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Evaluation of thermal and rheological characteristics of CNT-PAG nanolubricant for the development of energy efficient refrigeration systems

S.S. Sanukrishna [a,*], Vivek Mathew Jose [b]

[a] *Department of Mechanical Engineering, Sree Chitra Thirunal College of Engineering, Thiruvananthapuram 695018, India*
[b] *Department of Mechanical Engineering, National Institute of Technology, Kozhikode 673601, India*

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ABSTRACT

The addition of nanoparticles is one of state of the art methods to enhance the thermophysical and heat transfer characteristics of cooling and lubricating fluids. Exploring the energy-saving potentials of novel material Carbon Nano Tube (CNT) as a lubricant additive is the primary focus of this study. The thermal and rheological properties of Poly Alkylene glyco l (PAG)-CNT nanolubricant at different volume fractions are investigated to pose as an energy-efficient alternative lubricant in vapour compression refrigeration systems. Furthermore, genetic algorithm-based regression correlations are proposed to predict the thermal conductivity and viscosity of the nanolurcant. The results show that the CNT has the potential to improve the thermophysical and rheological characteristics of the lubricant. Experimental results show that the presence of tubular-shaped CNT particles enhances the thermal and rheological characteristics of the colloidal suspension. The proposed regression models exhibit excellent agreement with the experimental data. Studies revealed that the potentials of CNT-PAG nanolubricant as an alternative lubricant for refrigerant compressors is excellent and will eventually improve the energy efficiency and overall performance of refrigeration systems and which in turn leads to the development of energy-efficient HVAC systems.

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1. Introduction

The world energy consumption is expanding exponentially per year. The increase in the numbers of refrigeration and air-conditioning systems both in commercial, industrial, and residential sectors is one of the major reasons for the expanding pattern of energy consumption across the globe. Because of energy security and environmental concern, the energy efficiency of such systems needs to be enhanced. The emergence of nanotechnology leads to the development of superior materials and heat transfer media having better thermal, mechanical, and morphological characteristics which will benefit in energy, communication, biomedical, and other diverse sectors [1,2]. Increasing demands in energy, miniaturization of systems, and precarious economic crisis mandate energy-efficient and high-performing cooling media and lubricating fluids in diverse thermal applications and systems.

One [2] of the fortunate approaches to increase the thermal transport phenomena in conventional heat transfer fluids is the use of nanoparticles as colloidal material [3]. Low thermal conductivity and heat transport capabilities are the primary hurdles to overcome for the development of sustainable and efficient systems in the arena of heat transfer. Thus it is imperative to increase the thermophysical and heat transport characteristics of these fluids from an energy-conserving perspective. Present and future HVAC systems would necessitate energy-efficient primary and secondary working fluids such as refrigerants and lubricants. Consequently, investigations on energy saving through heat transfer enhancement and better tribological performance have gained great attention nowadays [4]. The addition of nanoparticles to the conventional heat transfer fluids as a heat transfer modifier has been gained consideration for the past few years [5]. Recently carbon and its novel allotropes such as CNT, fullerene, and nanotubes

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[*] Corresponding author.
E-mail address: sanukrishna@sctce.ac.in (S.S. Sanukrishna).

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have emerged as an excellent additive to the coolant, lubricants, and heat transfer fluids including refrigerants, due to its remarkable, unique thermal, mechanical, electrical, and optical properties[6,7]. However, CNT, among them is not effectively explored as an additive to the lubricants and refrigerants to enhance the thermophysical and tribological performance. The innovative lubricants appended with novel one-dimensional CNT nanoplatelets are expected to have outstanding potentials in energy conservation outlook, especially in refrigeration and air conditioning systems. The application of ultra-fine metal, ceramic, oxides, composite particles has been employed as an additive to lubricating oils for improving their thermophysical, heat transfer, friction reduction, and anti-wear properties [8,9,10,11]. The studies about the thermal, rheological, and tribological properties of coolants, lubricants, thermal fluids, etc. suspended with nano-sized particles in the literature emphasize the heat transfer augmenting potentials [12,13,14]. Many researchers have established the potentials of nano-sized metallic, ceramic, and oxide particles as an additive to improve thermo physical properties thermo fluids [15]. The rheological behavior of nano lubricants is least characterized by researchers [17,18,14], few of them established the temperature and particle concentration dependence on these properties. The nanolubricants display reduced apparent viscosity at elevated temperature, moreover, with smaller particle size, a significant increase in viscosity has not been observed. However, reverses trends were reported with increased volume fraction [19]. As far as the rheological properties of nanofluids are concerned, we cannot forecast a specific behaviour. Different nanoparticles have different morphological characteristics, which may exhibit unusual behaviour within the host fluids. Aberoumand et al. reported that Ag-based nano-oil behaved as a non-Newtonian fluid at a very low particle mass fraction. The comprehensive experimental studies concerning the thermal and rheological features of CNTs appended with poly alkylene glycol-based refrigerant compressor oil are not reported in the literature. Unfortunately, the studies about the shear-dependent viscosity and flow behaviour of CNT-PAG nanolubricants and correlations to predict the behaviour are unavailable in literature to the best of the author's knowledge and belief. In the present investigation, comprehensive studies on the thermophysical and rheological behaviours of CNT-PAG (Refrigerant compressor oil) nanolubricant at different volume fractions, temperature, and shear rates have been performed according to ASTM standards. Moreover, genetic algorithm-based regression correlations are proposed to predict the thermal conductivity and viscosity of CNT-PAG nanolubricant by considering the effect of particle concentration, temperature, density, and shear rate. These studies will eventually lead to the development of energy-efficient refrigeration systems.

