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Nanoparticle-infused oils for improved lubrication and wear resistance in internal combustion engines: Exploring nanoscience applications in automotive parts

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Abstract. Wear from friction is a major cause of component failure in internal combustion engines, as parts frequently come into contact with each other. Engine oils are used to lubricate these parts and minimize wear. A common approach to reducing friction is to use higher-viscosity oils, which form a thicker protective film between moving components, preventing direct contact. However, while thicker oils can reduce wear, they also increase the energy required to keep the engine running, leading to higher power dissipation. In recent years, the use of nanoparticle-infused lubricants has gained attention for their ability to improve surface properties, enhance heat transfer, boost engine efficiency, and lower maintenance costs. This study explores the effects of adding nanoparticles to engine oils, focusing on their impact on the lubrication and wear resistance of gears and other automotive parts. The results revealed that oils with a higher concentration of nanoparticles significantly reduced the coefficient of friction and wear on stationary discs, confirming the superior lubricating performance of nanoparticle-infused oils. Furthermore, the pressure and anti-wear characteristics of these nano-oils were evaluated, showing marked improvements over conventional oils without nanoparticles.

Keywords: automotive nanotechnology; internal combustion engines; lubrication enhancement; nanoparticle-infused oils; wear resistance

1. Introduction

Friction represents a significant factor contributing to energy loss in mechanical systems. Inadequate lubrication of machines not only reduces efficiency but also leads to excessive wear and premature failure (Presting and König 2003). Therefore, selecting the appropriate lubricant plays a crucial role in machine performance. By forming a suitable thin layer on friction surfaces, lubricants create separation, dissipate heat, and prevent the generation of wear particles (Hatami *et al*. 2020). In recent years, nanotechnology has been employed to enhance the performance of lubricants (Golabchi *et al*. 2018, Khazaei and Mohammadimehr 2020, Arjomandi and Asl 2021, Harrat *et al*. 2021, Rajabi and Mohammadimehr 2021, Ahmad *et al*. 2022, Sonebi *et al*. 2022). The efficiency of a lubricant heavily depends on the type and quantity of additives incorporated into the base oil. Lubrication is defined as the science of facilitating relative movement between contacting surfaces (Hemmat Esfe *et al*. 2018a). Insufficient lubrication not only decreases mechanical and time efficiency but also results in excessive erosion, wear, and premature failure (Alirezaie *et al*. 2017). Various types of petroleum-based products are employed in different industries, including lubricants for automotive and machinery applications (Ettefaghi *et al*. 2013).

Tribology, derived from the Greek words “tribe” meaning wear and “logy” meaning knowledge, encompasses the study of surface interaction and motion. This branch focuses on examining friction, lubrication, and wear (Hemmat Esfe *et al*. 2019). Initially applied in ancient Greece to understand the transportation of large stones on the Earth’s surface and improve it, tribology has evolved into a comprehensive science that investigates frictional forces, erosion, and the development of new lubricants to mitigate these effects (Asadi *et al*. 2018). Research conducted over the past century has been dedicated to developing long-lasting lubricants, leading to the utilization of additives to improve their quality (Yang *et al*. 2019). The ultimate goal of this research field is to develop lubricants that do not require replacement or repair. As a result, lubricants consisting of organic and inorganic particles have been identified (Afrand *et al*. 2016).

In recent years, the integration of nanomaterials into lubricants has emerged as a promising approach due to their enhanced surface properties, improved heat transfer characteristics, increased engine efficiency, and potential cost savings in maintenance and repairs (Alsultan Abdulmajeed 2021, Dai *et al*. 2021, Alimoradlu and Zamani

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2022, Behdinan and Moradi-Dastjerdi 2022, Thakur *et al*. 2022, Zhao *et al*. 2022). Synthesizing nanoparticles and incorporating them into solid materials on a small scale poses significant challenges (Hemmat Esfe *et al*. 2016). Furthermore, the inherent instability of colloidal solutions has presented a major obstacle in implementing this technology in lubricants. Researchers have explored different types of nanomaterials composed of metallic, organic, and mineral substances to produce nano-lubricants (Hemmat Esfe *et al*. 2018b). The key advantage of utilizing nanomaterials in lubricants stems from their small size, which increases their contact surface area. Moreover, they exhibit effectiveness at ambient temperatures (Bhaumik *et al*. 2020).

