Effect of Nano Particles on Tribological Behavior of Reciprocating Air Compressor Oil Using Fourball Tribometer: An Experimental Investigation

P. Cheng Reddy¹* and S. Arumugam ²

¹, ²Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya, Enathur, Kanchipuram - 631561, Tamil Nadu, India.

Chengareddy.p@kanchiuniv.ac.in

Abstract. This paper presents an experimental investigation of tribological properties of pentaerythritol ester (PE) as biolubricant with the addition of nanoparticles i.e. copper oxide (CuO). The nanoparticle was added with pentaerythritol ester by wt.% as 0.1, 0.3 and 0.5%. The experimental work was conducted on a fourball tribometer under various conditions such as applied load of 40 kg; speed of 1200 rpm, experimental duration of 1 hr and a temperature of 75°C under the standard of ASTM 4172. The 0.3% PE based nanoparticle lubricant shows the low coefficient of friction (COF), frictional torque (FT) and wear scar diameter (WSD) as compared to other nano based lubricants and with base oil. The tested worn surface was examined with SEM analysis and results are reported that the 0.3% nanoparticle lubricant shows the smoother and low surface roughness.

1 Introduction

In current scenario, the crude (mineral) oil plays a significant role in automobile and other applications. At the same time there is a huge demand in fuel and lubrication area. But in other side, these mineral oils create many problems such as emission of pollutants, toxic gases, degradability problems which damages environment, increasing of crude oil cost due to the depletion of its reserves. With this connection, world needs an environmentally friendly lubricants to avoid such type drawbacks with the crude oil. One such alternative lubricant is vegetable based biolubricant which fulfill the requirement of mineral oil [1]. But the usage of straight vegetable oil having some problems like poor thermo-oxidative stability and cold flow properties [2]. This can be rectified by modifying the vegetable oil via chemically to improve the cold flow properties and thermo-oxidative stability by conventional methods [3]. These conventional methods are taking more reaction time leads more power consumption and produces low yields which increases the cost of final product [4]. So, the researchers are attempted a few experimental works on the production of biolubricant with high yield percentage with high conversion rate at low reaction time using ultrasonic assisted transesterification process.

Many researchers are produced high yield biodiesel from various vegetable oils (namely castrol oil, coconut oil, rapeseed oil, soybean oil, etc.) using ultrasound assisted transesterification process [5-9]. But very rare attempts were completed to produce biolubricants by using ultrasonic irradiation process. Arumugam et al [10] produced pentaerythritol ester as biolubricant using ultrasonic assisted transesterification process under nitrogen atmosphere, results are revealed that the ultrasonic irradiation process produces the high yield percentage of pentaerythritol ester (PE) with low reaction
time and PE shows low coefficient friction and low wear depth. Another work carried out by optimizing the ultrasonicator process parameters like ultrasonic amplitude, ultrasonication time, catalyst concentration and ultrasonic pulse for high yields. Reported that the yield about 81.4% of pentaerythritol ester was obtained at optimal conditions i.e. 15 s ultrasonic pulse, 60% of ultrasonic amplitude, 1.5 wt% of catalyst concentration, and 100 °C reaction temperature [11]. However, the addition of nanoparticles are shows significant role on tribological properties in terms of reduction in friction and wear rate. Baskar et al [12] was investigated the tribological characteristics of chemically modified rapeseed oil by addition of with and without different nanoparticles like CuO, WS2 and TiO2. From the experimental results the addition of CuO nanoparticle lubricant shows improved tribological properties in terms of wear and friction reduction, also it shows smoother wear scar images than that of other nanoparticles. Gulzar et al [13-14] was used nano based chemical modified palm oil as lubricant to investigate the anti wear properties. They reported that the nano lubricants are shown better anti wear properties than that of without nano addition lubricants. Rajaganapathy et al [15] suggested that the addition of 0.5% CuO nanoparticle with vegetable-based lubricant shows improved viscosity, thermal conductivity and reduction in friction and wear than that of other lubricants. Another work was carried out by Kashyap and Harsha [16] on oxide nanoparticle with the addition of chemically modified rapeseed oil and the nano-based biolubricants are shown better wear reduction properties than that of raw rapeseed oil and mineral based oils. Tribological tests were conducted using four-ball tribometer and pin-on-disc tribometer under nano-based biolubricants and it shows remarkable results in terms of reduction in friction and wear [17-18].

