Influence of ZnO nanoparticles on thermophysical and tribological properties of polyolester oil

V P Suresh Kumar 1, K Manikanda Subramanian 2, B Stalin 3 and J Vairamuthu 4

1 Department of Mechanical Engineering, P.A. College of Engineering and Technology, Pollachi 642002, Coimbatore, Tamil Nadu, India
2 Department of Mechanical Engineering, Coimbatore Institute of Engineering and Technology, Thondamuthur, Coimbatore 641109, Tamil Nadu, India
3 Department of Mechanical Engineering, Anna University, Regional Campus Madurai, Madurai 625 019, Tamil Nadu, India
4 Department of Mechanical Engineering, Sethu Institute of Technology, Kariapatti, Virudhunagar Dist., Tamil Nadu, India

E-mail: vpsuresh4@gmail.com

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Abstract
An experimental assessment of thermo-physical, tribological, and eco-friendly properties of polyolester (POE) oil with zinc oxide (ZnO) nanoparticles for use as nanolubricant in refrigeration compressor. The ZnO nanolubricants were added in the mass fractions in the range from 0.1% to 0.5%, at the temperatures of 0 °C, 20 °C, 30 °C, 40 °C, and 60 °C. The thermophysical properties include thermal conductivity, kinematic viscosity, flash point, fire point, pour point, and cloud point with respect to various proportions. The morphology and size of ZnO nanoparticles are studied using the scanning electron microscope test. The tests findings suggest that ZnO nanoparticles greatly improved the friction characteristics of pure POE oil. The addition of the concentration decreases the pour point by 13.6%; at the same time, the flashpoint is improved by 3.5% when the POE oil is blended with ZnO. Zinc oxide nanoparticles could improve the refrigerants’ performance by extending life and avoiding friction problems. The optimum ZnO content of nanolubricants is, therefore, 0.3% for the POE/ZnO nanoparticles addition. The COF values are reduced by 6.95% at the optimum concentration over that with POE oil. The nanoparticles’ addition up to 0.3% results in less wear as they provide a defensive film between the surfaces during their motion. The mass loss value increased due to the aggregation of ZnO nanoparticles. The higher thermal conductivity is obtained for the 0.3% volume fraction of nanoparticles, and other 0.1% and 0.5% volume fractions lesser.

Nomenclature

| Symbol | Definition |
|--------|------------|
| Al_2O_3 | Aluminium oxide |
| COF | Coefficient of friction |
| D_ρ_{nf} | Density of nanofluid |
| t_2 | Final temperature of fluids (K) |
| q | Heat supplied (W) |
| t_1 | Initial temperature of fluids (K) |
| MoS_2 | Molybdenum Disulphide |
| Fe_3O_4 | nanostructured magnetite |
| POE | Polyolester oil |
| k | Thermal conductivity of the fluid (W/mK) |
| t | Time taken for the temperature rise (s) |
| ZnO | Zinc oxide |
1. Introduction

Vapour–compression refrigeration system utilised for domestic, industrial, and commercial applications is a major source of energy [1, 2]. Thermal conductivity can be enhanced by nanoparticles, as reported by Maxwell over 90 years ago [3]. Improving heat transfer is one of the most successful ways to reduce energy consumption in the industrial sector. A study is currently underway on nanofluids to determine their potential for use as heat transfer fluids. Nanofluids are the latest generation of lubricants; dispersion of nanoparticles of metals and metal oxides are diluted on a scale of 1–100 nm. It can be used in lubricating oil, hydraulic oil, etc [4–6]. In the internal combustion engine cooling system, all elements responsible for lowering the temperature can be reduced through the water pump, thermostat, radiator, hoses, and oil [7–9]. The assimilation of oil in the engine parts for lubrication will act as the cooling medium, and in the compressor, lubrication oil as the smoothness and loss of cycle efficiency. The compressors generate excessive amount of heat due to their moving parts [10]. Approximately 10% of the heat generated by the compressor is dissipated by lubricating oil [11–13].

