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Effect of SiO_2 Nanoparticle Dispersion on The Stability and Thermal Conductivity of Polyvinyl Ether-Based Nanolubricant

Safril[1]✉, Edwin Sahrial Solih[2], Ridho Hans Gurning[3], Adinda Rahmah Shalihah[4], Abdul Wahid Arohman[5]

[1, 2, 3, 4, 5] Department of Automotive Engineering Technology, Politeknik STMI Jakarta, Indonesia

✉ **Corresponding Author :** Safril (e-mail: safril@kemenperin.go.id)

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ABSTRACT

Heat transfer efficiency in lubrication systems can be achieved by utilising nanolubricants by dispersing nanoparticle additives into pure lubricants to increase nanolubricant stability and thermal conductivity. This study aims to investigate the effect of silicon dioxide (SiO_2) nanoparticle dispersion in polyvinyl ether (PVE)-based lubricants on the stability and thermal conductivity characteristics of nanolubricants. SiO_2/PVE nanolubricant was prepared using a two-step method with a volume concentration of 0.007%. Stability evaluation was carried out through UV–Vis spectrophotometry testing over a period of 30 days. Thermal conductivity was measured using KD2-Pro at a temperature range of 30 ℃ to 80 ℃. The results of the study showed that SiO_2/PVE was declared stable after 144 hours with an absorbance of 80%. Thermal conductivity characteristics decreased with increasing temperature, and the nanolubricant increased compared to PVE lubricants. The maximum increase in thermal conductivity was 2.72% compared to the pure lubricant, and at a test temperature of 30 °C, SiO_2/PVE was compared to SiO_2/corn oil, SiO_2/paraffin oil, SiO_2/sunflower SiO_2/oil, and SiO_2/soybean oil; the results showed an increase in thermal conductivity of 66.69%, 80.63%, 67.70%, and 46.45%, respectively. The thermal conductivity behaviour tends to increase when SiO_2 nanoparticles are dispersed into the pure lubricant, compared to the pure PVE lubricant and previous studies. These findings indicate that SiO_2/PVE nanolubricant produces a significant increase in thermal conductivity, resulting in accelerated heat transfer, reduced friction and wear, and ultimately leading to increased energy efficiency and improved overall system performance.

INTRODUCTION

Improving compressor performance is one way to upgrade new technology to increase business competitiveness (Ahmed & Ahamed, 2022). The lubrication system is the most crucial component for enhancing compressor performance in mechanical systems (Kumar et al., 2018; Yilmaz, 2020). Friction between rubbing components will be reduced with an effective lubrication system (Jason et al., 2020). Therefore, the right technique is needed to improve lubricant performance. Researchers have discovered a technique to enhance the performance of the lubrication system, one of which involves dispersing nanoparticles into pure lubricants, known as nanolubricants. The two-step method is a familiar method among researchers and is effective in making nanolubricants. As proof, nanolubricants made using this method can increase stability by

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up to >70% according to Sharif et al. (2017), and they revealed that SiO_2/PAG nanolubricant does not agglomerate immediately and maintains its stability for more than 30 days. In addition, TiO_2 nanoparticles added to canola and PVE lubricants, both nanolubricants, showed significant stability (Dhanola & Garg, 2020; MF Ismail et al., 2022). According to the latest study by Zawawi et al. (2023), the dispersion of SiO_2/POE (Polyol ester) nanoparticles produces good stability for up to 30 days. This shows that the SiO_2 nanoparticles have strong particle bonds to the pure lubricant. Due to the literature is limited about the dispersion of SiO_2 into PVE lubricants, this research has novelty from the nanolubricant side. In addition, the results of SiO_2 nanoparticles dispersed into various pure lubricants are very satisfactory, thus providing the opportunity that SiO_2/PVE may produce the same potential.