From the literature studies, ultrasonic irradiation method is plays most significant role on production of biolubricants with high yields at low reaction time. Also, the CuO nanoparticles having good antiwear properties in terms of reduction in wear and friction. This present study is to investigate the synthesis of pentaerythritol ester as bio-based compressor oil using ultrasonic irradiation process and also tribological studies were to be carried out under nano-based biolubricants using four-ball tribometer.

2. Experimental

2.1 Ultrasonic Irradiation Transesterification Process

A two-stage transesterification process was used to synthesis the pentaerythritol ester from rapeseed oil using ultrasonicator. An ultrasonic sonicator of Oscar make, Model PR-1000, 750W Ultrasonic Power, 1 min of pulse duration, adjustable frequency of upto 25 kHz was used for this transesterification process. In first stage: the products of raw rapeseed oil (1500ml), catalyst of sodium hydroxide (13.38g), alcohol as methanol (267.6ml) was taken in three necked flask and kept in ultrasonicator for the duration of 20 min reaction time at 55°C temperature (not to be exceed 60°C). The excess alcohol was removed from the obtained product by warm water wash. Afterwards the methyl ester was separated from glycerol by using separating funnel. Then the obtained methyl ester was heated up at a temperature of 55°C to evaporate the presence of excess water. Second stage: the obtained quantity of final product of methyl ester of 960ml, p-TSA of 1.5 g as catalyst, 224.5 g of pentaerythritol and solvent of xylene as 20 ml was taken in a three necked flask and placed in a ultrasonicator chamber followed by transesterification process. The whole reaction was operated under nitrogen atmosphere with 1h reaction time, 20 kHz of frequency and at a temperature of 100°C. Later, the reactants were heated up at a temperature of 70°C to evaporate the presence of rest of the water in the reactants and warm water is used to take off the excess alcohol by wash from the products [10]. The obtained final product is pentaerythritol ester (PE).

2.2 Preparation of Nano Lubricants

The nanoparticles of CuO was added with formulated pentaerythritol ester on wt.% (0.1%, 0.3% and 0.5%) basis using ultrasonic bath as shown in Fig 1. The anti-wear properties of the material were improved by the addition of nano additives with the pentaerythritol ester. For this purpose, an ultrasonic sonicator (Make: LMUC-2A, Model: LABMAN, Ultrasonic frequency: 40±3 kHz, Ultrasonic wattage: 50W) was used to ensure homogenous mixing and well scattering of nano particles into the formulated lubricant i.e. pentaerythritol ester [19]. The CuO nanoparticles was
supplied by Nano labs, India. 99% of mass purity, the average diameter of the nanoparticles is about 30-50 nm. The weight of the nanoparticles is measured by precision digital electronic weighing balance machine.

![Fig. 1. Ultrasonic Bath](image1.png)

The measured nanoparticles are mixed with pentaerythritol ester on wt.% basis i.e. 0.1%, 0.3%, and 0.5% (prepared samples are shown in Fig. 2.) and placed the mixture on a magnetic stirrer for 30 min. Afterwards, the mixture was set down in ultrasonic sonicator with a duration of 1 h. The prepared sample properties are shown in Table 1. PE with 0.3wt.% of CuO nanoparticle was shown improved physico-chemical properties in terms of viscosity, viscosity index, flash point, pour point and total acid number than that of other lubricants.