Existing nanofluid preparation processes involve a one- or two-step process. In the first step, a nanoparticle is purchased or synthesised and then added to a fluid lubricant for nanofluid preparation. The key and expected properties of nanofluid preparation include an equitable, uniform, and continuous, minimal risk of chemical reactions, and little chance of aggregation [14]. For experiments on copper/engine oil’s thermal conductivity, the thermal conductivity of nanoliquid at volume fractions of 0.2%, 0.5%, and 1% at temperatures between 40 °C and 100 °C are investigated. The maximum increase in thermal conductivity is 49% at 1% volume fraction and at a temperature of 100 °C. Thermal conductivity at the constant air pressure, temperature, and volume fraction, and hybrid nanoliquid thermal conductivity of fluids increased by up to 45% at a temperature of 50 °C [15]. A comparative study on nanolubricants’ thermal conductivity and viscosity is conducted, and a correlation is reported to predict thermal conductivity and viscosity of nanolubricants [16].

The rate of heat conduction through nanoparticles is relatively high and, because the base fluid molecules are smaller than those made up of larger molecules, there is no risk of fouling or clogging [17, 18]. As a result, a reduction in overheating will be achieved to improve the efficiency of heat dissipation. Some studies have shown that the absorption is due to the increment in thermal conductivity. Similar to traditional oil-based fluids, nanolubricant/fluid is viscous at low concentrations but behaves like oils with a consistency comparable to traditional liquids. As the medium heats, the properties of the lubricating fluid change just like oils. By using nanolubricants, friction may be significantly reduced [19, 20]. The various nanoparticle thermophysical properties are analysed using nano-liquid insulation (NLI) [21]. The data clearly show that nanoparticle concentrations influence the temperature of NLI. They found that silver nanoparticles have remarkably increased the lubricant contact area, which improves the anti-wear properties [22, 23]. The thermal properties of the cutting fluid with the addition of TiO$_2$ nanoparticles have been investigated [24]. The findings show that applying nanoparticles in fluids improve the heat transfer efficiency.

Exploring the tribological characteristics of ZnO nanoparticles in castor oil [25], viscosity was improved with increasing concentrations of ZnO nanoparticles. The study suggests that ZnO nanoparticles improved the anti-wear properties of the base oil specimens. Tribological and rheological properties of silica nanoparticles in formulations have been reported [26, 27]. The viscosity of the lubricant increased as the particle load increased. In the long run, higher temperature will decrease the viscosity of the lubricant due to lesser particles. Nanoparticles of Al$_2$O$_3$ and ZnO were mixed with water and nano-hybrid water-based nanofluids were prepared [28]. The heat stabilities and viscosity of the synthesised nanoparticles are investigated. As the climate warms, the presence of nanoparticles is more pronounced. The synthesis of ZnO nanoparticles using a thermochemical process is investigated [29]. When ZnO nanoparticles are added, the samples’ thermal conductivity, tribological, and mechanical properties are improved [30]. It is reported that the diluted nanofluids increase thermal conductivity by adding small amounts of Molybdenum Disulphide (MoS$_2$) nanoparticles. Nanoparticles of MoS$_2$ have been studied and reported to reduce the wear of lubricating oil. The viscosity and thermal conductivity of various nanofluids were calculated [31]. It is reported that adding the powder of MoS$_2$ with the diluted nanofluids increases the thermal conductivity [32]. The tribological characteristics of pure oil with MoS$_2$ nanoparticles are investigated [33] and observed that it causes less wear of the lubricant oil. The addition of nanoparticles in the oil increased the kinematic viscosity, viscosity index (VI), and flash point. They further stated that the lowest abrasion was associated with 0.1% TiO$_2$ nanoparticles by mass. It is experimentally confirmed that the glycol-ZnO nanofluid could be used in spectral T’s splitting method [34].

