Thermo-physical Investigation of Vegetable Oil-Based Nano-lubricant

Om Prakash, Ashwani Kumar, and Subrata Kumar Ghosh

Abstract This work aims to study thermo-physical properties, including thermal conductivity, viscosity, viscosity index, and rheology of vegetable oil-based nano-lubricant. Synthesis of nano-lubricant was done using vegetable seed oil (castor oil) and copper oxide (CuO) nano-particles using a magnetic stirrer and probe-type sonicator for breaking agglomerate. The thermal conductivity of samples was measured using transient hot-wire liquid thermal conductivity meter, and the effect of nano-particles was analyzed. Viscosity and viscosity index (VI) of the nano-lubricants thus prepared have been analyzed by Stabinger viscometer. The variation of viscosity of nano-lubricant with the shear rate was reported using an advanced air bearing rheometric system. The viscosity variation with respect to shear rate showed a decreasing trend, whereas the viscosity variation with respect to concentration showed an increasing trend. The results show that it is possible to increase the stability of samples in terms of viscosity variation with temperature and shear rate using nano-particles, hence makes it suitable for lubricant applications.

Keywords Nano-lubricant · Viscosity · Thermal conductivity · Rheology

1 Introduction

The surge in energy consumption and demand for economically restricted-energy sources have made us move toward efficient use of energy and energy savings [1–3].

O. Prakash · S. K. Ghosh
Department of Mechanical Engineering, Indian School of Mines, Indian Institute of Technology, Dhanbad, Jharkhand 826004, India
e-mail: ompr.18mt0149@mech.iitism.ac.in

S. K. Ghosh
e-mail: subrata@iitism.ac.in

A. Kumar (✉)
Kalinga Institute of Industrial Technology, Deemed To Be University, Bhubaneswar, Odisha 751024, India
e-mail: kumarashwani004@gmail.com

© Springer Nature Singapore Pte Ltd. 2021

S. Revankar et al. (eds.), *Proceedings of International Conference on Thermofluids*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-7831-1_39

Environmental challenges posed by lubricant use, such as toxicity, have made us pursue the development of biodegradable and environmentally friendly industrial fluids [4]. Lubrication is an essential element for any known system involving the relative motion of parts in contact with each other. Lubricant development for any mechanical system is known to be a complicated process. It involves some crucial steps such as selection of base oil (stock), selection of additives to serve individual needs like corrosion inhibition, oxidation resistance, or extreme pressure lubrication, etc., and evaluating combination of additives that can work along to serve the needful along with optimization between performance and cost ending with full-scale test [5]. Environmental degradation and toxicity of mineral and synthetic lubricants reflected in the near past have stepped-up the need for environmental-friendly lubricant and industrial oil many-folds. Vegetable oil owing to their biodegradable nature comes up as a viable alternative. Most of the vegetable oil is an ester-based containing triglycerides. Triglycerides being more polar over petroleum-oil have high adherence to the metal surface, but it also has a short-coming of low thermo-oxidation stability and corrosion inhibition [5]. Study of thermo-physical properties of the lubricants in development has seen importance in previous works. The effect of concentration on viscosity for CuO nano-fluid was analyzed as engine oil and reported along with the tribological study of the same [6]. Effect of temperature and concentration on rheological property was analyzed as thermo-physical properties for various hybrid nano-lubricants out of MWCNT/SiO_2 in SAE 40 oil and reported, and an empirical relation was also established for proper rheological study different form normal relations [7]. Work has also been executed on the study of rheological properties experimentally and then the development of the model on neural networks and its sensitivity analysis for validation of the same [8]. Carbon nanostructures have been a center of attraction for nano-scientist in their works and proceedings; the rheological study was also done using graphene solute in organic media glycerol followed by characterizations and rheological studies revealing the shear function of nano-fluid being a function of mass function and temperature [9].

Thermal conductivity enhancement of engine oil using SAE50 motor oil and ZnO nano-oxide was reported by the preparation and characterization of nano-lubricant and then thermal conductivity measurement using KD2 pro thermal analyzer device over a temperature range of 25–55 °C, and finally a correlation for results were developed [10]. An experimental study to reveal the effect of MWCNT on thermal properties like viscosity, flash-point, and thermal conductivity as a parameter affecting the quality application of engine oil was presented in earlier works [11]. CuO microparticle suspension stability was analyzed by FTIR and thermal stability by the TGA method; the suspension was made in API GL-5 gear oil with the purpose of enhancement of thermal and physical properties. DSC thermographs were used to study the thermal effects, and enthalpy interaction prediction for the sample micro-suspension was done and presented [12].