2. Materials and characterization

Multiwalled CNTs procured from SIGMA ALDRICH (USA) are used for the experimental studies. Polyalkylene Glycol (PAG) lubricant is used as the base lubricant. The morphological properties such as shape, size, etc., of the particles, are carried out with the help of Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). The distribution and shape of dry CNT nanoparticles and their suspension are shown in the SEM and TEM images Fig. 1(a) and (b) respectively. SEM images of the particles show that they are tubular in shape and are seems to be flocculated in the dry state. These flocculants can be segregated using a magnetic stirrer and ultrasonic agitator during the preparation of nanolubricants. According to TEM images, the suspension is found to be homogeneous and the particles are well dispersed and distributed within the host fluid. It is also observed that the nanoparticles exhibit similar morphological characteristics such as physical appearance, shape, and size in the suspension.

The two-step method is used to prepare the nanolubricants at various volume concentrations. Five different particle concentrations are considered for the studies (0.03–0.2 vol%). The primary disintegration process of CNTs within the base lubricant was carried out with the aid of a magnetic stirrer for 1 h, and the samples are ultrasonically agitated using an ultrasonic agitator at a frequency of 40 kHz to homogenize the colloid, for 6 h. Visual inspections are performed first to identify any indication of sedimentation or coagulation. No evidence was noticed after five days of preparation according to visual inspection. To quantify the stability of nanolubricant samples, U-V visible spectroscopy analysis is conducted.

2.1. Measurement of stability

Ultraviolet–visible spectroscopy is widely used to analyze fluids and solids with the help of ultraviolet radiant energy and visible and near-infrared energy of the electromagnetic spectrum. The transmitted light from the sample provides the absorbance spectra of the sample fluid. The analytical values can be represented in terms of the absorbance of light energy. The basic principle of analysis is Bouguer-Beer law or Beer-Lambert rule, which states that the absorbance of a solution is directly proportional to the concentration of the species in the solution and the path length. In the present study, the stability of nanolubricants is measured with UV–vis spectroscopy, by determining the absorbance after the first and fifth days of preparation.

2.2. Measurement of thermal conductivity

The thermal conductivity of base lubricant and nanolubricants at different volume concentrations are measured with KD2 Pro thermal property analyzer. The principle of operation is the transient hot-wire method. Thermal conductivity with an accuracy of ±0.001 could be measured by this device. The apparatus meets international standards such as ASTM D5334-14 and IEEE 442-1981. A constant temperature circulator with an accuracy of 0.01 °C is used to maintain the temperature of the sample constant. Measurements are conducted repetitively. Based on the deviation between the thermal conductivity of calibration standard fluid and the measured thermal conductivity, the measurement error is estimated and the thermal conductivity data reported in the study represents an average of fifteen measurements with an estimated standard error of ±1.2%. The thermal conductivity of nanolubricant at different volume fractions is determined in the temperature range of (20–50 °C).

2.3. Rheological characterization

The rheological behaviour of the pure lubricant and nanolubricants are determined with a Brookfield rotational type rheometer, having a measurement range between 1.0 and 2000 cP. ASTM D2196-10 standard is followed for the measurements. Rheocalc software along with a PC-based data acquisition system is employed to record the measurements. The maximum uncertainty in the measurement is found to be 1.6%. The experiments are conducted with different volume fractions (0.03–0.2%), and temperatures (20–90 °C). The shear rate is varied (3.75/s to 225/s) to explicate the effect of shear rate on the viscosity and flow behaviour of the pure and nanolubricant. Five sets of data corresponding to each test condition are logged and average values are considered for the representation of experimental results. The flow behaviour of the pure lubricant and CNT-PAG nanolubricant are predicted using Ostwald De Waele or power-law model, which is the most

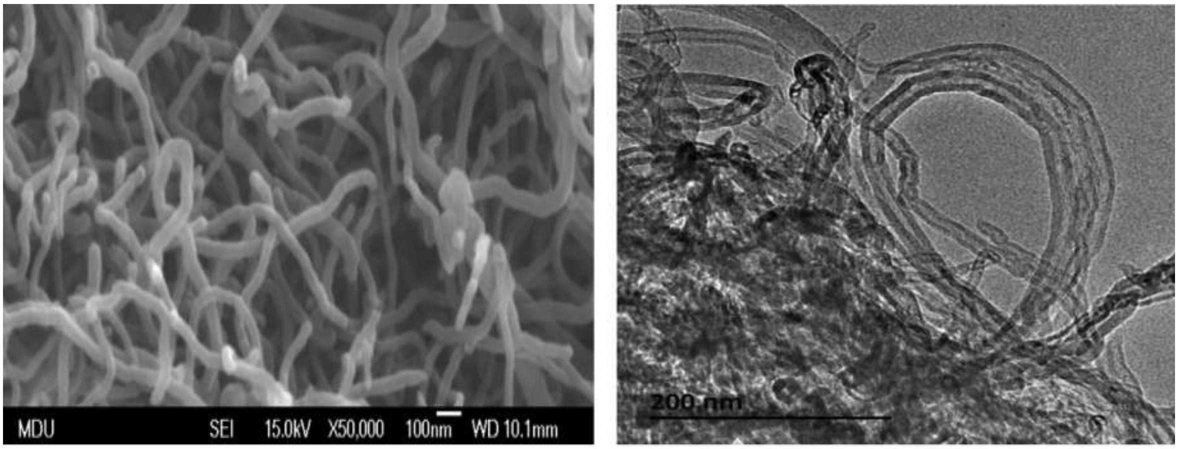

Fig. 1. (a) SEM image of CNT. (b) TEM image of CNT suspenion.