According to the literature studies, polyolester (POE) lubricant oil can be replaced as a lubricating oil in the refrigeration system, abundantly available in India. To enhance the thermophysical and tribological properties of the POE oil is needed to be reported. In this work, the ZnO nanoparticles are added with POE oil to enhance the nanolubricants’ property. The effect of the addition of the ZnO particles is investigated. The ZnO nanoparticles at various concentrations, such as 0.1%, 0.3%, and 0.5% are added with the POE oil. The stability
of the nanolubricants, thermal conductivity, flash point, fire point, pour point, and cloud point are analysed for the ZnO/POE oil’s at various concentrations. The scanning electron microscope (SEM) is used to study the morphology and size of ZnO nanoparticles.

2. Materials and method

2.1. Pretreatment process
Cryogenic treatment processes for ZnO nanoparticles (DCTs) consist of three main periods of ascending time, descending time, and soaking time. The linear ramp from ambient temperature to $-196 \degree C$ at $2 \degree C \text{min}^{-1}$ (ascending time), dwelling at $-196 \degree C$ for 24h (soaking time), then returning to ambient heat gain in a closed chamber for approximately 10h at $1.2 \degree C \text{min}^{-1}$ (descending time), dwelling at ambient temperature for 5h. Finally, allow the temperature to cool back to room temperature in an open chamber. The temperature difference is very high, and the rapid cooling will reduce the particle size and shape. The base oil (POE) properties and ZnO nanolubricants are listed in tables 1 and 2.

2.2. Preparation of the nanolubricant
The properties of the base oil are shown in table 1 by MOL-LUB Ltd The nanofluid preparation process is shown in figure 1. The required amount of solid phase ZnO is weighted for nanofluid preparation at different concentrations of 0.1%, 0.3%, and 0.5% using liquid-phase refrigerant oil as a base fluid is depicted in figure 2. The magnetic stirrer is used to mix the ZnO and the refrigerant POE oil grade 68 for 1 h. Uniform dispersion of nanoparticles in the base oil is finally achieved after 3 h of ultrasonic oscillation.

2.3. Experimentation
The thermal conductivity of ZnO nanofluids is measured by the transient hot-wire method. It is most suitable for the measurement of nanofluid thermal conductivity materials. A nichrome wire of diameter 0.38 mm is utilised for the hot wire. Initially, the nichrome wire is immersed in the nanofluids, which are kept in equilibrium with the surroundings. When a constant voltage is supplied to the circuit, the electrical resistance of the nichrome wire increases the temperature of wire, and a suitable A/D converting system measures the output voltage.

2.4. Density measurement
Density is determined by the psychometric method. A 25 cm$^3$ pycnometer has a magnitude of uncertainty of 0.001 cm$^3$. The density of the nanofluid can be determined by the following equation.

\[
\text{Density (kg/m}^3) \quad 885 \\
\text{Viscosity at 100} \degree \text{C centistokes} \quad 10-12 \\
\text{Viscosity at 40} \degree \text{C centistokes} \quad 125.4 \\
\text{Viscosity index (VI)} \quad 150
\]

Table 2. Properties of nanoparticles.

| Particulars             | ZnO       |
|------------------------|-----------|
| Atomic no              | 30        |
| Relative atomic mass   | 81.408 g mol$^{-1}$ |
| Density                | 5.606 g cm$^{-3}$ |
| Melting point          | 2248 K    |
| Boiling point          | 2248 K    |
| Young’s modulus        | 203 GPa   |
| Max use temperature    | 1965 \degree C |
| Co-efficient of linear expansion | $9 \times 10^{-3}$ |
| Compressive strength   | 1854 MPa  |
| Electronegativity      | 1.7       |
| Ionic radius           | 0.064 nm  |
| Flexural strength      | 1752 MPa  |
Where \( m_t \) and \( m_{pc} \) are respectively, the total flask mass with the nanofluid and the empty pycnometer mass. Five temperatures are measured: 20°C, 30°C, 40°C, and 60°C. Temperatures are continuously measured using a thermostat. A precision thermocouple is used to measure the temperature.