The thermophysical characteristics of lubrication systems are significantly improved by dispersing nanoparticles into pure lubricants (Kedzierski et al., 2017; Sezer et al., 2019). For example, the thermal conductivity of POE and MO (mineral oil) based nanolubricants has also been studied by Joshi et al. (2022). According to them, Al_2O_3 nanoparticles dispersed into MO and POE lubricants experienced a significant increase in thermal conductivity by 57% and 55%, respectively. In addition, TiO_2/PVE nanolubricant showed similar performance, where thermal conductivity increased with increasing temperature and viscosity increased by 1.5% compared to pure lubricant (MF Ismail, WH Azmi, R Mamat, & A. H. Hamisa, 2022). This evaluation showed that nanoparticles dispersed into pure lubricants showed different directions of improvement, not only in stability, however also in thermal conductivity characteristics, while having a positive impact on the lubrication system. Nanoparticles in this case, showed their presence in increasing thermal conductivity. Therefore, the study of nanolubricants is becoming increasingly interesting. For example, Taha-Tijerina et al. (2019) conducted a study on the dispersion of SiO_2 nanoparticles into soybean, paraffin, sunflower, and corn lubricants. The results showed that all lubricants experienced increased thermal conductivity compared to the pure lubricant. This indicates that SiO_2 nanoparticles dispersed into pure lubricants have a positive impact. Due to the nanoparticles having the potential to be developed, this study attempted to disperse them into PVE lubricants. This can lead to an increase or even a decrease, depending on the method and type of pure lubricant used.

The contribution of SiO_2 nanoparticles to thermal stability and conductivity is clear. However, studies on SiO_2/PVE nanolubricants in the literature are limited, primarily to the evaluation of thermal stability and conductivity. Therefore, this study aims to investigate stability and thermal conductivity, as both are important components of lubricant and thermophysical properties. A two-step method was used to prepare the nanolubricants at a volume concentration of 0.007%. Stability evaluation was conducted over 30^{th} days using a UV-Vis spectrophotometer, and thermal conductivity was then measured using a KD2 pro apparatus over a temperature range of 30°C to 80°C. The thermal conductivity investigation for pure PVE lubricant was compared with that of SiO_2/PVE nanolubricant to identify the difference in enhancement. The thermal conductivity was then compared with previous studies in terms of enhancement and effective thermal conductivity.

RESEARCH METHODS

SiO_2 nanoparticles and PVE lubricant were used in this study; the specifications of both are shown in **Table 1**. SiO_2 nanoparticles were obtained from DKNANO, a company based in Beijing, China, which focuses on the advancement of science and technology. SiO_2 nanoparticles have a size of 30 nm with a density of 2220 kg/m^3. The properties of PVE lubricant have a density, g/cm^3 @15 ℃, of 0.94 and a dynamic viscosity, mPa @40 ℃, of 62.58. The preparation of SiO_2/PVE hybrid nanolubricant followed the same two-step procedure as previous studies (MF Ismail, WH Azmi, R Mamat, & R.Ab Rahim, 2022; Safril et al., 2023; Zawawi et al., 2017). Equation 1 was identified as the answer to calculate the volume concentration of nanoparticles.

$$\phi = \left(\frac{m\rho}{\rho p}\right) / \left(\frac{m\rho}{\rho p} + \frac{ml}{\rho l}\right) x100 \qquad 0.1$$

The volume concentration is denoted by ϕ, the mass of PVE and nanoparticle lubricant are denoted by $m\rho$ and ml, and their densities are denoted by ρp and ρl. The first step in the process of making SiO_2/PVE nanolubricant involves combining nanoparticles with 60 ml of pure PVE lubricant, and a nanoscale balance is used in determining the volume concentration of nanoparticles. A magnetic stirrer type HS0707V2 is used for mixing for half an hour. The nanolubricant is then placed into an ultrasonic water bath for a homogenization procedure to distribute the nanoparticles into smaller aggregation sizes. During this process, the ultrasonic pulses generated in the homogenization process have a frequency of 75 ± 3 kHz. The homogenization process is used to ensure that the nanoparticles are dissolved in PVE. It also improves the measurement properties, reduces the size of nanoparticle aggregations, and increases stability (Zawawi et al., 2018). To prevent agglomeration, homogenization works by distributing frequency vibrations through the liquid medium in the immersion area.