generalized model for the flow prediction of non-Newtonian fluids. According to Ostwald–De Waele power-law model (Eq. (1)) the shear stress and rate of shear can be correlated as

$$\tau = m\gamma^{n} \tag{1}$$

The Power Law model is described by two parameters, consistency coefficient or consistency index (m) and flow behaviour index (n). The consistency index pertains to the consistency of the fluid at a particular moment, which portrays how much viscous the fluid is. If the magnitude of $n < 1$, the fluid is known as shear-thinning or pseudoplastic fluid. This means that the apparent viscosity decreases with an increase in shear rate. When $n > 1$, it is shear-thickening or dilatant fluid, i.e. their apparent viscosity increases as shear rate increases. To obtain these indices, rheograms are plotted and the indices are calculated.

2.4. Modelling of thermo physical properties of nanolubricant

Genetic algorithm-based regression correlations have been generated to predict the thermal conductivity and viscosity of CNT-PAG nanolubricants, using Eureqa Data Robot, the A.I. powered modelling engine. The evolutionary algorithms generate solutions according to the theory, survival of the fittest, to optimize problems and predictive regression correlations using methods motivated by natural evolution, such as inheritance, mutation, selection, and crossover. A population of individuals is maintained within search space and each representing a possible solution to a given problem. These individuals are similar to chromosomes and the variables are analogous to genes. During the successive generation, a proportion of the existing population is selected to breed a new generation. The various steps involved in the genetic algorithm are shown in Fig. 2. The regression curves are fitted with R-squared values greater than 0.998.

3. Results and discussion

3.1. Dispersion stability of nanolubricants

Fig. 3 shows the UV–vis spectra of the nanolubricant after the 1st and 5th days of preparation. The maximum absorbance is obtained within a wavelength range of 200–320 nm. It is clear from the figures that in standstill conditions, the decrease in peak absorbance value is trivial (from 1.03 to 0.84) on the fifth day of preparation. This is a clear indication of stability, which means there is the presence of a higher population of nanoparticles in the base lubricant to interact with the light even after 120 h of preparation.

3.2. Thermal conductivity

Fig. 4 depicts the thermal conductivity of nanolubricant as a function of nanoparticle volume fraction at various temperatures. The nanolubricants exhibit higher thermal conductivity than that of pure lubricant at all particle volume fractions. The thermal conductivity of the colloid increases with an increase in particle concentration and the maximum thermal conductivity ratio was observed as 1.18 at a particle concentration of 0.2 vol%. There major reasons for this enhancement are: (i) The Brownian motion effect (ii) interfacial 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 (iii) the organized chain like clustering of particles within the fluid and the increased thermal conductivity of suspended solid particles. The thermal conductivity of pure lubricant and nanolubricants at all particle concentrations decreases with an increase in temperature. This is due to the following phenomena: (i) at lower concentrations and at elevated temperatures, the mean path between the nanoparticle increases and thus reduces the probability of collision between particles and may also lead to a decline in the near-field radiation effect.

3.3. Modelling of thermal conductivity of CNT nanolubricant

The correlations proposed to forecast the thermal conductivity of CNT-PAG nanolubricant by considering various parameters such as temperature, particle concentration, and thermal conductivity of base fluid and particle are shown in Eqn.2 [1]. A comparison of experimental thermal conductivity and that predicted from the available models in literature and the proposed model is presented in the subsequent sections. The proposed model can predict the thermal conductivity of CNT-PAG nanolubricant for various temperature and volume fractions. The model is valid for $0.03 \leq \phi \leq 0.2\%$ and $20 \leq T \leq 50$ °C.

$$\begin{aligned} k_{NL} = {} & 0.0366T + 1.61\Phi^{2} + \frac{1.01e - 5T - 0.00313}{\Phi} + 2.59e \\ & - 50.0091^{(0.117T - 36.4)} + 7.9e - 5\Phi 0.0091^{(0.117T - 36.4)} \\ & - 5.25 - 6.22e - 5T^{2} - 6.46\Phi^{3} \end{aligned} \tag{2}$$

where Φ the particle concentration in %, T is is the temperature in K, and k_{NL} is the thermal conductivity of the nanolubricant. The comparison of experimental thermal conductivity and that predicted from the present correlation is portrayed in Fig. 5. The regression