![Fig. 2. Nano-based compressor oil samples](image2.png)

Table 1. Properties of compressor oil samples

| Sl.No. | Properties                      | Standards      | SAE 30 | PE      | PE+0.1wt.% of CuO | PE+0.3wt.% of CuO | PE+0.5wt.% of CuO |
|--------|---------------------------------|----------------|--------|---------|-------------------|-------------------|-------------------|
| 1      | Kinematic viscosity at 100°C, cSt | ASTM D445      | 9.16   | 9.02    | 10.6              | 10.8              | 10.2              |
| 2      | Viscosity index                 | ASTM D2270     | 95     | 124     | 118               | 126               | 112               |
| 3      | Flash point, °C                  | ASTM D92       | 210    | 208     | 252               | 254               | 242               |
| 4      | Pour point, °C                   | ASTM D97       | < -10  | < -10   | -11               | -11               | -11               |
| 5      | Total acid number (TAN)          | ASTM D664-04   | 0.99   | 1.87    | 2.54              | 2.42              | 2.74              |
2.3 Tribological tests

The four ball tribometer (Make: M/S Ducom Instruments Pvt. Ltd., Bangalore; Model: TR-30L-IAS) was used to test the lubricity performance of the prepared lubricant samples i.e. SAE30, PE, PE with 0.1wt.% of CuO nanoparticle, PE with 0.3wt.% of CuO nanoparticle and PE with 0.5wt.% of CuO nanoparticle. For this test a 12.7mm diameter of ball is made with AISI E52100 chrome alloy steel and its hardness has 65 HRC. For each test, 10 ml of prepared compressor oil sample was filled in a ball pot for the evaluation of lubricity properties. The tribological properties of the lubricants are tested as per ASTM D4172. The testing conditions are as follows: sample oil temperature is 75 °C, load as 40 kg, 1200 rpm of ball rotational speed with 1 h operational time for each test setup. The wear scar spots of the tested balls are analyzed using optical microscope was shown in Fig. 3. Frictional torque was measured with a load cell and co-efficient of friction (μ) was determined using given Eq. (1) [20].

\[ \mu = \frac{T\sqrt{6}}{3wr} \]  

Where T= frictional torque in Nm, w=applied load in N and r=distance from the center of the contact point on the lower balls to the axis of rotation in m.

Fig. 3. Four-ball tribometer

3 Results and Discussions
3.1 Frictional Torque Analysis
Fig. 4. Frictional torque

Fig. 4 demonstrates the frictional torque for various compressor biobased nano lubricants. The frictional torque value of all the nano-based lubricants are closer to each other but PE and PE based nano lubricants are shows low mean frictional torque than that of petroleum-based lubricant i.e. SAE 30. Among all the lubricants PE with 0.3 wt.% of CuO nano lubricant shows minimal frictional torque than that of other biolubricant samples and with base oil, this is due to the presence of nano particles with the pentaerythritol ester. The turbo layer forms between the moving ball and stationary ball which minimize the friction, this is only due to the presence of ester groups and dissolved nano particles in the pentaerythritol ester. However, PE with 0.1 wt.% CuO nano lubricant and SAE30 mineral lubricant shows the high frictional torque [20 & 21].

3.2 Analysis of co-efficient of friction

Fig. 5 illustrates the co-efficient of friction for various lubricants. The least coefficient of friction (COF = 0.0761) was observed with the lubricant of PE with the addition of 0.3 wt.% of CuO nano particle as compared with the other lubricants. The highest COF was noted as 0.1009 and 0.09934 for SAE30 and PE with 01 wt.% CuO nano lubricant this is due to the oil layer lost between the contact area of the tested ball. Pentaerythritol ester along with nano particles has a good enough to maintain a stable film formation between the contact area [10].