### 2.5. Thermal conductivity measurement

For calculating the thermal conductivity of ZnO/POE nanofluid, a transient hot-wire system has been used. This approach is mainly used to study thermal conductivity in soil, bulk solids, and noble gases. Also, changing
the process can calculate thermal conductivity for nano fluids, acting as electrical conductors. In this case, the linear thermal source is an integrated system. The wire embedded in the nano fluid sample is used as an actuator and a thermal detector. The thermal conductivity is determined based on a linear thermal source. A well-known final formula for the calculations of nano fluid thermal conductivity is given as follows:

\[ k = \frac{q}{4\pi(Tf - Ti)} \ln \frac{t2}{t1} \]  

(2)  

Thermal POE oil and ZnO/POE nano fluid with three particle volume concentrations of 0.1%, 0.3%, and 0.5% at the temperatures of 20 °C, 30 °C, 40 °C, and 60 °C experiments are conducted. Measurements have been carried out in three phases. The temperature is stabilised in the first 30 s. During this time, the sensor is heated by a known current of 30 s. The temperature change and the cooling speed are calculated at the third stage of the 30 s. The thermistor calculates the temperature change when the microprocessor processes the data. Thermal conductivity is automatically determined equation (2). Measurements were made six times for each test fluid. In the end, the average value of the following measurements is taken. The instrument used in the study is shown in figures 3 (a), (b).

2.6. Measurements of viscosity  
Viscosity tests are conducted using the Brookfield R/S Plus programmable rheometer. The rheometer is utilised to measure POE viscosity as a base fluid and POE/ZnO nano fluid at varying particle sizes and temperatures. A double-slit measuring device (DG DIN 53453) has been installed. The measuring components consisted of a cylindrical sample holder, a nano fluid-filled ring gap, a ring-shaped spindle, and a double water jacket. The water jacket is attached to a rotating water bath that regulates the water temperature between 20 °C and 60 °C. The ring-shaped spindle has an internal and external circumference of 18.99 mm and 21.2 mm and a spindle length of 110 mm. The viscometer influences the spindle, which is embedded in the sample liquid. The measuring device makes it possible to measure viscosity between 0.0002 mPa and 190 mPa at shear values between 0.043 and 4340. The viscometer is attached to the computer control and the data processing and storage device. Dedicated Rheo 3000 software is used to analyse ZnO/POE nano fluid, which is characterised by volume concentrations at 0.1%, 0.3%, and 0.5%. Tests are conducted at temperatures 20 °C, 30 °C, 40 °C, and 60 °C. The experiment is conducted at the weight and measurements for 500 random rotational speeds per seconds over 50 s.

2.7. Tribological properties  
Tribological behaviours of ZnO nanolubricant were carried out through the computer-aided friction and wear testing machine. A pin-on-disc tribometer is utilised to analyse the tribological properties of the synthesised samples at different volumetric percentages compared to ASTM G99. This test runs most of the life-threatening machinery and the tribological behaviour of limited lubrication regimes at 25 °C with a velocity of 0.314 m/s and an applied load of 50N. The distance between the lane and the runner was 1000 m, and the pin material is EN31 [35–37]. The friction was measured by mass loss using a precision balance of 0.0001 g. Meanwhile, the values of the cohesion measure have also been recorded. The test runs are performed and recorded for each sample at different volume concentrations. The surface morphological examination was conducted for selected tested pin samples by SEM and electron dispersive X-ray (EDX) spectroscopy tests.