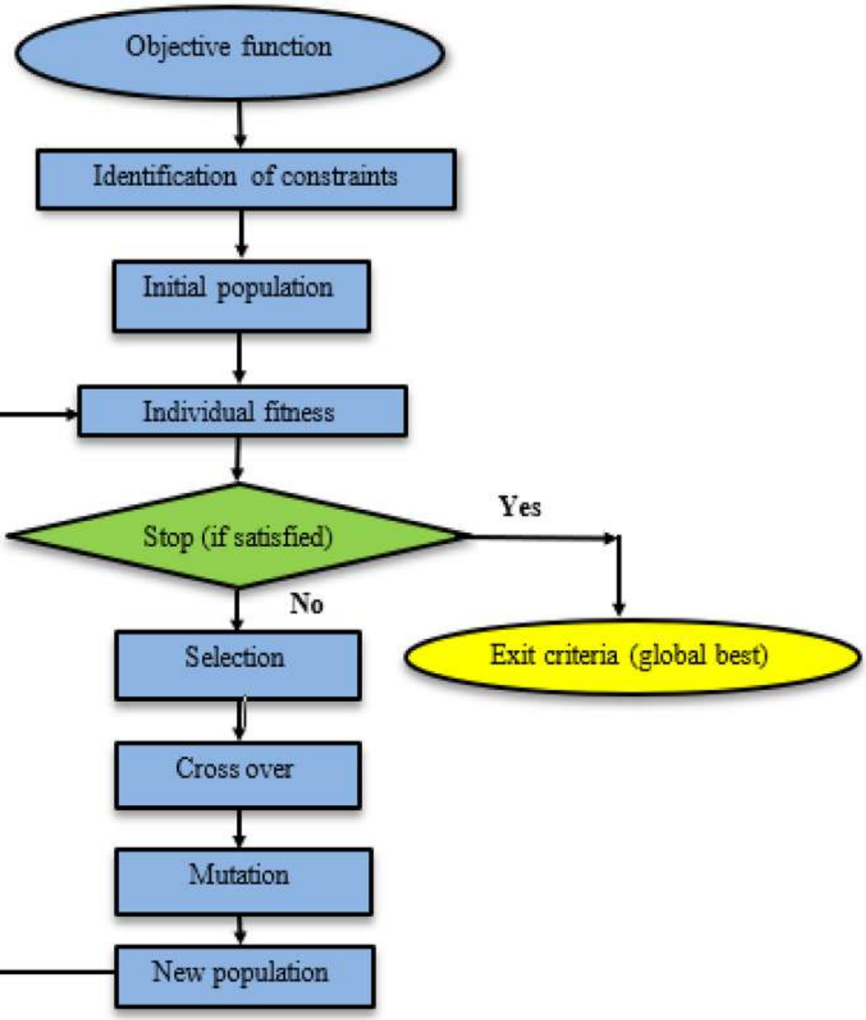

Fig. 2. Steps involved in a genetic algorithm.

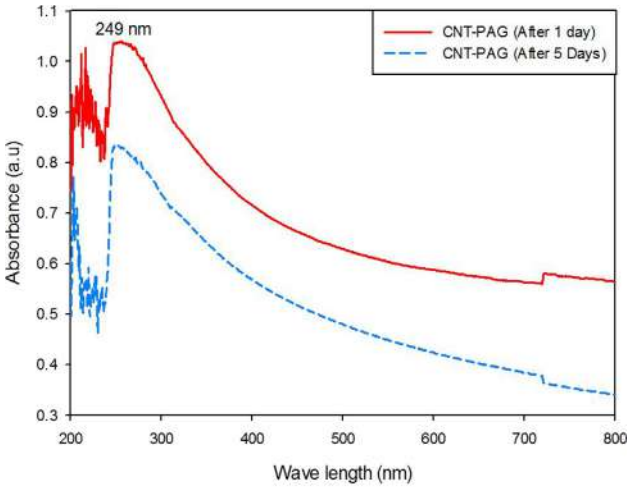

Fig. 3. Uv–vis spectrum of CNT nanolubricant (0.2 vol%).

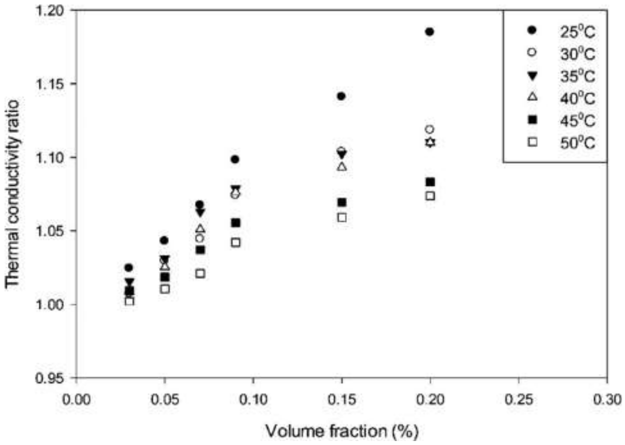

Fig. 4. Effect of volume fraction and temperature on thermal conductivity of CNT-PAG nanolubricant.

model displays excellent agreement with the experimental data within the specified range within an error band of ±0.5%. Fig. 5(a) shows the comparison of thermal conductivity obtained from experiments and that predicted from the present correlation. In addition to classical models available in the literature, Xue model, which is proposed exclusively for carbon nanotube-based nanofluids is used for the comparison of CNT-PAG nanolubricant. From Fig. 5(b) it is obvious that the classical model underpredicts the experimental thermal conductivity. The Xue model, which is appli-