Tabel 1. Properties of SiO_2 and PVE lubricant

Properties	SiO_2	PVE
Density, [kg/m^3]	2220	-
Molecular mass, [g/mol]	60.08	-
Average particle diameter, [nm]	30	-
Dynamic Viscosity, mPa @40 ℃	-	62.58
Density, g/cm^3 @15 ℃		0.94
Flash point, ℃		>180

Stability of SiO_2/PVE nanolubricant

The SiO_2/PVE nanolubricant sample with a volume concentration of 0.007% was selected based on a similar study. M. F. Ismail et al. (2022) have investigated SiO_2 and TiO_2 dispersed into PVE lubricant at a volume concentration of 0.001% to 0.010% which showed that the stability, thermal conductivity, and friction coefficient for SiO_2/PVE increased by 15% at a volume concentration of 0.003%. This indicates that the trend for SiO_2/PVE with a volume concentration lower than 0.01% shows satisfactory results. Therefore, this study determined a volume concentration of 0.007% for the observation of the stability and the investigation of thermal conductivity nanolubricant. The difference between the previous study is the observation of the zeta potential to evaluate the stability of the nanolubricant, unlike the current study of nanolubricant stability, which uses a UV-Vis spectrophotometer. In addition, the previous thermal conductivity observation used a TCi thermal conductivity analyzer by C-Therm, while the current study uses a KD2 pro. The methods used for each observation differ, allowing for varying trend results.

In the initial stage, the observation began by measuring the test sample to determine the wavelength, an then the SiO_2/PVE nanolubricant samples were observed again for absorbance values on the UV-Vis spectrophotometer equipment over a time span of 0 hours to 720 hours or for 30 days. Observation of nanolubricant aggregation affects stability, which triggers agglomeration in the sample. The inherent tendency of nanoparticles to clump as a result of van der Waals forces or the impact of gravitational forces in the tube is the source of agglomeration (Azman & Samion, 2019; Devendiran & Amirtham, 2016; Ramadhan et al., 2019). Therefore, the aim of researchers who try to solve this problem by including surfactants (Azmi et al., 2013; Koshy et al., 2015), is to increase the stability of the nanolubricant by changing the surface of nanoparticles (Fontes et al., 2015; Lou et al., 2015). However, in this study, there was no additional surfactant or other addictive element binder besides SiO_2 nanoparticles.

Thermal Conductivity Characteristics

At this stage, the thermal conductivity of nanolubricants was tested using the KD2-Pro equipment. The test sample was placed into a water bath with a temperature setting of 30 °C to 80 °C, while the KD2-Pro equipment collected measurement data during the observation process. The KD2-Pro working system complies with ASTM D5334 and IEEE 442-1981 regulations for

equipment and uses a heat source on the transient path to measure the thermal value or characteristics of nanolubricants (Ismail & Azmi, 2023). The sensor is used by this equipment to collect data, which is then displayed digitally on the KD2-Pro screen. The sensor of this instrument can measure fluid conductivity between 0.002 and 2.00 W/Mk (Zawawi et al., 2018). While the calibration of this instrument is around 0.35%, the average value of glycerin that can record data is 0.286 W/Mk at 25 °C.

RESULTS AND DISCUSSION

Based on UV-Vis spectrophotometer measurements, the stability of nanolubricants was assessed using absorbance measurements with a wavelength accuracy of ±0.8 nm and a range of 190-1100 nm. The wavelength evaluation of SiO_2/PVE nanolubricants, which showed a wavelength of 282 nm, is shown in **Figure 1**. The wavelength was measured based on the wave peak; although the wavelength was dominated by 0.004 nm, the wave peak was determined to be at 292 nm. The stability of the SiO_2/PVE nanolubricant showed a significant increase after preparation (zero hours) and up to 24 hours, however gradually decreased before increasing again at 120 hours. The nanolubricant sample began to stabilise after passing through the fluctuating phase at 144 hours, with an average absorbance of 80%. This stability is influenced by several factors, including the method, volume concentration, and appropriate homogenization time. Therefore, the nanoparticles did not experience agglomeration due to gravitational forces (Safril et al., 2025). These results indicate that the SiO_2/PVE nanolubricant sample has the right balance of concentration, volume and homogenization time, resulting in the stability of the nanolubricant being maintained until day, 30 is shown in **Figure 1**. Meanwhile, the effect of stability on the tendency of good thermal conductivity is discussed in the next session.

