2.4. *Modelling of viscosity*

Fig. 18 illustrates comparisons between experimental data of viscosities and that obtained from different classical models. It is observed that all models underpredict the viscosity of TiO_2/PAG nanolubricants, especially at higher particle volume fractions. This

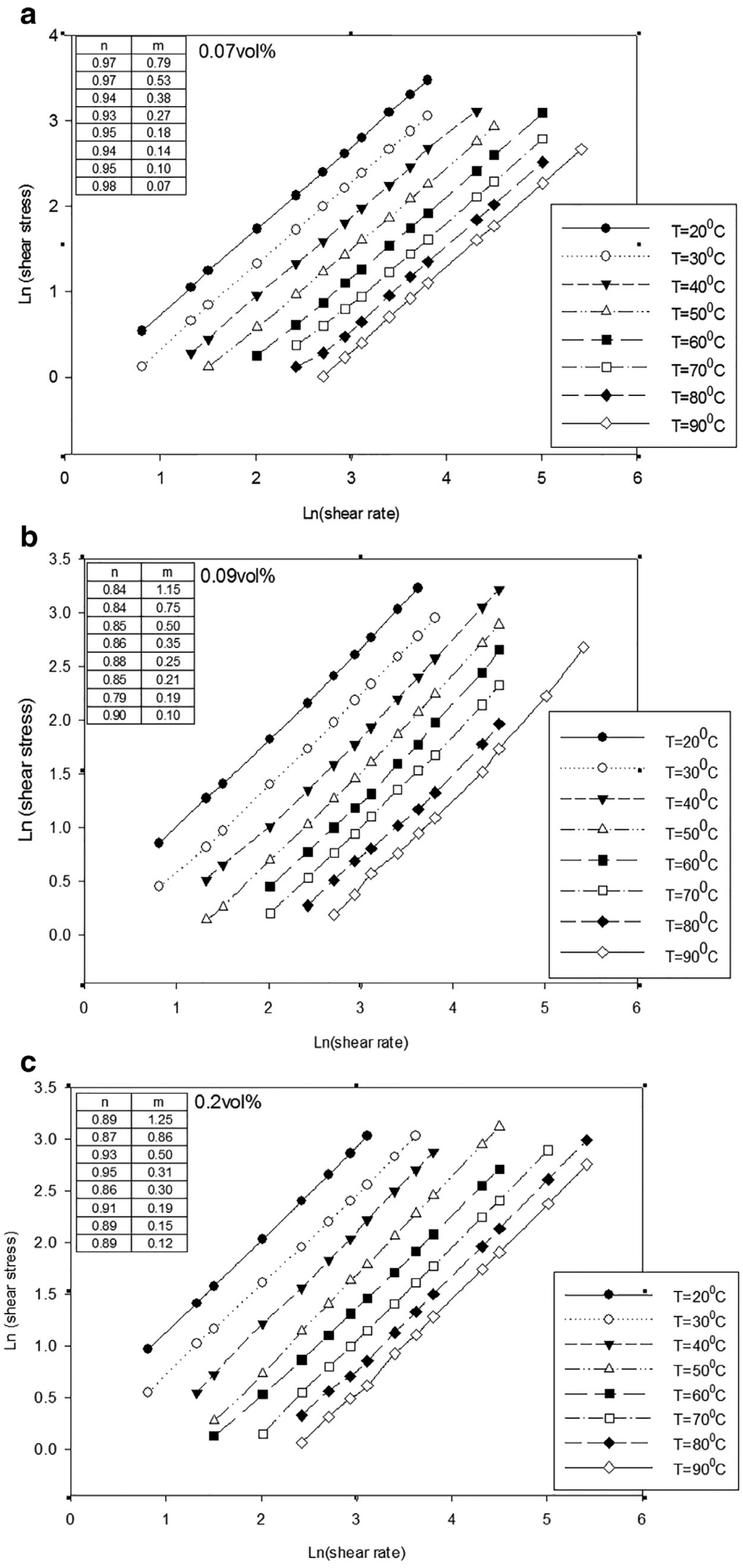

Fig. 15. Logarithmic diagram of shear stress-shear rate at different temperatures, at (a) volume fraction = 0.07%, (b) volume fraction = 0.09%, (c) Volume fraction = 0.2%, (d) Volume fraction = 0.4%, (e) Volume fraction = 0.6%.