There have been limited studies presented over the enhancement of bio-stocks as industrial fluids. Thus, the presented study highlights the investigation of various thermo-physical properties of a vegetable seed oil-based nano-lubricant. Castor oil

Table 1 Sample nomenclature

Sample	Designation	Detail
Plain oil	PO	Plain oil without additive
Nano-lubricant (0.05%)	No.05	Plain oil with 0.05 wt% additive concentration
Nano-lubricant (0.10%)	No.10	Plain oil with 0.10 wt% additive concentration

is selected as base stock, and CuO nano-particles were dispersed by mixing and sonication processes to form a stable particle-oil suspension. Viscosity and its variation with the temperature being the most crucial property of concern for the base stock (principal constituent for any lubricant) as it is the last line of defense for lubricant is reported for different concentrations along with a temperature range of 20–100 °C. Also, a variation of viscosity w.r.t shear rate being other important properties for industrial fluids was also studied using an advance air bearing rheological setup over a shear strain range of 0–40 s^{-1} at 40 °C. Finally, the thermal conductivity of the lubricant samples crucial for heat conduction, which in turn affects the viscosity of lubricant was studied to understand the effect of metal oxide nano-particle additive.

2 Materials and Methods

2.1 Sample Preparation

Samples of nano-lubricant were prepared by adding dehydrated CuO nano-particles (40–70 nm in size) in castor oil. The details of the samples are presented in Table 1. Nano-particles have been mixed by stirring over magnetic stirrer at 500 rpm for 3 h, followed by ultra-sonication using probe-type sonicator (ultrasonic processor; piezo-U-sonic) for 1 h. Obtained samples have been kept under inspection for 2 h to observe stability following which no sedimentation was observed.

2.2 Viscosity and Viscosity Index

Lubricants serve an essential purpose of frictional loss optimization and minimization of wear of component applied to cooling or heat dissipation and contaminant suspension [13]. The evaluation of oil viscosity is a critical parameter for both fresh and used oil (condition monitoring). For every particular application, there is a prescribed ASTM standard. For condition monitoring, change in viscosity can reveal important conclusions about oil, such as oxidation of base stock, build-up, shear breakdown of additives or dilution.[14]. Viscosity index is a measure of variation of viscosity with the temperature.

Fig. 1 Photographic view of Stabinger viscometer

A higher VI value signifies that the fluid undergoes a lower change in viscosity when subjected to different temperatures [15]. Viscosity and viscosity index of samples have been measured using Stabinger viscometer (SVM 3000; Anton Paar), the photographic view of viscometer is shown in Fig. 1. A sample of 2 ml is taken for the measurement of viscosity at a pre-fixed temperature. In this work, viscosity was measured at an increment of 10 °C in the range of 20–100 °C.

2.3 Rheology

Industrial fluid often undergoes a situation where it faces a variety of shear zone in the same machinery, as in the case of rotating machines like compressors, transmission fluids, and gear oils. The same oil passes over different shear zones; hence, the evaluation of the shear response of lubricant is essential; in rheology, the lubricant is subjected to shear strain rate and variation of viscosity is observed which tell us about the shear response of oil. This test helps predict shear thinning and thickening of the oil, which can disrupt the desired lubrication system. Advanced air bearing rheometer (Bohlin Gemini 2; Malvern Instruments, UK) was used in this study for measurement of viscosity within shear strain rate range: 0–40 s^{-1} at a temperature of 40 °C which is depicted in Fig. 2. Rheometer works on air pressure generated from an attached compressor at 6 bars. A cup and bowl arrangement is used to generate the shear rate, and the gap between the cup and bowl is maintained at 150μ.