2.8. Experimental uncertainty  
Precision measurements are important for laboratory research on ZnO nano fluids’ thermophysical properties in maintaining the accurate interpretation of the results obtained. To provide a quantitative explanation for the
significance of experimental findings, it is necessary to examine the uncertainty. The difficulty in assessing the concentration and density of nanoparticles in the parameters is unknown. And they are evaluated directly. A simple technique is used to assess ambiguity. The average uncertainty of the sum of absolute value.

$$\frac{\Delta X}{X} = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial X}{\partial Z_i} \Delta Z_i \right)^2}$$

where $\Delta Z_i$— mean uncertainty in the partial calculation. Professional equipment has been used for viscosity and thermal conductivity tests. As a result, the uncertainty of $m$ and $k$ results directly from the measuring instrument’s precision. The values for the estimation of the parameter uncertainties of the instruments are listed in table 3.

3. Results and discussion

3.1. Nanoparticles

The morphology and size of ZnO nanoparticles are studied utilising the SEM test. Images have been shown by magnification to study the surface structures of nanoparticles. The results showed that cryo-treated nanoparticles have a mean diameter of fewer than 20 nm. The size of nanoparticles improves the quality of the lubricant. Adding spherical nanoparticles to lubricating fluids, friction reduction, and increased abrasion resistance can be achieved on different surfaces.

Figures 4 (a), (b) shows the SEM images of ZnO nanoparticles before and after the cryogenic process used in this experiment. The SEM image shows that the oil/lubricant completely swirls the nanoparticles. It has been shown that the cryo-treated nanoparticles used are more similar in volume to weight than the untreated ZnO nanoparticles used in the fluid. Solubility is a vital factor affecting the performance of nanofluid. The preparation of nanofluid solidity depends on the pH value, the accumulation, and the clogging of particles. The aggregation of nanoparticles in the fluid forms a cluster cation that reduces the fluid’s thermal conductivity—an aggregation of the formation due to Vander Waals coherent forces between the particles.

The transmission electron microscopy (TEM) image was compared based on Singh et al. [36] of the ZnO nanoparticles (figures 5(a)–(c)), found that the ZnO nanoparticles turned to agglomerate and did not allow the recognition of a single particle owing to the high surface energy of nanoparticles. Also, TEM image shows that the ZnO nanoparticles are spherical in shape and the average diameter of the nanoparticles is 15 nm (figure 5).

Figure 4. (a)–(b) SEM image of ZnO (a) before the cryogenic process and (b) after the cryogenic process.

Figure 5. (a)–(c) TEM image of ZnO (a), (b) before the cryogenic process, and (c) after the cryogenic process mixed with POE oil.
3.2. Dispersion stability study
Spectral absorbency analysis is a superior approach to the determination of nanofluid stability \[40, 41\]. UV–Visible spectroscopy showed that nanolubricants are stable. The absorbance is measured at room temperature to determine the dispersion stability of the nanolubricants. Figure 6(a) shows the absorbance results, and figure 6(b) shows the absorbance of ZnO after treatment. These nanoparticles highlight the presence of a higher population of nanoparticles interacting with nanolubricants. Therefore, 0.3 vol% cryo-treated ZnO nanoparticles-mixed POE oil is better than the other two concentrations. The samples are tested from 200 nm to 600 nm wavelength. The results in figures 6(a), (b) show the visible UV spectrum of untreated and cryo-treated ZnO nanoparticles produced at 0.1 vol%, 0.3 vol%, and 0.5 vol% concentration of soluble starch. Also, the solubility of the nanofluid will be enhanced by the cryo-treated nanoparticles. The peak absorbance value is between 350 nm and 360 nm wavelength in both untreated and cryo-treated nanofluids. Figures 6(a), (b) shows that 0.3 vol%, 1 and 0.540 are more absorbent compared to 0.1 vol% and 0.5 vol%.