Nano-additives contribute to anti-wear mechanisms in two ways: either by melting and adhering to friction surfaces or by forming a protective layer through surface reactions (Qi *et al*. 2024, Wang *et al*. 2022, Jia *et al*. 2023, Zhang *et al*. 2023a, b, c, Wang *et al*. 2024, Yan *et al*. 2024). Research in this field has shown that when the size of these materials falls below 100 nm, their structure undergoes significant changes (Yu *et al*. 2020). The resulting product is referred to as nano-lubricants. The primary components of nano-lubricants are spherical particles or nanotubes that act as miniature balls sliding between moving surfaces during operation, leading to reduced friction, temperature, and improved machine efficiency (Kamel *et al*. 2021). These particles can penetrate the tiniest pores of machine parts, enhancing lubrication capabilities (Ding and She 2021, Cuong Bui 2022, Soltanieh *et al*. 2022, Wu *et al*. 2022). Nano-lubricants exhibit superior performance on uneven surfaces compared to conventional lubricants, resulting in reduced machining needs and associated time and cost savings in manufacturing machine parts (Cai *et al*. 2013). Nano-lubricants, available in solid and liquid forms, minimize friction force, power consumption, and fuel consumption in machines. They can be used as additives in lubricants or in combination with other materials or as standalone lubricants. Another significant advantage of nano-lubricants is their improved environmental compatibility compared to conventional lubricants (Ahmad and Nadeem 2020). Numerous tests conducted by pharmacology laboratories in America and Europe have confirmed the environmentally friendly nature of these lubricants, as they are non-toxic and do not cause water, soil, or air pollution.

Nanotribology plays a crucial role in advanced technologies such as surface smoothing of computer memory disks to enhance information storage quality, reduce friction force and energy consumption, and prevent corrosion of parts (Raina and Anand 2017). In traditional industries such as automotive and aerospace, the integration of nano-lubricants offers benefits such as eliminating the need for oil changes, superior adhesion to parts in the form of single-layer films, and high tolerance to mechanical stress and operating temperatures (Rosenkranz *et al*. 2021). Nano-lubricants can even be applied to the outer surfaces of ships or airplanes to reduce friction caused by water or air. Several companies are currently engaged in research on the next generation of lubricants (Chen *et al*. 2021, Esparham *et al*. 2021, Raj *et al*. 2021, Shahram Ghaedi Faramoushjan Hossein Jalalifar 2021, Cai *et al*. 2021, Maheswaran *et al*. 2022, Shariq *et al*. 2022). One notable organization has developed a new product composed of multiple stacked film layers with hollow spaces for increased flexibility. This product employs nano-bearings made of tungsten disulfide (WS_2) and exhibits superior performance, aiming to replace all current lubricants with 6 to 10 times higher efficiency (Kalyani *et al*. 2017). WS_2-based nano-lubricants operate through sliding layers that reduce friction and flexible empty spaces, enabling the lubricant to withstand high pressures and mechanical shocks while moving as hard spherical particles between rough surfaces. Additionally, unlike conventional lubricants, these substances can penetrate the crevices and pores of uneven surfaces, forming a smooth, single-molecule layer for improved lubrication (Rauf *et al*. 2022).