2.4 Thermal Conductivity

Industrial fluids (lubricants) not only reduces friction and wear but are also needs to be efficient in heat transfer as in the case of engine oil, for this purpose, thermal conductivity is a very crucial property to be measured as it directly affects the efficiency of heat transfer. Thermal conductivity is also a crucial parameter of performance and design [16]. Thermal conductivity also affects the samples viscosity indirectly

Fig. 2 Advance air bearing rheological system

as it controls the heat transfer capacity of lubricant. The thermal conductivity of the samples has been measured using transient hot-wire liquid thermal conductivity meter (THW-L2; thermotest thermo-physical instruments). Thermal conductivity meters measure the thermal conductivity value by the technique outlined in (ASTM D7896-14) [17]. A sample of 20 ml in isothermal condition has been taken in a slit-cylindrical container at 20 °C, and then the hot-wire sensor was immersed into it to measure the thermal conductivity at set temperature. Thermal conductivity meter is shown in Fig. 3

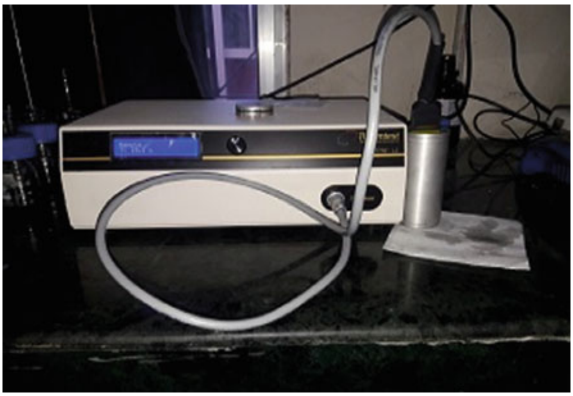

Fig. 3 Transient hot-wire thermal conductivity meter

3 Results and Discussion

3.1 Viscosity

Variation of viscosity w.r.t change in temperature is depicted in Figs. 4 and 5. The viscosity of the nano-lubricant decreases with an increase in temperature, as is the case of the base oil. The decrease in viscosity of the fluid with temperature can be attributed to the weakling of the intermolecular forces due to temperature. It was also seen that the viscosity slightly increase with the increase in concentration. The increase in viscosity can be attributed to nano-particle between the fluid layer of lubricants, causing ease in movement of fluid layer decreasing resistance to flow, i.e., viscosity but as concentration increases agglomeration of a particle causes formation asymmetric and larger particles, thereby hindering the ease of flow thus increasing the viscosity [6].

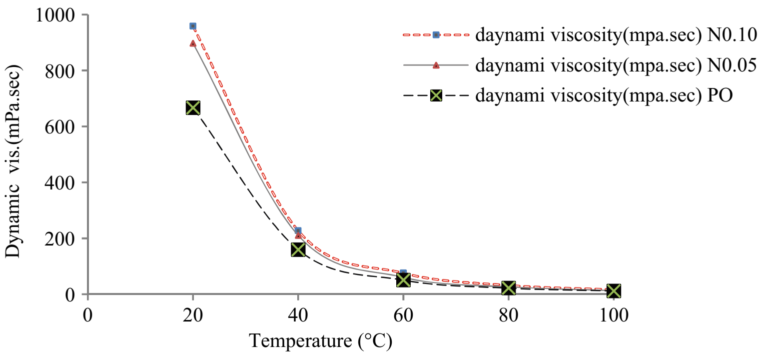

Fig. 4 Variation of dynamic viscosity (m Pa s) versus temperature

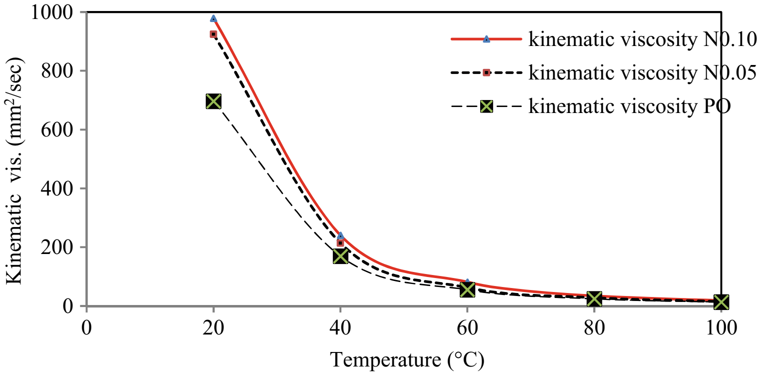

Fig. 5 Variation of kinematic viscosity (mm^2/s) versus temperature

Table 2 Viscosity index of samples

Sample	VI
PO	85.8
N0.05	86.6
No.10	87.2

The VI of the sample has been reported in Table 2. It can be seen that the VI of the samples increase with the increase in concentration this is due to the fact that the thermal conductivity increases with concentration enhancing the heat transfer efficiency, thereby a lesser change in viscosity can be seen at higher concentration, and thereby a high VI is obtained.