3.3. Flash and fire point
Other things to take into account when choosing a lubricant are the melting point and the flash point. The flash point and fire point in this lubricant show the maximum operating temperature of the lubricant. Figure 7 graphically demonstrates the fire point, cloud point, pour point, and flash point of base oil and nanolubricant given in the study. The increase in the mass of lubricant particles increases the POE oil nanolubricant flash and fire points \[42, 43\]. As a result of these factors, the heat required to start the lubricant’s vapourisation and the temperature at which the vapourisation begins. Similar to the lowering of the cloud and the plummeting of the ZnO nanolubricant. The maximum increase in flash and fire points for POE/ZnO nanolubricantis found to be 8% and 5.8%.

3.4. Kinematic viscosity
The VI is used to measure changes in fluid viscosity at the temperature of the surrounding area. If the fluid’s viscosity is high, the fluid will become very viscous. Figure 8 shows the properties of base oil and nanolubricant kinematic viscosity. It shows a reduction in the viscosity of the fluid when exposed to temperature changes. The VI can be seen in table 4. The viscosity of each substance tends to decrease with temperature and increase with an

![Figure 6. UV–Visible spectrum of (a) untreated ZnO nanoparticle and (b) treated ZnO nanoparticle.](image)
increase in mass. On decreasing viscosity, lubricant usually lowers friction and reduces energy losses. Nanolubricants are much less viscous at high temperatures than conventional lubricants. Nano oil may be thinner because it has fewer lubricant additives than base oil so that the lubricant is not as thick as base oil. All the nanolubricant proportions’ viscosity increased slightly by 7% for the 0.5% POE/ZnO nanolubricant. The results of this research further showed that, by adding ZnO nanoparticles, the rate of reduction of kinematic viscosity would be suppressed due to high-temperature application requirements [44].

3.5. Biodegradability and toxicity
A salinity and turbidity assay can estimate the value of toxicity and biodegradability of the studied lubricants. The lubricant should have the characteristics that make it environmentally friendly. The data in tables 5 and 6...

![Figure 7. Flash, fire, cloud, and pour points of the POE oil and POE/ZnO nanolubricant.](Image)

![Figure 8. Kinematic viscosity of the POE oil and nanolubricant.](Image)

| Table 4. The viscosity index of ZnO-blended lubricant and base POE oil. |
| Sample | POE oil | 0.1% ZnO | 0.3% ZnO | 0.5% ZnO |
| VI | 150 | 152 | 155 | 158 |
give information about the biodegradability and toxicity of the materials used. Turbidity is the measurement of the bacterial growth in oil and grease. The base lubricant (POE) and ZnO nanolubricant compositions are toxic and biodegradable at fairly high concentrations. The non-toxicity is important because of one’s ability to decompose/degrade.

The tested configuration of the POE oil turbidity is 1.7 at the end of the first day. It seems 101.7 and 145.1 at the end of the second day. Similarly, the POE with 0.1% ZnO is 98.7 and 144.2 at the end of the day. The POE with 0.5% ZnO reports the lesser turbidity of the oil mixtures.

### Table 5. Biodegradability of the base oil and POE/ZnO nanolubricants.

| Configuration     | Turbidity (Ntu) 1st day | Turbidity (Ntu) 2nd day |
|-------------------|-------------------------|-------------------------|
| POE Oil           | 1.7                     | 101.7                   |
| POE + 0.1% ZnO    | 1.7                     | 98.7                    |
| POE + 0.3% ZnO    | 1.8                     | 98.3                    |
| POE + 0.5% ZnO    | 1.85                    | 98.2                    |

### Table 6. Toxicity of the base oil and POE/ZnO nanolubricants.

| Configuration     | Brine shrimps | Mortality (%) |
|-------------------|---------------|---------------|
| POE Oil           | 14            | 30            |
| POE + 0.1% ZnO    | 12            | 35            |
| POE + 0.3% ZnO    | 12            | 35            |
| POE + 0.5% ZnO    | 11            | 35            |