Although carbon nanotubes have been utilized by some manufacturing companies to produce nano-lubricants, research efforts continue to optimize these materials, as they tend to disintegrate and decompose under frictional forces over time (Wei *et al*. 2025, Wu *et al*. 2025, Zhu *et al*. 2025). The National Institute of Standards and Technology (NIST) is currently investigating the method of creating single-layer films by mixing various molecules (Hu *et al*. 2020). The additives used in lubricants serve different purposes, including anti-friction, anti-wear, antioxidant, detergent, and dispersant functions. WS2-based greases, known for their graphite-like structure, reduce friction by stacking layers together (Radhika *et al*. 2021). The active edges of these layers cause gradual disintegration or reactions, particularly under high temperatures and pressures, leading to bonding and interaction with the metal surface (Wang *et al*. 2020). However, as these layers are relatively large, they cannot penetrate surface crevices and pores, resulting in build-up and hindered lubrication over time. Consequently, lubricants lose their properties and increase friction between metal surfaces, necessitating the use of smaller, more resilient particles (Moazami-Goudarzi and Nemati 2018). Currently, WS_2 nanoparticles are employed to enhance lubrication and reduce friction and wear. These spherical particles, which form the basis of products like Nanolub, significantly outperform regular lubricants, reducing friction, wear, and temperature, particularly under high system loads. Consequently, equipment life is extended, and maintenance and repair costs are reduced (Xu *et al*. 2018). WS_2 nanoparticle-based greases can be used in industrial machinery, equipment, and aerospace applications. These minute nanoparticles act as small bearings when placed between two surfaces, leading to a substantial reduction in friction (Xie *et al*. 2016). Numerous tests demonstrate the superior performance of these lubricants compared to other solid lubricants, especially under high loads (Charoo *et al*. 2017). Additionally, they prevent burning, sticking, and detachment of metal surfaces. Nanolub Grease can be utilized as an additive in liquid lubricants, as a standalone lubricant, as solid powders, or as thin composite coatings on metal and composite polymer surfaces (Ruiz *et al*. 2019). Greases containing WS2 nanoparticles exhibit excellent performance on rough surfaces, eliminating the need for extensive surface polishing and smoothing, thereby reducing costs and precision requirements (Naddaf and Zeinali Heris 2018). Over time, contact surfaces polish automatically as the lubricant fills the surface pores, gradually releasing and providing lubrication. Consequently, surfaces with high roughness become self-lubricating, mitigating he need for extensive surface preparation (Yan *et al*. 2023). When utilizing Nano or Lubricant, the coefficient of friction remains relatively stable even under high loads, in contrast to conventional greases where the coefficient of friction increases significantly over time (Deepthi *et al*. 2010). Currently, WS_2 nanoparticles are used in four forms: as oil additives, lubricant additives, incorporation into polymer composite layers, and as coatings for metal composites (Spalvins 1984).

While this study offers valuable insights into the benefits of using WS2 and ZnO nanoparticles in 40W10SN engine oil for enhanced lubrication and wear resistance, it is not without limitations. One of the primary shortcomings is the focus on a specific oil and nanoparticle combination, which limits the broader applicability of the findings (Zhang *et al*. 2017, Han *et al*. 2020, Zhang *et al*. 2020). The study does not explore the effects of different types of engine oils or nanoparticle mixtures, leaving the potential synergistic benefits of other combinations unaddressed. Furthermore, the research is conducted under controlled conditions, and real-world scenarios with varying temperatures, pressures, and load conditions may produce different results. These factors could impact the long-term stability and effectiveness of nanoparticle-infused lubricants in diverse engine environments (Cheng *et al*. 2023, Fu *et al*. 2023, Jin *et al*. 2023, Lau and Li 2023, Li *et al*. 2023, Wang *et al*. 2023b, Zhang and Huang 2023).

Despite these limitations, this research bridges the gap between traditional lubricants and emerging nanotechnology applications, offering a promising avenue for improving engine performance (Cai *et al*. 2024, Wei *et al*. 2024, Yue *et al*. 2024). The novelty of the work lies in its specific investigation of WS2 and ZnO nanoparticles in automotive engine oil, an area that has seen limited exploration. By conducting rigorous standard oil tests, the study highlights how these nanoparticles can reduce friction and wear more effectively than conventional additives. The findings lay the groundwork for future studies to further examine the potential of nanoparticle-infused lubricants, particularly in exploring how various combinations and real-world conditions could influence performance. This research contributes to the evolving field of automotive lubrication, opening new possibilities for enhancing engine efficiency and extending the lifespan of critical components.

2. Experimental section

2.1 Materials and devices

In order to make a nano-lubricant, there is a need for lubricating oil as a base fluid, as well as the desired nanoparticles to be added to the lubricating oil. API:SN and SAE:40W10 lubricating oil, which is the highest quality level in the world for gasoline engines, is used in this research. Polyalphaolefin (PAO_4) and Group III base oils are used to prepare this lubricating oil.In order to check the stability of nanoparticles, visible-ultraviolet spectrometer model Conc 100 Cary and photodynamic scattering device manufactured by Malvern Instruments Ltd company were used to determine the size distribution of nanoparticles. Tescan Mira model scanning tunneling microscope was used for the morphology of nanoparticles. Nanoparticles were homogenized with an ultrasonic device. The four-shot test was performed with Stanhop-Seta’s device and according to ASTM D 2783 standard method. Also, Falex test has been investigated with FalexPin & Vee Block Test Machine and according to ASTM D 3233 standard method (Han *et al*. 2024, Qiu *et al*. 2024, Sun *et al*. 2024).