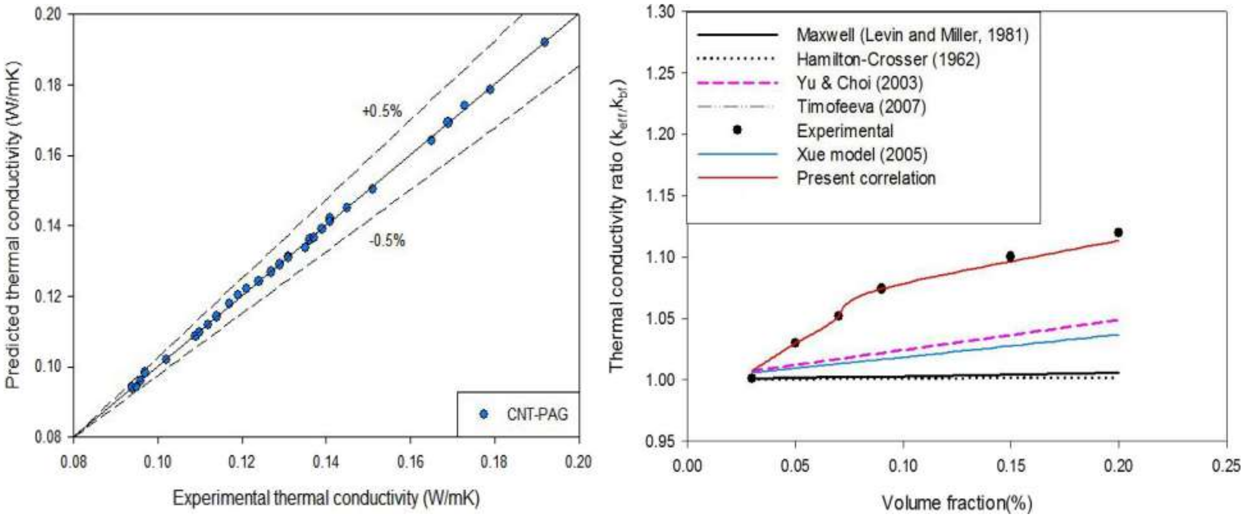

Fig. 5. Comparison of thermal conductivity (a) experimental vs correlation results, (b) experimental vs model predictions.

cable for CNT based nanofluids also fails to predict the results. The present correlation well predicts the thermal conductivity of CNT-PAG nanolubricant within the experimental conditions.

3.4. Effect of particle concentration on the viscosity of nanolubricants

Fig. 6(a) shows the variation of viscosity with volume fraction at different shear rates. From the figure, it is evident that volume fraction and shear rate have a crucial impact on the viscosity of the nanolubricant. As the shear rate increases, the relative viscosity is found to be decreasing. Besides, the nanolubricants sustain adequate relative viscosity at elevated temperatures and moderate shear rates and prove that they are more appropriate to use at elevated temperature and shear rates. This is in line with the operating conditions in refrigerant compressors. Fig. 6(b) provides a better understanding of viscosity variation with temperature. The results reveal that irrespective of the shear rate and volume fraction, the viscosities nanolubricants diminish with an increase in temperature. A similar trend was displayed by pure lubricant as well. This possible reason is, 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 a decrease in viscosity.

3.5. Rheological characterization

The rheological studies were performed over the range of shear rate from 3.75/s to 225/s covering a wide range of temperatures. Fig. 7(a) shows the variation of viscosity with the shear rate for pure lubricant. As expected, pure lubricant exhibits Newtonian behaviour within the shear rate range considered.

The same measurement ranges of shear rates are considered to measure the viscosity of the nanolubricant as well and are represented in Fig. 7(b). Irrespective of the temperature and concentrations, the apparent viscosity diminished with an increase in shear rate. The alteration in viscosity of nanolubricant is found to be trivial at lower particle concentrations. Though, a significant decrease in viscosity is manifested at higher volume fractions. That is the nanolubricant exhibits severe non-Newtonian behaviour. The force of interaction will be decreased at an elevated shear rate and which in turn reduces the resistance against the flow and hence the apparent viscosity. Fig. 8(a) and (b) show rheogram of pure lubricant and nanolubricant respectively. The curves are fitted with an R-squared value higher than 0.99. Here, n and m represent the power law and consistency indices respectively. From the fig-

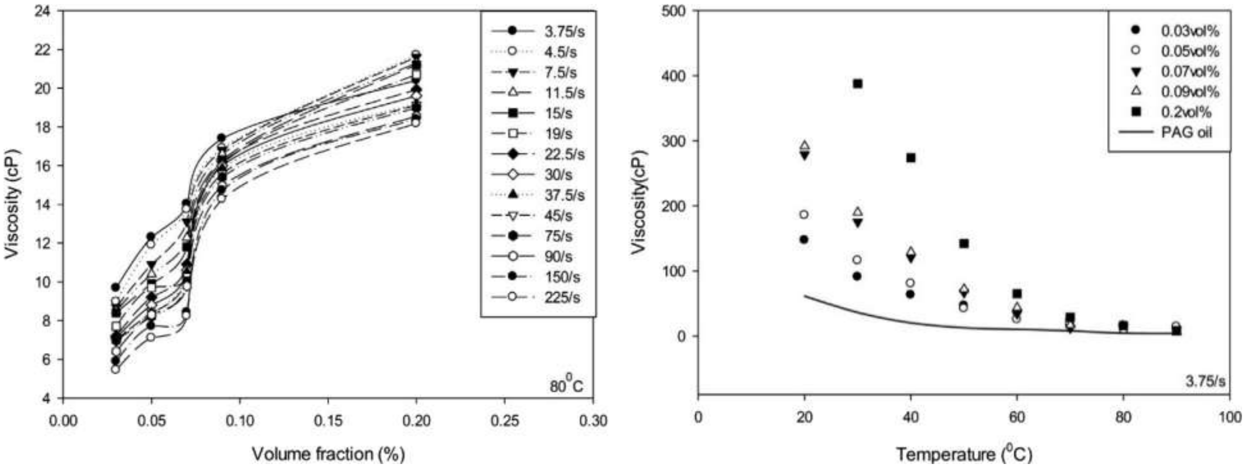

Fig. 6. (a) Variation of viscosity with volume fractions at different shear rates, (b) Effect of temperature on viscosity, of nanolubricant.