3.3 Wear analysis
Fig. 6 Wear scar images of various lubricants (a) SAE30, (b) PE, (c) PE with 0.1 wt.% (d) PE with 0.3 wt.% and PE with 0.5 wt.% CuO nanoparticles

Fig. 6 and 7 shows the wear scar images and its morphology. From Fig. 6, it is noted that the wear scar diameters (WSD) are decreased drastically between 0.9662 to 0.452 with the addition of nano CuO with pentaerythritol ester. Among all the lubricants 0.3 wt.% nano CuO lubricant shows the minimal WSD is about 0.452 mm than that of other lubricants i.e. SAE30, PE, PE with 0.1 wt.% and PE with 0.3 wt.% . This is strongly believed that the oil film formed between the moving ball and stationary ball to protect from the friction and wear. This oil film was maintained till the end of experiment is only due to its high viscosity of the PE with 0.3 wt.% CuO nano lubricant. Fig. 7 illustrates the morphology of the tested wear samples under various compressor oil samples i.e. SAE30 and PE with nano lubricants. PE with 0.3 wt.% nano lubricant shows the smoother surface as compared to the other lubricants i.e. base oil, pure pentaerythritol ester and other nano based lubricants. The other tested samples are showed as rough surfaces, pits, grooves, scuffing and deep pits [19].

Fig. 7 Sem images of various lubricants (a) SAE30, (b) PE, (c) PE with 0.1 wt.% (d) PE with 0.3 wt.% and PE with 0.5 wt.% CuO nanoparticles

4 Conclusions

In this study, the tribological characteristics were carried out using four ball tribometer under various PE based nano lubricants. The following conclusions were made from the obtained results:

- The ultrasonic irradiation process is most effective and efficient method to produce high yield percentage of pentaerythritol ester than that of conventional method i.e. mechanical stirring.
- The improved physico-chemical properties (i.e. viscosity, viscosity index, flash point, pour point and total acid number) of the prepared nano-based lubricants are meets the ASTM standards.
- PE with 0.3 wt.% CuO nano lubricant shows the low frictional torque and least co-efficient of friction than other nano based lubricants and with base oil.
- Low wear scar diameter was observed with the PE with 0.3 wt.% CuO nano lubricant.
- SEM images of the tested specimens confirmed that the PE with 0.3 wt.% CuO nano lubricant specimen shows the flatter surface.

From the tribological study, it can be suggested that the CuO nano lubricant have great anti friction stability than that of other lubricants.
References

1. Mobarak, H. M., Niza Mohamad, E., Masjuki, H. H., Kalam, M. A., Al Mahmud, K. A. H., Habibullah, M., & Ashraful, A. M. (2014). The prospects of biolubricants as alternatives in automotive applications. Renewable and Sustainable Energy Reviews, 33, 34–43.

2. Reeves, C. J., Menezes, P. L., Jen, T.-C., & Lovell, M. R. (2015). The influence of fatty acids on tribological and thermal properties of natural oils as sustainable biolubricants. Tribology International, 90, 123–134.

3. McNutt, J., & He, Q. (Sophia). (2016). Development of biolubricants from vegetable oils via chemical modification. Journal of Industrial and Engineering Chemistry, 36, 1–12.

4. Heikal, E. K., Elmelawy, M. S., Khalil, S. A., & Elbasuny, N. M. (2017). Manufacturing of environment friendly biolubricants from vegetable oils. Egyptian Journal of Petroleum, 26(1), 53–59.

5. Mahamuni, N. N., & Adewuyi, Y. G. (2009). Optimization of the Synthesis of Biodiesel via Ultrasound-Enhanced Base-Catalyzed Transesterification of Soybean Oil Using a Multifrequency Ultrasonic Reactor. Energy & Fuels, 23(5), 2757–2766.

6. Encinar, J., Pardal, A., Sánchez, N., & Nogales, S. (2018). Biodiesel by Transesterification of Rapeseed Oil Using Ultrasound: A Kinetic Study of Base-Catalysed Reactions. Energies, 11(9)

7. Thanh, L. T., Okitsu, K., Sadanaga, Y., Takenaka, N., Maeda, Y., & Bandow, H. (2010). Ultrasound-assisted production of biodiesel fuel from vegetable oils in a small-scale circulation process. Bioresource Technology, 101(2), 639–645.