2.2 Method

In this research, in order to investigate the tribological performance of nanoparticles WS_2 and ZnO in improving anti-wear properties and reducing friction in multi-grade motor oil compared to normal motor oil, a sample of normal multi-grade motor oil was prepared according to the relevant structure. Then it was stirred at a temperature of 60°C using a magnetic stirrer for a maximum of 90 minutes for complete uniformity. This fluid was also used as the base fluid for the absorption test. In the following, a mixture of ordinary multi-grade engine oil with nanoparticles with weight ratios of 5, 10, and 15 has been used. The obtained mixture was stirred for one hour at 50°C with a magnetic stirrer. Then, to reach a mixture that forms a stable nanofluid, an ultrasonic homogenizer was used for twenty minutes. Since the temperature of the mixture increases as a result of ultrasonic waves. By interrupting the application of the wave, excessive heating of the mixture (up to 70°C) and possible destruction of the nanoparticles were prevented. Then, the absorbance value and wavelength were measured with a visible-ultraviolet spectrometer at different time intervals. After ensuring the stability of the nanofluid, the desired samples with different concentrations of iron nano-oxide were subjected to abrasion tests (Chen *et al*. 2024, Liu *et al*. 2024, Mei *et al*. 2024).

3. Results and discussion

3.1 Visible-ultraviolet spectroscopy

By taking the absorption spectrum of nanoparticles, the optical properties of nanoparticles can be investigated. Particles in the nanometer range have a specific absorption peak. Unlike bulk materials, nanoparticles have unique optical properties. Factors such as the size and dielectric constant of the medium strongly affect the displacement of the absorption peak of nanoparticles (Rong *et al*. 2022, Dong *et al*. 2023, Wang *et al*. 2023a). Over time, the particles tend to stick together, and the size of the particles becomes larger. In order to ensure the stability of the nanofluid, the amount of absorption and the wavelength of nanoparticles in different concentrations from the base fluid (regular 40W10 multi-grade racing oil) are measured at different times with a visible-ultraviolet spectrometer. At

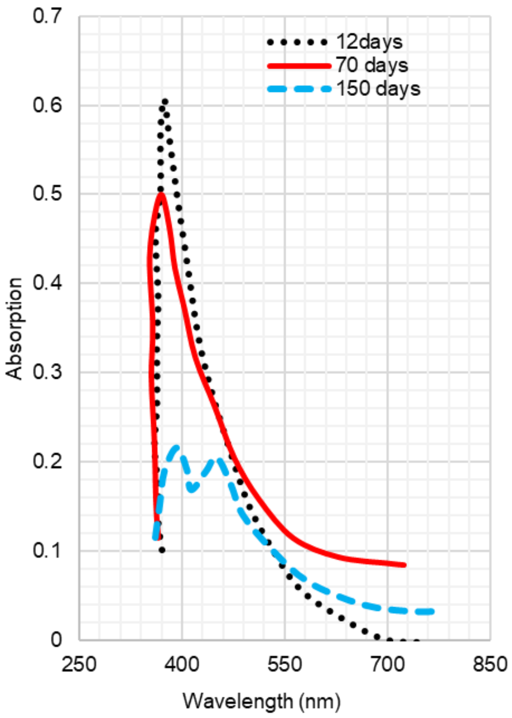

Fig. 1 Absorption spectrum of nanoparticles at a concentration of 10 at different times

different time intervals, the absorption spectrum is taken. It is compared with the primary absorption spectrum. If the position of the peaks tends towards longer wavelengths, this means that the particles have become larger and the so-called particles are stuck together, and if the optical absorption peak is in the same place as before and its position does not change compared to the initial value, this means that It means that the size of the particles has not changed over time and the nanoparticles are stable. In Fig. 1, the value of the wavelength of nanoparticles at zero times (moment of preparation of nanofluid), 12, 70, and 150 days after sample preparation is shown in concentration 10. With the passage of time, the amount of absorption and the wavelength of nanoparticles remained unchanged in this concentration, which shows that the size of the particles has not changed with the passage of time, and the nanoparticles are stable in the form of a single nanoparticle (Pourpasha *et al*. 2020).