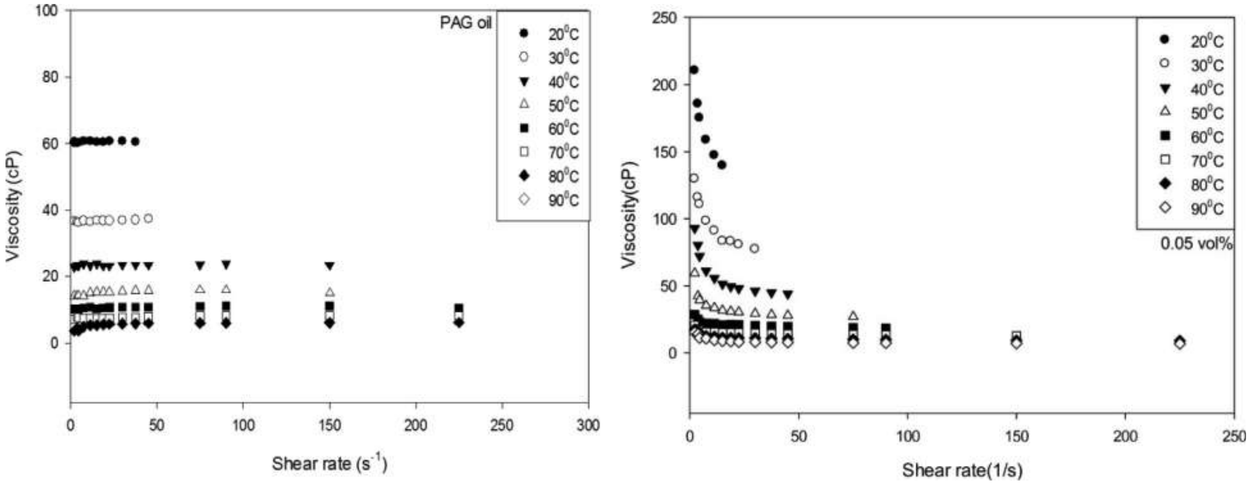

Fig. 7. Viscosity of (a) pure lubricant, (b) nanolubricant, with shear rates at different temperatures.

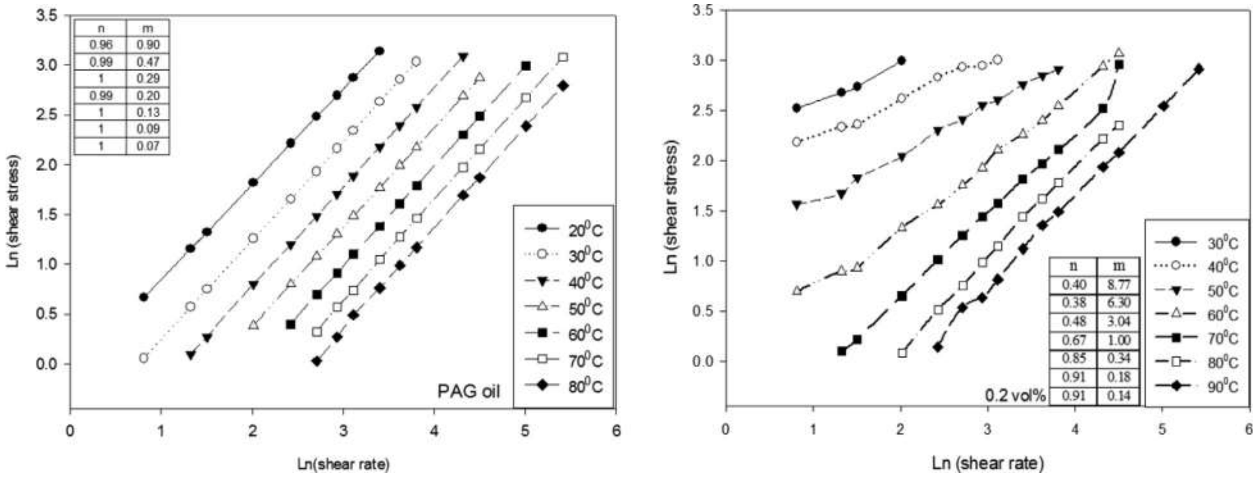

Fig. 8. Rheogram (a) pure lubricant, (b) nanolubricant, at different temperatures.

ures, it is clear that regardless of temperature nanolubricant behave as non-Newtonian fluid with a power-law index less than unity. Meanwhile, the pure PAG oil behaves like a Newtonian fluid with a power-law index approximately equal to one.