8. Choedkiatsakul, I., Ngaosuwan, K., & Assabumrungrat, S. (2013). Application of heterogeneous catalysts for transesterification of refined palm oil in ultrasound-assisted reactor. Fuel Processing Technology, 111, 22–28.

9. Choudhury, H. A., Malani, R. S., & Moholkar, V. S. (2013). Acid catalyzed biodiesel synthesis from Jatropha oil: Mechanistic aspects of ultrasonic intensification. Chemical Engineering Journal, 231, 262–272.

10. Arumugam, S., Chengareddy, P., & Sriram, G. (2018). Synthesis, characterisation and tribological investigation of vegetable oil-based pentaerythyl ester as biodegradable compressor oil. Industrial Crops and Products, 123, 617–628.

11. Arumugam, S., Chengareddy, P., Tamilarasan, a., and Santhanam, V. (2019). RSM and Crow Search Algorithm-Based Optimization of Ultrasonicated Transesterification Process Parameters on Synthesis of Polyol Ester-Based Biolubricant. Arabian Journal for Science and Engineering. 44, 5535–5548.

12. Baskar, S., Sriram, G., & Arumugam, S. (2016). Experimental analysis on tribological behavior of nano based bio-lubricants using four ball tribometer. Tribology in Industry, 37, 449–454.

13. Gulzar, M., Masjuki, H., Varman, M., Kalam, M., Mufti, R. A., Zulkifli, N., … Zahid, R. (2015). Improving the AW/EP ability of chemically modified palm oil by adding CuO and MoS2 nanoparticles. Tribology International, 88, 271–279.

14. Gulzar, M., Masjuki, H. H., Kalam, M. A., Varman, M., Zulkifli, N. W. M., Mufti, R. A., & Zahid, R. (2016). Tribological performance of nanoparticles as lubricating oil additives. Journal of Nanoparticle Research, 18(8).

15. Rajaganapathy, C., Vasudevan, D., & Murugapoopathi, S. (2020). Tribological and rheological properties of palm and brassica oil with inclusion of CuO and TiO2 additives. Materials Today: Proceedings. doi:10.1016/j.matpr.2020.05.032

16. Kashyap, A., & Harsha, A. (2016). Tribological studies on chemically modified rapeseed oil with CuO and CeO2 nanoparticles. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 230(12), 1562–1571.
17. Chaurasia, S. K., Sehgal, A. K., & Singh, N. K. (2020). Improved Lubrication Mechanism of Chemically Modified Mahua (Madhuca indica) Oil with Addition of Copper Oxide Nanoparticles. Journal of Bio- and Tribo-Corrosion, 6(3).
18. Singh, Y., Sharma, A., Singh, N. K., & Chen, W.-H. (2020). Development of bio-based lubricant from modified desert date oil (balanites aegyptiaca) with copper nanoparticles addition and their tribological analysis. Fuel, 259, 116259.
19. Arumugam, S., & Sriram, G. (2014). Synthesis and characterization of rapeseed oil bio-lubricant dispersed with nano copper oxide: Its effect on wear and frictional behavior of piston ring–cylinder liner combination. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 228(11), 1308–1318.
20. Aziz, N. A. M., Yunus, R., Rashid, U., & Zulkifli, N. W. M. (2016). Temperature effect on tribological properties of polyol ester-based environmentally adapted lubricant. Tribology International, 93, 43–49.
21. Zulkifli, N. W. M., Azman, S. S. N., Kalam, M. A., Masjuki, H. H., Yunus, R., & Gulzar, M. (2016). Lubricity of bio-based lubricant derived from different chemically modified fatty acid methyl ester. Tribology International, 93, 555–562