3.2 Zeta potential

One of the things that can be measured using a dynamic light scattering device is zeta potential. If all the particles inside the suspension have a negative or positive charge, the particles tend to repel each other and do not show a tendency to accumulate, leading to good suspension stability. The tendency of charged particles to repel each other has a direct relationship with zeta potential. In general, the limit of suspension stability and instability can be determined in terms of zeta potential. Particles whose zeta potential is greater than 30 mV or less than -30 mV are stable, and at the isoelectric point where the zeta potential is zero, the colloidal system is the least stable. In fact, the zeta potential is a factor for the potential stability of the colloidal system. According to the objectives of this research, to ensure the stability of the nanofluid, the value of the zeta potential was measured at a concentration of 5% by weight of the nanofluid, which was equal to 138 mv. The obtained result indicates the absence of clumping of particles and the stability of the suspension (Habibi *et al*. 2024).

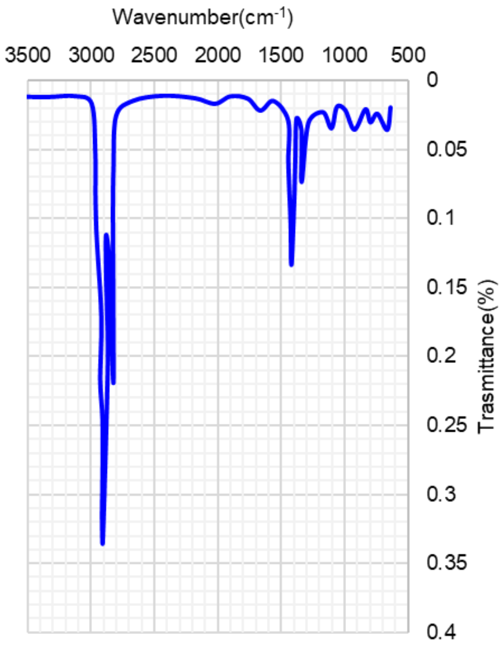

Fig. 2 FTIR of an oil sample containing nanoparticles

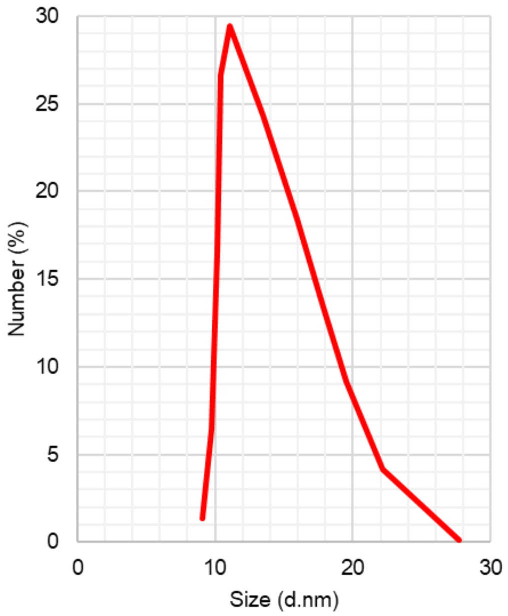

Fig. 3 Size distribution of nanoparticles in engine oil

3.3 Identifying and measuring the diameter of nanoparticles

In order to identify nanoparticles from the oil sample containing nanoparticles, the FTIR spectrum was taken which can be seen in Fig. 2. In this spectrum, the peaks in