3.6. Thermal conductivity

The base oil’s thermal conductivity is calculated by the hot-wire method and the result is shown in figure 9 and compared with the ASHRAE standard of POE oil. The thermal conductivity of nanofluids is investigated, and the following observations are made. Figure 9(a) shows base oil’s thermal conductivity containing untreated ZnO nanoparticles with various volume fractions ranging from 0.1% to 0.5% and the input temperature ranging from 20 °C to 60 °C. It is confirmed that the fraction of the volume of nanoparticles increases the base oil’s thermal conductivity. The higher thermal conductivity is obtained for the 0.3% volume fraction of nanoparticles, and other 0.1% and 0.5% volume fractions lesser. The thermal conductivity of untreated ZnO
nanoparticles volume fraction in the base fluid property is not changed with increased concentration. This may be due to the nanoparticles in the suspension aggregate in clusters of the spherical-shaped nanostructure.

Figure 10(b) shows base oil’s thermal conductivity containing deep cryogenic ZnO nanoparticles with different volume fractions ranging from 0.1% to 0.5% and the input temperature ranging from 20 °C to 60 °C. The thermal conductivity of the volume fraction of the deep cryogenic ZnO-treated nanoparticles in the base fluid increases the thermal conductivity. The cryogenic concentration of ZnO nanoparticles treated in base oil showed higher thermal conductivity than the untreated concentration of ZnO nanoparticles. This is related to the clustering of treated ZnO nanoparticles in the base oil dispersion time which is lower than that of the untreated particles, mainly due to the Brownian motion of the particles.

The thermal conductivity of all lubricants is measured at a wide temperature range from 20 °C to 60 °C. Figures 11 (a), (b) illustrates the ZnO nanolubricant thermal conductivity at different volume fractions at different temperature values. POE–ZnO nanolubricants have the highest thermal conductivity ratio. This example describes a method for increasing thermal conductivity by 1.48% to 0.3% volume and 20 °C. An abnormal improvement in thermal conductivity of nanofluids may be due to many potential factors, such as the Brownian motion effect of nanoparticles in the base fluid. There is less heat conductivity at higher temperatures, which, in turn, lowers near-field radiation [45, 46]. The thermal conductivity of nanolubricants is higher in the fraction of volume than that of pure lubricants. ZnO particles have lower thermal conductivity than other oxides.
3.7. Tribological of nanolubricants

Figure 12 shows the coefficients of friction (COF) for both the base oil and the ZnO nanolubricant. The COF values have been recorded and arranged at 50 N. Despite a decrease in the COF of the ZnO nanolubricants, the COF of the ZnO nanoparticles increased with an increment in the concentration. Reduction in efficiency can be due to the aggregation of ZnO nanoparticles.

The optimum ZnO content of nanolubricants is, therefore, 0.3% for the POE/ZnO nanoparticles addition. The COF values are reduced by 6.95% at the optimum concentration over that with POE oil. The effect is less than purported because the oil’s viscosity made nanoparticles less likely to be expelled. To properly use nanoparticles in certain applications, you need to modify them with a surfactant or a polymer. A study of tribological features is performed using a pin-on-disc tribometer. Figure 13 shows the loss in mass increased with an increment in the concentration of ZnO particles.

Reducing pin weights at concentrations of 0.1%, 0.3%, and 0.5% decreased on average by 85.22%, 84.8%, and 83.39%, respectively. POE oil with 0.1% of ZnO nanoparticles is the lowest among the three. This may be because there are ZnO nanoparticles in the abrasive object’s free space. The ZnO nanoparticles could form large clusters that cause an increase in mass losses in the oil, thereby significantly reducing the oil. At a higher level, the loss of mass is increased by increasing concentration.