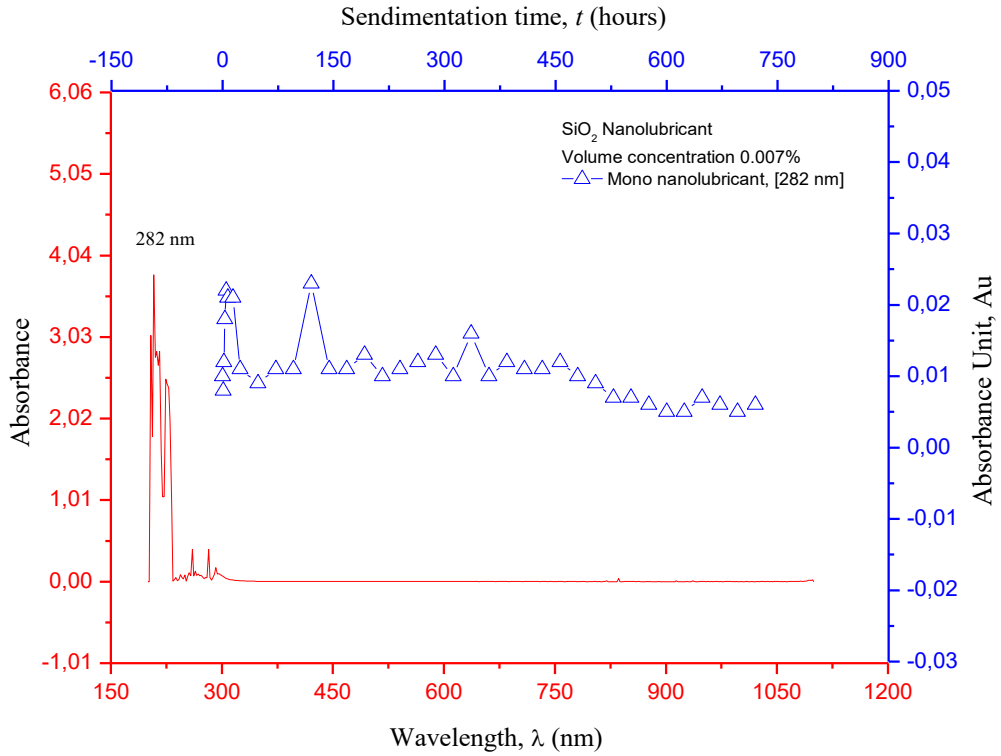

Figure 1. Wavelength and absorbance nanolubricant SiO_2/PVE evaluation using UV-Vis Spectrophotometer

Thermal Conductivity of SiO_2 Evaluation

The thermal conductivity of SiO_2/PVE nanolubricant is shown in **Figure 2.** The impact of nanolubricant on temperature variations is part of the assessment observed over a test temperature range of 30°C to 80°C. The thermal conductivity test results between pure PVE and SiO_2/PVE

nanolubricant showed an average absolute deviation of 0,22%. The nanolubricant trend was predominantly better than the pure PVE lubricant. The thermal conductivity behaviour for all samples decreased with increasing temperature. This is because each nanolubricant sample has a nonlinear pattern, and another factor is the resistance of the nanoparticle structure to heat (MF Ismail, WH Azmi, R Mamat, & R.Ab Rahim, 2022). Therefore, the nanoparticles within the lubricant aggregate due to increased thermal energy, resulting in a gradual decrease in thermal conductivity with increasing temperature (Redhwan et al., 2017; Stacy et al., 2014).