3.2 Rheology

The variation of viscosity with shear rate is shown in Fig. 6. It can be observed that the oil sample undergoes a shear thinning at a higher shear rate, and viscosity decreases with a decrease in concentration. The same trend is observed for all samples. The reason of shear thinning at a higher shear rate is due to the introduction of high shear and the particle aggregates are broken in much smaller size, thereby enhancing the symmetry of particle and these smaller aggregates being present between oil layers enhance the ease of flow, and thereby causes a reduction in the viscosity of sample [18]. It can also be deduced from the curve that at all shear rates, the viscosity increases with the increase in the concentration of nano-particle, i.e., the volume fraction of the suspension, which is in accordance with the conventional Einstein model for infinitely dilute suspension of the non-interacting hard sphere [19].

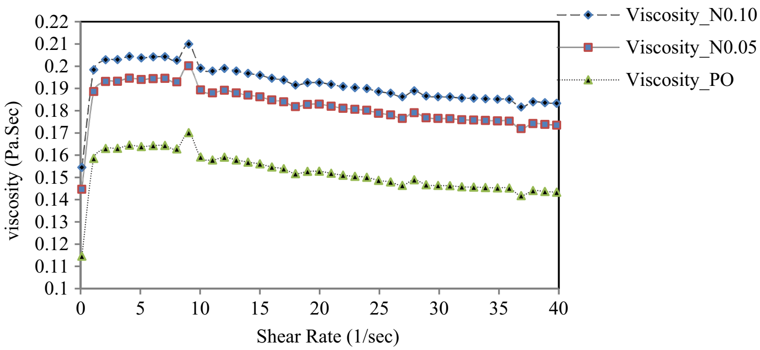

Fig. 6 Variation of viscosity (Pa s) versus shear rate at 40 °C

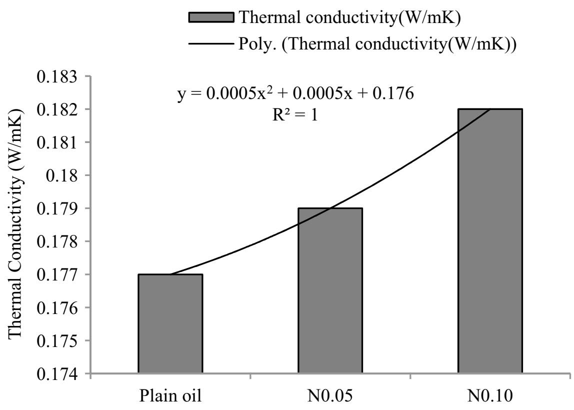

Fig. 7 Variation of thermal conductivity with concentration of nano-lubricants

3.3 Thermal Conductivity

Variation of thermal conductivity can be seen with respect to concentration at a constant temperature of 20 °C for the castor oil-based nano-lubricants. Clearly, the enhancement of thermal conductivity can be seen above in Fig. 7. The variation of thermal conductivity was increasing in nature and found to be nonlinear w.r.t increase in concentration.

The presence of metal oxide nano-particles causes an increment in the surface interface for heat exchange inside the fluid, thereby increasing fluid-particle interfacial heat exchange, and thus an increment in heat transfer properties can be observed [20]. Enhancement of 2.82% in thermal conductivity was obtained by the suspension of copper metal oxide nano-particle in base stock over plain base oil.

4 Conclusions

Viscosity decreases with temperature, and the same trend has been seen for all the samples. It was observed that both the kinematic and dynamic viscosity decreased as temperature increases at a particular concentration of nano-lubricants and plain oil samples. It has also been seen that the viscosity across the sample is observed to be increasing with concentration, i.e., the viscosity has a direct proportionality with the volume fraction, which is in accordance with the theoretical Einstein model. The result shows that viscosity with shear rate is decreasing, i.e., the nano-lubricant is found to be shear thinning in experimental behavior. The nano-particle owing to its geometry was expected to create an ease of flow and decrease the viscosity of the sample at a higher shear rate, which would cause the breakdown of aggregates. A nonlinear increment in thermal conductivity can be observed w.r.t concentration in the case of nano-lubricants due to the enhancement of fluid-particle interfacial heat exchange. The obtained results show that the thermo-physical properties of vegetable oil can be enhanced with the addition of nano-particles. This shows that the nano-lubricant has the potential to replace mineral oil for lubrication applications.