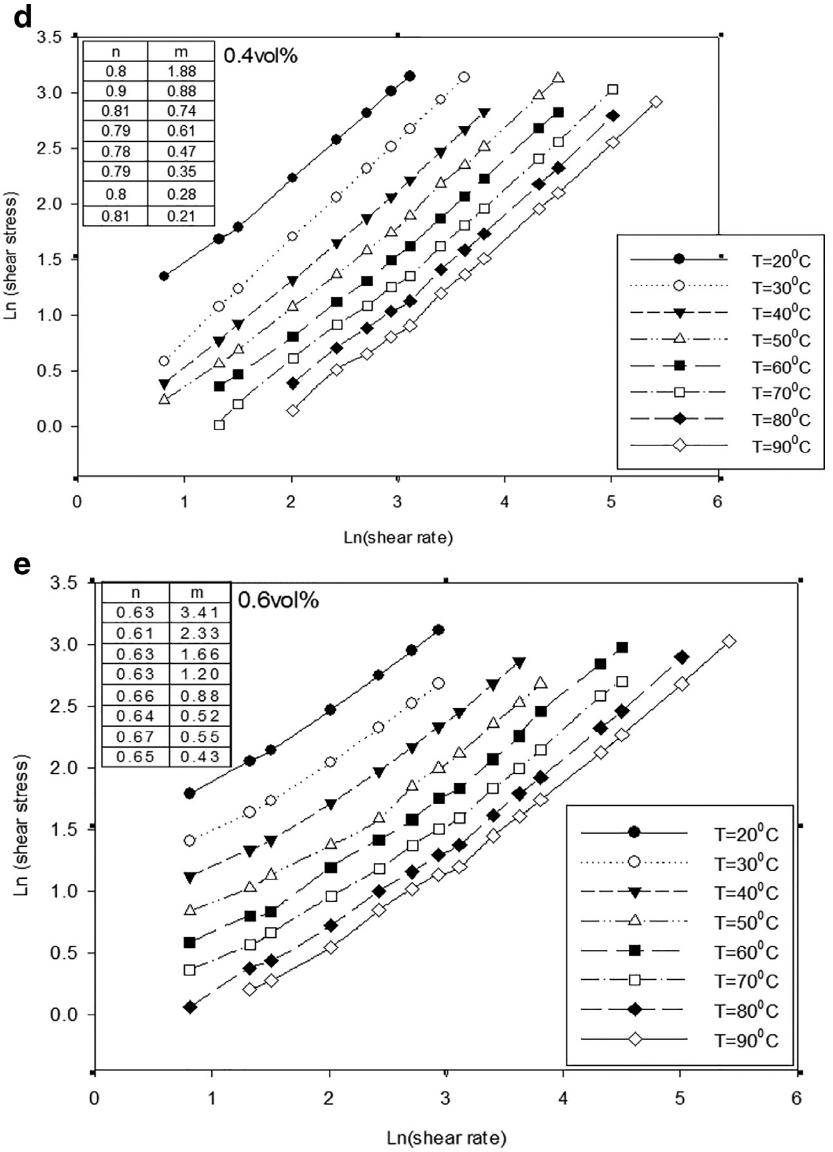

Fig. 15. Continued

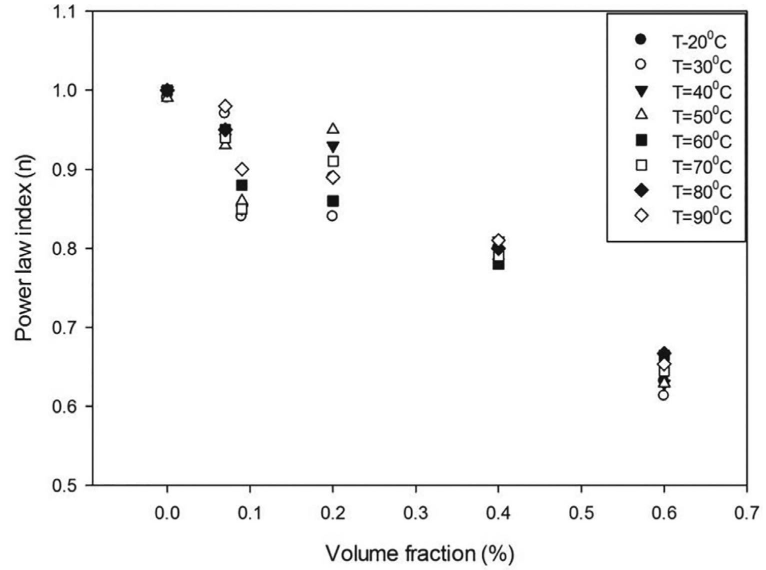

Fig. 16. Power law index of TiO_2-PAG nanolubricant with volume fractions at different temperatures.