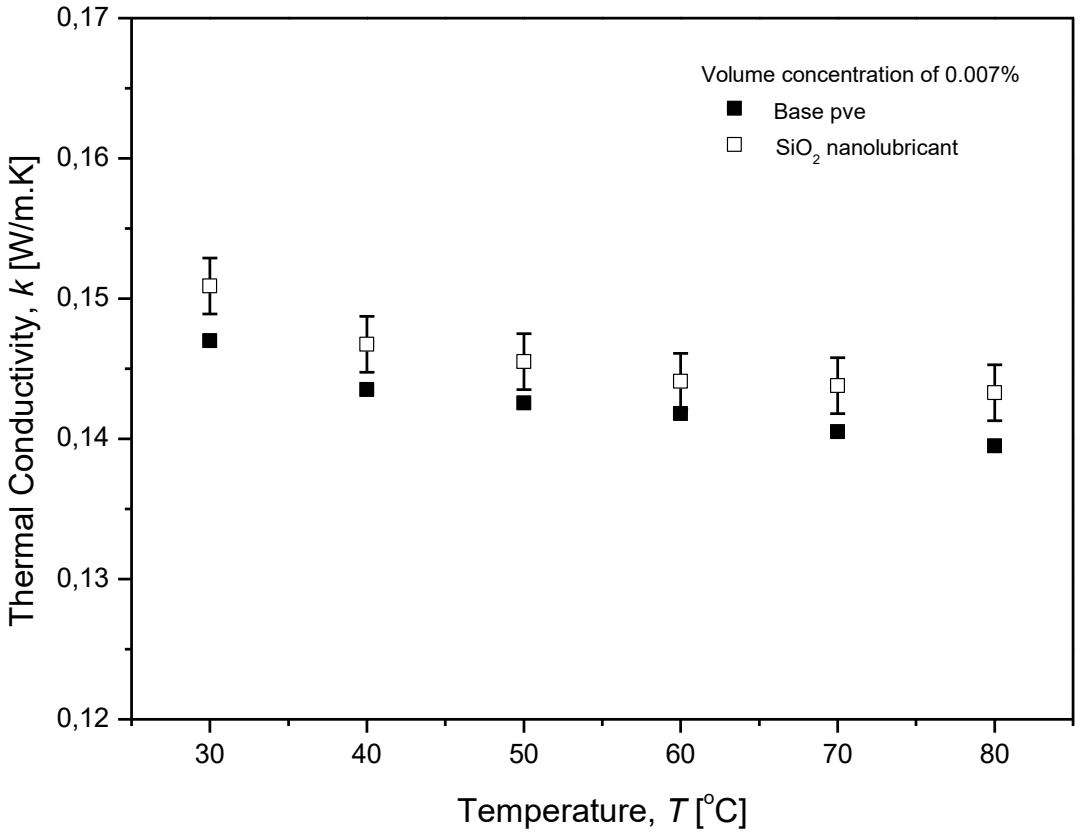

Figure 2. Thermal conductivity evaluation with a range temperature of 30°C to 80°C

The increase in thermal conductivity compared to PVE is shown in **Figure 3**. Where the trend of increasing thermal conductivity occurs in all nanolubricant samples. Observations at low and high temperatures produce an average increase of 2.28%. Meanwhile, the maximum increase in nanolubricant thermal conductivity is 2.72% at 80 °C. The behaviour of thermal conductivity decreases as the temperature is increased, as a result of this tendency to particle separation at higher temperatures, thereby reducing particle collisions along the particle path (Al-Janabi et al., 2021; Zawawi et al., 2017). Nevertheless, SiO_2/PVE nanolubricant samples at higher temperatures are able to maintain the nanoparticle structure in the lubricant and then that the resistance of the nanolubricant surface can be maintained. This is in line with the stability of nanolubricant in observations using a UV-Vis spectrophotometer, which tends to be stable. This correlation may have implications for thermal conductivity because the nanolubricant is able to maintain the effectiveness of Brownian motion (Murshed, 2011).