References

1. Huminic A, Huminic G, Fleaca C, Dumitrache F, Morjan I (2015) Thermal conductivity, viscosity and surface tension of nanofluids based on FeC nano-particles. Powder Technol 284:78–84
2. Zhai Y, Li L, Wang J, Li Z (2019) Evaluation of surfactant on stability and thermal performance of Al_2O_3-ethylene glycol (EG) nanofluids. Powder Technol 343:215–224
3. Esfe MH, Raki HR, Emami MRS, Afrand M (2019) Viscosity and rheological properties of antifreeze based nanofluid containing hybrid nano-powders of MWCNTs and TiO_2 under different temperature conditions. Powder Technol 342:808–816
4. Hsien WLY (2015) Towards green lubrication in machining. Springer, Singapore
5. Perez JM (2000) Oxidative properties of lubricants using thermal analysis. Thermochim Acta 357:47–56
6. Jatti VS, Singh TP (2015) Copper oxide nano-particles as friction-reduction and anti-wear additives in lubricating oil. J Mech Sci Technol 29(2):793–798
7. Esfe MH, Afrand M, Yan WM, Yarmand H, Toghraie D, Dahari M (2016) Effects of temperature and concentration on rheological behavior of MWCNTs/SiO_2 (20–80)-SAE40 hybrid nano-lubricant. Int Commun Heat Mass Transf 76:133–138
8. Esfe MH, Saedodin S, Rejvani M, Shahram J (2017) Experimental investigation, model development and sensitivity analysis of rheological behavior of ZnO/10W40 nano-lubricants for automotive applications. Phys E 90:194–203
9. Moghaddam MB, Goharshadi EK, Entezari MH, Nancarrow P (2013) Preparation, characterization, and rheological properties of graphene–glycerol nanofluids. Chem Eng J 231:365–372
10. Yang L, Mao M, Huang JN, Ji W (2019) Enhancing the thermal conductivity of SAE 50 engine oil by adding zinc oxide nano-powder: an experimental study. Powder Technol 356:335–341
11. Ahmadi H, Rashidi A, Nouralishahi A, Mohtasebi SS (2013) Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. Int Commun Heat Mass Transf 46:142–147
12. Maheswaran R, Sunil J, Vettumperumal R, Subhash SV (2018) Stability analysis of CuO suspended API GL-5 gear lubricant sol. J Mol Liq 249:617–622
13. Caines AJ, Haycock RF, Hillier JE (2004) Automotive lubricants reference book, vol 354. Wiley
14. Jakoby B, Buskies M, Scherer M, Henzler S, Eisenschmid H, Schatz O (2001) A novel multifunctional oil condition sensor. In: Advanced microsystems for automotive applications 2001. Springer, Berlin, Heidelberg, pp 157–165
15. Braga JWB, dos Santos Junior AA, Martins IS (2014) Determination of viscosity index in lubricant oils by infrared spectroscopy and PLSR. Fuel 120:171–178
16. Wrenick S, Sutor P, Pangilinan H, Schwarz EE (2005) Heat transfer properties of engine oils. In: World tribology congress III. American Society of Mechanical Engineers Digital Collection, pp 595–596
17. Nwaoha C, Idem R, Supap T, Saiwan C, Tontiwachwuthikul P, Rongwong W, Benamor A (2017) Heat duty, heat of absorption, sensible heat and heat of vaporization of 2–Amino–2–Methyl–1–Propanol (AMP), Piperazine (PZ) and Monoethanolamine (MEA) tri–solvent blend for carbon dioxide (CO_2) capture. Chem Eng Sci 170:26–35
18. Rashin MN, Hemalatha J (2013) Viscosity studies on novel copper oxide–coconut oil nanofluid. Exp Thermal Fluid Sci 48:67–72
19. Einstein A (1906) On the theory of the Brownian movement. AnnPhys 19(4):371–381
20. Karthikeyan NR, Philip J, Raj B (2008) Effect of clustering on the thermal conductivity of nanofluids. Mater Chem Phys 109(1):50–55