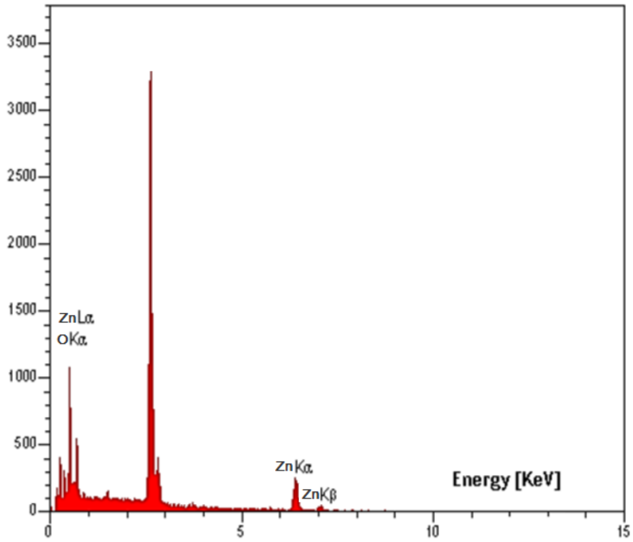

Fig. 4 Energy dispersive spectrum (EDS) of nano zinc oxide sample

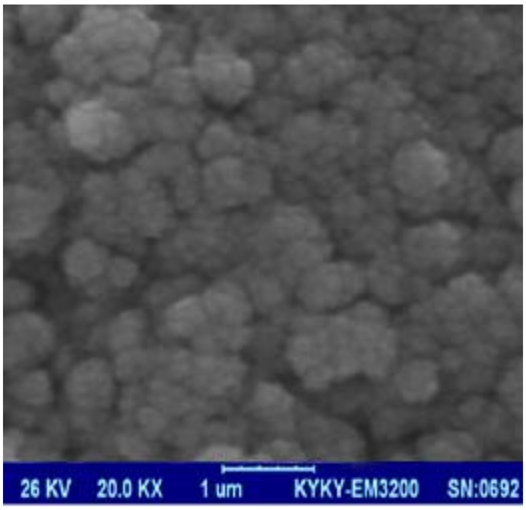

Fig. 5 SEM image of 10% nanoparticle

the region of 2921cm^{-1} and 2855cm^{-1} are related to the asymmetric and symmetric stretching vibrations of CH$_2$, and the peaks in the region of 1158cm^{-1} to 1460cm^{-1} are related to the bending vibrations of alkyl groups. The peak corresponding to the region of 670cm^{-1} is related to the stretching vibrations of Z-O in the presence of multi-grade engine oil.

A dynamic light scattering device was used to determine the distribution of nanoparticles in engine oil. The particle size distribution of the oil sample containing 5% nanomaterial was investigated. This distribution of particles is shown in Fig. 3.

Fig. 4 is related to the dispersive energy spectrum (EDS) of the zinc nanoparticles sample, where the peaks related to zinc oxide nanoparticles can be seen.

Scanning electron microscopy (SEM) images of nanoparticles with a concentration of 10% by weight are shown in Fig. 5. The morphology of the prepared compound indicates that the nanoparticles are well embedded in the matrix, and finally, it will create a homogeneous morphology of the compounds coated on the surface of the nanoparticles through various interactions.

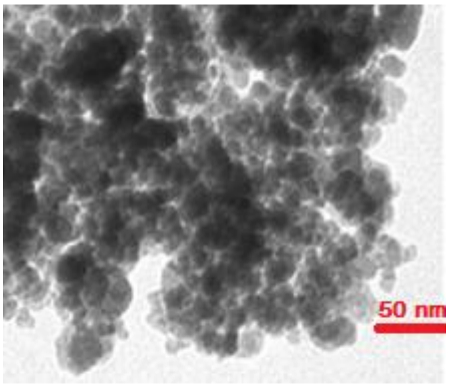

Fig. 6 TEM images of 10% nanoparticles by weight

Transmission electron microscope (TEM), as a useful and useful tool, shows the dimensions of nanoparticles and the uniformity of dispersion of nanoparticles in oil. It is natural that uniform dispersion of nanoparticles in oil is the best result that can be achieved. TEM images of 10% nanoparticles are shown in Fig. 6. As can be seen, the nanoparticles are well dispersed in the oil. This picture indicates that there is a strong interaction between the oil and nanoparticles, which is due to the proper interaction between the functional groups on the surface of the oil.

3.4 Viscosity test at 100 °C

Viscosity measurement is done with a special standard device that consists of a capillary tube with an orifice. The working method is that the time for a certain volume of oil to pass between two marks under the influence of the earth's gravity is measured in seconds. Then this time is multiplied by the constant number of the viscometer, and the kinematic viscosity is obtained in terms of CentiStock at a certain temperature. The longer the oil draining time is, the higher its viscosity is. The shorter this time is, the lower the viscosity. Viscosity change with temperature is measured and expressed by the viscosity index. If the temperature decreases, the viscosity increases, and if the temperature increases, the viscosity decreases. The viscosity index is a numerical value to show the change in viscosity of an oil with temperature change. The larger the viscosity index is, the means viscosity of the oil changes with temperature. ASTM D2270 standard method is used to measure the viscosity index. Viscosity test results for oil without nanoparticles and oils with nanoparticles in different mass ratios are shown in Fig. 7. The results show that by adding nanoparticles in a mass ratio of 5%, the viscosity at 100 °C has decreased, that is, the performance of the oil has improved, but it increases in a mass ratio of 10% and almost no significant change occurs in a mass ratio of 15%.