3.6. Modelling of viscosity of CNT nanolubricants

Most of the viscosity models available in the literature are based on spherical nanoparticles. Suitable models to predict the

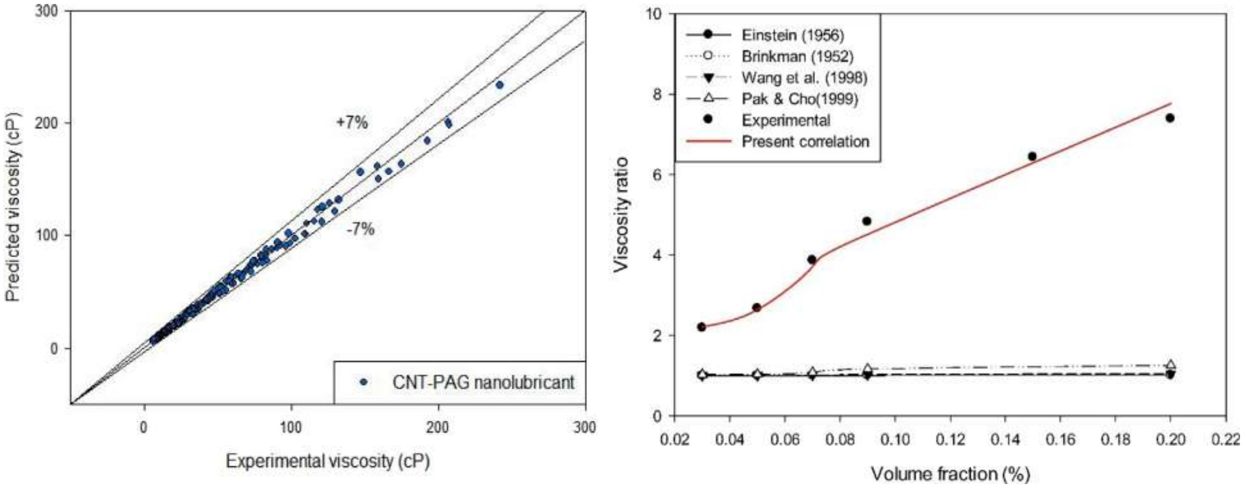

Fig. 9. Comparison between (a) experimental viscosity and predicted viscosity, (b) experimental viscosity and model predictions at room temperature.

viscosity of carbon-based nanolubricants are scarce in the literature. Hence a new correlation is proposed to predict the viscosity of CNT based nanolubricant. The proposed model for CNT-PAG nanolubricant is shown in Eq. (3).

$$\mu_{NL} = 28.4\Phi + \frac{2.11e3}{T} + \frac{4.71e8\Phi}{2.35e5 + \mathrm{Y}T^3} + \frac{13.3 + 18.6\cos(5.17T) - 893\Phi}{\mathrm{Y}} - 18.1 \tag{3}$$

The correlation is valid for $0.03 \leq \phi \leq 0.2\%$, $20 \leq \mathrm{T} \leq 90$ °C and $5 \leq \gamma \leq 200$ 1/s. where Φ is the particle concentration in %, T is the temperature in K, γ, the shear rate in 1/s and μ_{NL} is the viscosity of the nanolubricant. Fig. 9(a) shows the comparison between the experimental data of viscosity and that predicted from the proposed correlation in the case of CNT-PAG nanolubricant. From the figure, it is obvious that the model is successful in predicting the viscosity of nanolubricant.

Fig. 9(b) shows the comparison of experimental viscosity with that obtained from a few models available in the literature along with the present correlation. The viscosity at room temperature is used for the comparison. It can be seen from the figure that the classical models fail to predict the viscosity of the CNT nanolubricant, while the present model is in line with the experimental results.

4. Conclusions

Comprehensive experimental investigations on thermal and rheological characteristics of CNT-PAG nanolubricants are carried out. Regression correlations are proposed to forecast the thermal conductivity and viscosity of nanolubricants. The following key conclusions have been drawn from the experimental investigation. The thermal conductivity of the nanolubricants increases with an increase in volume concentration and decreases with the intensification of temperature. The viscosity of nanolubricants increases with an increase in volume fraction and decreases with an increase in temperature. Unlike pure lubricant, shear rate plays a vital role in the behavior of the nanolubricants. Non-Newtonian shear thinning of nanolubricants was evidenced. However, at higher shear rates, shear-thinning is insignificant and nanolubricants behave almost like a Newtonian fluid. Classical models fail to predict the thermal conductivity and viscosity of the CNT-PAG nanolubricants. The proposed regression models well predict the thermophysical properties of nanolubricant. At elevated temperatures and shear rates, nanolubricants sustain adequate viscosity than pure lubricant which is a desirable operating feature for refrigerant compressors. Thermal and rheological studies revealed that the potential of CNT-PAG nanolubricant as an alternative lubricant for refrigerant compressors is excellent. The application of the novel nanolubricant may lead to the development of energy-efficient HVAC systems.

CRediT authorship contribution statement

S.S. Sanukrishna: Conceptualization, Methodology. **Vivek Mathew Jose:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Sarit K. Das SUSC, Nanofluids Science and Technology. A John wiley & Sonc. Inc., Publication, New Jersey, Canada, 2007.

[2] S.U.S. Choi, J.A. Eastman, Enhancing thermal conductivity of fluids with nanoparticles, ASME Int. Mech. Eng. Congr. Expo. 66 (1995) 99–105, https://doi.org/10.1115/1.1532008.