Figures 14 and 15 show the pure POE oil’s friction behaviour and the nanoparticle-added oil. Figure 15 shows the minimum COF was obtained when the concentration of 0.3 wt% ZnO is present in the cryo-treated...
nanoparticle-mixed oil. The COF was reduced by about 24.75% when compared to the pure POE oil. The friction reduction mechanism involves the nanoparticles filling gaps on the surfaces, resulting in smoother and improved lubricity. It has shown that after treatment and before treatment in figures 14 and 15 that the blend POE oil with the 0.3% ZnO has provided the lowest value of COF when compared to the conventionally used base POE oil and other blends and this may be due to the fact that as the carbon chain length increases. The optimised of the 0.3wt% is considered due to the stabilised in the COF for a long time compared to the 0.1wt% ZnO in the POE oil. With the inclusion of the nanoparticles, an increment of contact surface area resulting in reduced applied pressure, and the rolling mechanism occur instead of sliding friction. A similar cause has also been identified by Ghaednia et al. [37].

Figure 14. COF with nanoparticle before treatment.

Figure 15. COF with nanoparticle after treatment.
3.8. Analysis of worn surfaces

Figure 16 depicts the SEM images of the lubricant samples developed for the worn surface examination, and it was confirmed by nanoparticles usage in the EDX test, as shown in figure 17. The SEM image of the base oil is shown in figure 16 (a). Several surface scratches have been noticed, and the ploughing effect is responsible for the creation of these scratches. As shown in figure 16 (b), the exclusion of the ploughing effects and surface delamination leads to the formation of a smooth surface for POE oil. It was owing to the surface forming –O–cross-linking, which defends it by assisting the lubricant film. The same justification for lubricant epoxidation has been reported in the literature [47–49]. The inclusion of nanoparticles in POE oil plays an important role in forming a protective layer on the surface.

The addition of nanoparticles up to 0.3% lead in even less wear because they form a protective film between the surfaces when their motion. Figure 16(c) depicts SEM images after the inclusion of 0.3% ZnO nanoparticles. The minimal surface damage was noticed as a result of the proper filling of the asperities present on the surfaces and the providing of resistant to the applied pressure. The scars and grooves on the contact point can be filled with...
nanoparticles in the lubricant oil. The ZnO nanoparticles in the lubricant provided a rolling mechanism rather than the mending effect, reducing wear between the surfaces during the sliding motion [50, 51]. However, due to the adhesive nature of nanoparticles, an increase in nanoparticles causes more wear. Adhesive wear occurs when the material is removed due to adhesion between both two surfaces. Adhesives are classified into two types: mild adhesion and extreme adhesion. Mild adhesion happens slowly and removes surface films like oxides. At the same time, extreme adhesion removes the metal by tearing, cracking, and melting metallic junctions. Figure 16(d) depicts the effect of adhesion and abrasion on the surface as the quantity of zinc oxide nanoparticles is increased significantly. This was caused by the accumulation of nanoparticles on the surface that induces surface wear [52].

4. Conclusions

Zinc oxide nanoparticles are added to enhance the tribological and thermophysical properties of POE oil. The flash point of the samples increases as the concentration of nanoparticles increases. Optimal results are achieved at 0.3%, with a 13.6% drop in the pour point and a 3.5% increase in the ash point. At optimum concentrations of ZnO nanolubricants, the COF values decreased by 24.75%. Also, the oil mass loss due to the heat transformation reaction is reduced by 84%. The optimum ZnO content of nanolubricants is, therefore, 0.3% for the POE/ZnO nanoparticles addition. The COF values are reduced by 6.95% at the optimum concentration over that with POE oil. The nanoparticles’ addition up to 0.3% results in less wear as they provide a defensive film between the surfaces during their motion. The mass loss value increased due to the aggregation of ZnO nanoparticles. The higher thermal conductivity is obtained for the 0.3% volume fraction of nanoparticles, and other 0.1% and 0.5% volume fractions lesser. Thermal conductivity is increased by 33% for the addition of 0.3% of ZnO nano fluids in the base fluid.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID IDs

V P Suresh Kumar https://orcid.org/0000-0002-3361-7088
B Stalin https://orcid.org/0000-0001-8908-2468
J Vairamuthu https://orcid.org/0000-0002-8344-0460

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