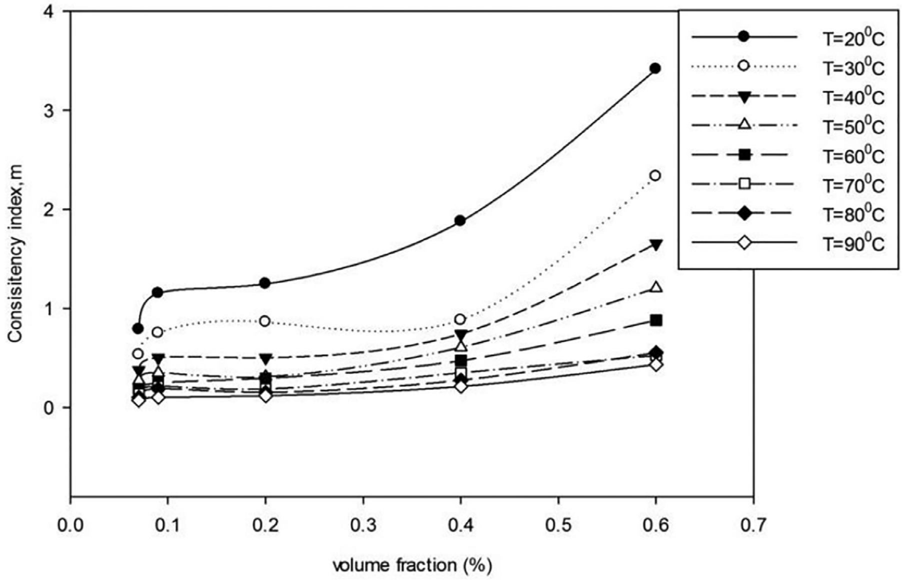

Fig. 17. Consistency index of TiO_2-PAG nanolubricant with volume fractions at different temperatures.

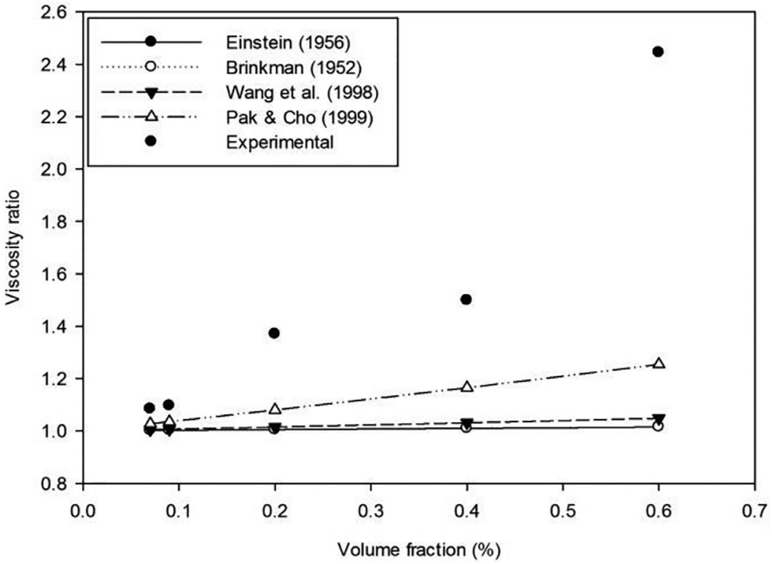

Fig. 18. Comparison between experimental viscosity ratio and model predictions at room temperature (28 °C).

in line with the findings of Sharif et al. (2016) for Al_2O_3/PAG nanolubricant. Prasher et al. (2006) reported that, the Einstein model could not adequately predict the viscosity of propylene glycol and ethylene glycol based nanofluids. The classical models utilise the parameters like volume concentration and viscosity of the base fluid as the depending factors of effective viscosity. The experimental results show that the temperature, type of nanoparticle, and shear rate has noteworthy influence on the effective viscosity of nanofluids.

4. Conclusions

Investigations on thermophysical and rheological properties of TiO_2/PAG nanolubricant have been carried out. Experiments were conducted to study the effect of particle concentration and temperature on thermal conductivity and viscosity. The rheological properties have also been investigated at various shear rates, particle concentrations and temperature. The following conclusions are derived out of the studies.

(i) The volume concentration and temperature have significant effects on the thermal conductivity and viscosity of nanolubricants.
(ii) The thermal conductivity of the nanolubricant increases with increase in volume concentration. But contrary to other nanofluids, the thermal conductivity of nanolubricants decreases with the intensification of temperature.
(iii) The classical models underpredict the thermal conductivity of TiO_2-PAG nanolubricant.
(iv) The viscosity of nanolubricants increases with increase in volume fraction. However, it decreases with increase in tem-

perature. For the same volume concentration, the viscosity increment rate was found to be larger compared to that of thermal conductivity.

(v) Unlike pure lubricant, shear rate has crucial impact on the behaviour of nanolubricant.
(vi) Non-Newtonian shear thinning behaviour of TiO_2-PAG nanolubricant was confirmed by computing power law and consistency indexes using Ostwald–de Waele relationship.
(vii) The classical models failed to predict the viscosity of nanolubricant.
(viii) The TiO_2-PAG nanolubricant with particle concentration up to 0.4% sustains adequate viscosity at elevated temperatures and shear rates compared to pure PAG lubricant, which is a desirable factor as far as refrigerant compressor oils are concerned.

Acknowledgement

The authors are grateful to Sophisticated Test and Instrumentation Centre (STIC), Cochin University of Science and Technology and Sophisticated Instrumentation and Computation Centre (SICC), University of Kerala, India for their assistance in material characterisation.

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