[3] S. Kakaç, A. Pramuanjaroenkij, International Journal of Heat and Mass Transfer Review of convective heat transfer enhancement with nanofluids, Int. J. Heat Mass Transf. 52 (13–14) (2009) 3187–3196, https://doi.org/10.1016/j.ijheatmasstransfer.2009.02.006.

[4] L. Yang, J.-N. Huang, F. Zhou, Thermophysical properties and applications of nano-enhanced PCMs: an update review, Energy Convers. Manage. 214 (2020) 112876, https://doi.org/10.1016/j.enconman.2020.112876.

[5] S. Bobbo, L. Fedele, M. Fabrizio, S. Barison, S. Battiston, C. Pagura, Influence of nanoparticles dispersion in POE oils on lubricity and R134a solubility, Int. J. Refrig. 33 (6) (2010) 1180–1186, https://doi.org/10.1016/j.ijrefrig.2010.04.009.

[6] Singh T, W. Almanassra I, Ghani Olabi A, Al-Ansari T, McKay G, Ali Atieh M. Performance investigation of multiwall carbon nanotubes based water/oil nanofluids for high pressure and high temperature solar thermal technologies for sustainable energy systems. Energy Convers. Manage. 225 (2020) 113453. <https://doi.org/10.1016/j.enconman.2020.113453>.

[7] E. Sadeghinezhad, M. Mehrali, R. Saidur, M. Mehrali, S. Tahan Latibari, A.R. Akhiani, et al., A comprehensive review on CNT nanofluids: recent research, development and applications, Energy Convers. Manage. 111 (2016) 466–487, https://doi.org/10.1016/j.enconman.2016.01.004.

[8] T. Luo, X. Wei, X. Huang, L. Huang, F. Yang, Tribological properties of Al2O3 nanoparticles as lubricating oil additives, Ceram. Int. 40 (5) (2014) 7143–7149, https://doi.org/10.1016/j.ceramint.2013.12.050.

[9] M. Gulzar, H.H. Masjuki, M.A. Kalam, M. Varman, N.W.M. Zulkifli, R.A. Mufti, R. Zahid, Tribological performance of nanoparticles as lubricating oil additives, J. Nanopart. Res. 18 (8) (2016), https://doi.org/10.1007/s11051-016-3537-4.

[10] W. Zhai, N. Srikanth, L. Bing, K. Zhou, Carbon nanomaterials in tribology, Carbon N.Y. 119 (2017) 150–171, https://doi.org/10.1016/j.carbon.2017.04.027.

[11] I.M. Mahbubul, A. Saadah, R. Saidur, M.A. Khairul, A. Kamyar, Thermal performance analysis of Al2O3/R-134a nanorefrigerant, Int. J. Heat Mass Transf. 85 (2015) 1034–1040, https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.038.

[12] M. Kole, T.K. Dey, Thermophysical and pool boiling characteristics of ZnO-ethylene glycol nanofluids, Int. J. Therm. Sci. 62 (2012) 61–70, https://doi.org/10.1016/j.ijthermalsci.2012.02.002.

[13] M.A. Akhavan-Behabadi, M. Nasr, S. Baqeri, Experimental investigation of flow boiling heat transfer of R-600a/oil/CuO in a plain horizontal tube, Exp. Therm. Fluid Sci. 58 (2014) 105–111, https://doi.org/10.1016/j.expthermflusci.2014.06.013.

[14] M. Hemmat Esfe, H. Rostamian, Non-Newtonian power-law behavior of TiO2/SAE 50 nano-lubricant: an experimental report and new correlation, J. Mol. Liq. 232 (2017) 219–225, https://doi.org/10.1016/j.molliq.2017.02.014.

[15] M.H. Esfe, M. Afrand, S.H. Rostamian, D. Toghraie, Examination of rheological behavior of MWCNTs/ZnO-SAE40 hybrid nano-lubricants under various temperatures and solid volume fractions, Exp. Therm. Fluid Sci. 80 (2016) 384–390, https://doi.org/10.1016/j.expthermflusci.2016.07.011.

[17] A. Kumar, A. Rai, Rheological behaviour of nano fluids : a review 53 (2016) 779–791. <https://doi.org/10.1016/j.rser.2015.09.033>.

[18] M.A. Kedzierski, R. Brignoli, K.T. Quine, J.S. Brown, Viscosity, density, and thermal conductivity of aluminum oxide and zinc oxide nanolubricants, Int. J. Refrig. 74 (2017) 3–11, https://doi.org/10.1016/j.ijrefrig.2016.10.003.

[19] M.A. Serebryakova, S.V. Dimov, S.P. Bardakhanov, S.A. Novopashin, International Journal of Heat and Mass Transfer Thermal conductivity, viscosity and rheology of a suspension based on Al2O3 nanoparticles and mixture of 90 % ethylene glycol and 10 % water, HEAT MASS Transf 83 (2015) 187–191, https://doi.org/10.1016/j.ijheatmasstransfer.2014.12.002.

Further reading

[16] S. Aberoumand, A. Jafarimoghaddam, M. Moravej, H. Aberoumand, K. Javaherdeh, Experimental study on the rheological behavior of silver-heat transfer oil nanofluid and suggesting two empirical based correlations for thermal conductivity and viscosity of oil based nanofluids, Appl. Therm. Eng. 101 (2016) 362–372, https://doi.org/10.1016/j.applthermaleng.2016.01.148.