3.5 Flash point

The flash point is the lowest temperature at which the oil must be heated in order to generate enough steam or gas

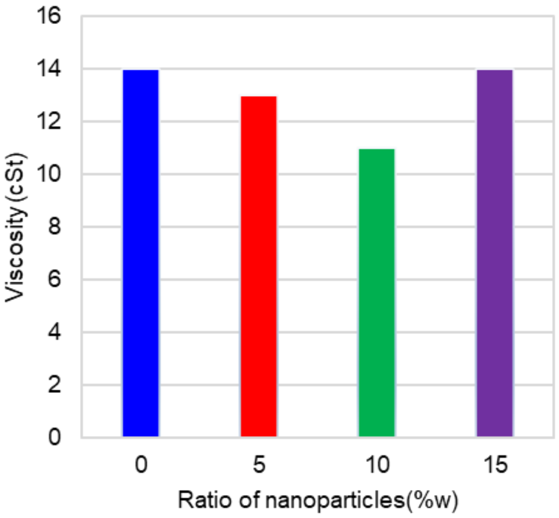

Fig. 7 Effect of adding nanoparticles in different mass ratios on oil viscosity

to form a flammable mixture with air under certain conditions, and if a small flame or torch is brought near it, the liquid surface will catch fire for a moment. This test is performed based on the ASTM D92 standard. Flash point test results for oil without nanoparticles and oils with nanoparticles in different mass ratios have been reported. The comparison of data shows that with the addition of WS_2 nanoparticles, there is no effect on the flash point of the oil, but with the addition of ZnO nanoparticles, the flash point has increased, which is due to the increase in the thermal conductivity of the oil due to the addition of nanoparticles.

3.6 Drop point

The pour point of an oil is the lowest temperature at which the oil can flow under predetermined standard conditions. The ASTM D97 standard method is used to measure the pour point. This test for the oil with ZnO nanoparticles in a mass ratio of 5% has shown a decrease in the pour point temperature compared to the oil without nanoparticles, which has caused the oil to lubricate at the moment of starting, but in No change has been seen in the case of WS_2 nanoparticles.

3.7 Evaluation of tribological characteristics of nanoparticles

The tribological behavior of nanoparticles in different concentrations was evaluated with multi-grade ordinary oil by four-ball and Falk's test. In the four-ball test, three balls are placed at the bottom and kept tightly together in a chamber, and the other ball rotates on one axis on these three balls. The pellets are tested in the oil. This test is used to measure the ability of gear oil and other lubricants to prevent the wear of parts. The test was performed at a certain speed, temperature, and load. After the end of the test, the average diameter of the wear effect on the top three fixed balls rotates on the bottom three fixed balls at a speed of 1770 ± 60 rpm (but the temperature of the test is not controlled). The time of each test is ten seconds. If the balls do not fuse together in this period of time, the amount of load increases, and this procedure continues until the rotating ball is welded to three fixed balls. In practice, with the increase of load (pressure), the oil is pulled away from between the metal parts, and as a result, two metal parts come into contact with each other. This problem is combined with temporary welding and successive separation of oil and causes severe erosion of parts. In the end, the result of this test is reported as the welding point (the amount of load that caused the balls to weld) and the wear index. The wear load index is equal to the average loads used for ten tests before reaching the point of welding four balls together. This index shows the lubricant's ability to minimize wear under the applied load and is the only factor that shows the compressibility behavior of the lubricant before the welding point. The higher this value, the better the compressibility properties of the system.

4. Conclusions

The investigation of adding metal nanoparticles to lubricating oils has demonstrated its potential to enhance the quality and characteristics of these oils. Through the systematic experimentation with different nanoparticles and varying mass ratios, significant progress has been made towards achieving the desired oil quality. Based on the findings of this study, it has been observed that the incorporation of WS_2 and ZnO nanoparticles into the lubricating oil effectively improves its wear properties. Comparatively, the nanoparticles exhibit a 10% superior performance. Moreover, while the addition of nanoparticles did not exhibit a pronounced impact on reducing wear in the lubricating oil, it did demonstrate a favorable enhancement in the oil's thermal conductivity. These outcomes underscore the potential of metal nanoparticles as promising additives for enhancing the performance of lubricating oils. Further research and exploration in this area are warranted to fully comprehend the mechanisms and optimize the utilization of nanoparticles in lubrication applications.

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