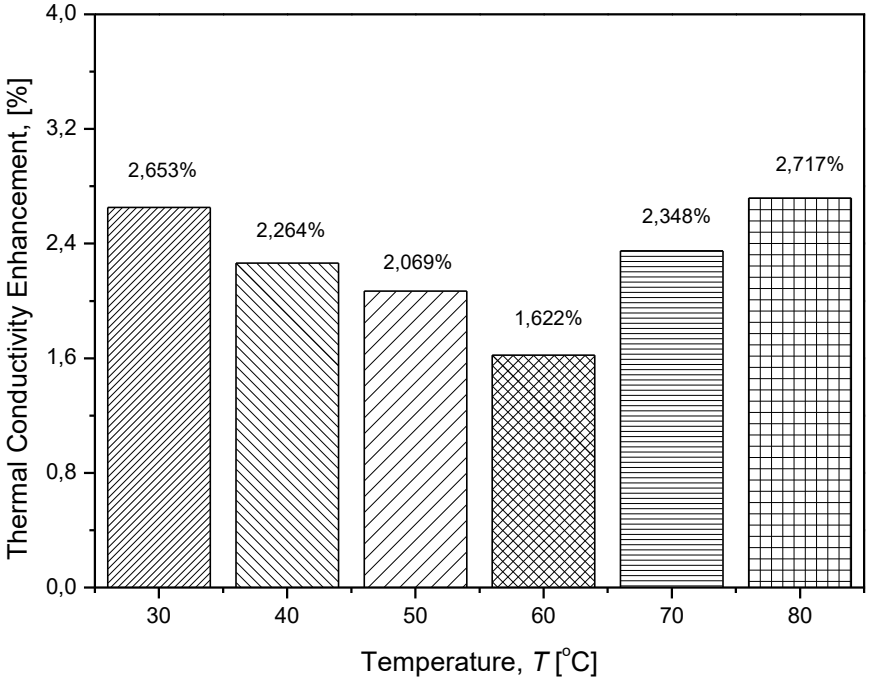

Figure 3. Thermal conductivity enhancement at the temperature variations

The impact of SiO_2 on thermal conductivity

The effect of SiO_2 nanoparticles dispersed into pure lubricants compared to previous studies is shown in **Figure 4**. The current study is compared with previous studies conducted with temperature variations of 30 °C, 40 °C, and 50 °C, for four different types of pure lubricants, such as soybean, paraffinic, sunflower, and corn, based on SiO_2 nanoparticles (Taha-Tijerina et al., 2019). Thermal conductivity for the four lubricants experienced a maximum increase in thermal conductivity to pure lubricants of 2.67%, 2.08%, 2.05%, and 1.75%, respectively. Although SiO_2/PVE nanolubricant in the temperature range of 30 °C to 50 °C experienced an increase in thermal conductivity of 2.65% lower than SiO_2/soybean, but at a temperature of 80 °C, SiO_2/PVE nanolubricant produced a better increase in thermal conductivity. This is possible due to the more ideal nanoparticle structure when SiO_2 is dispersed into PVE lubricants. Furthermore, SiO_2/PVE has superior thermophysical properties, a homogeneous mixture in terms of stability, and low interfacial resistance, compared to nanolubricant SiO_2/soybean, SiO_2/paraffin, SiO_2/sunflower, and SiO_2/corn.

The correlation between increased thermal conductivity and pure lubricants indicates that SiO_2 nanoparticles have advantages. Observations show that the thermal conductivity of SiO_2 dispersed into pure lubricants increases in the range of ~0.13–0.16 W/m·K, while the pure lubricants range in the range of ~0.11–0.14 W/m·K. This is due to several factors, one of which is the Brownian motion of nanolubricants, which causes the nanolayer surface to form more structured bonds, resulting in more efficient heat transfer (Shukla et al., 2016). This characteristic becomes more dominant due to the stability of the SiO_2/PVE nanolubricant, and its relatively low effective viscosity at temperature conditions of 30 °C and 80 °C, causing the SiO_2 nanoparticles to move randomly through Brownian motion. In contrast, in SiO_2/soybean, SiO_2/paraffin, SiO_2/sunflower, and SiO_2/corn, the viscosity is relatively high at these temperatures, resulting in the Brownian motion of the nanoparticles tending to limit their amplitude. However, at a temperature range of 40 °C to 50 °C the thermal conductivity of SiO_2/soybean, SiO_2/paraffin, SiO_2/sunflower, and SiO_2/corn showed a small increase compared to SiO_2/PVE. This is because at these temperatures, agglomeration in the nanolubricant results in an increased effective surface area of the particles, and the intensity of dispersed micro-convection. It was concluded that SiO_2/PVE was superior at temperatures of 30 °C and 80 °C because the contribution of Brownian

motion was more effective compared to other nanolubricant samples. The effectiveness of thermal conductivity for SiO_2 nanoparticle-based nanolubricants is illustrated in **Figure 5**.

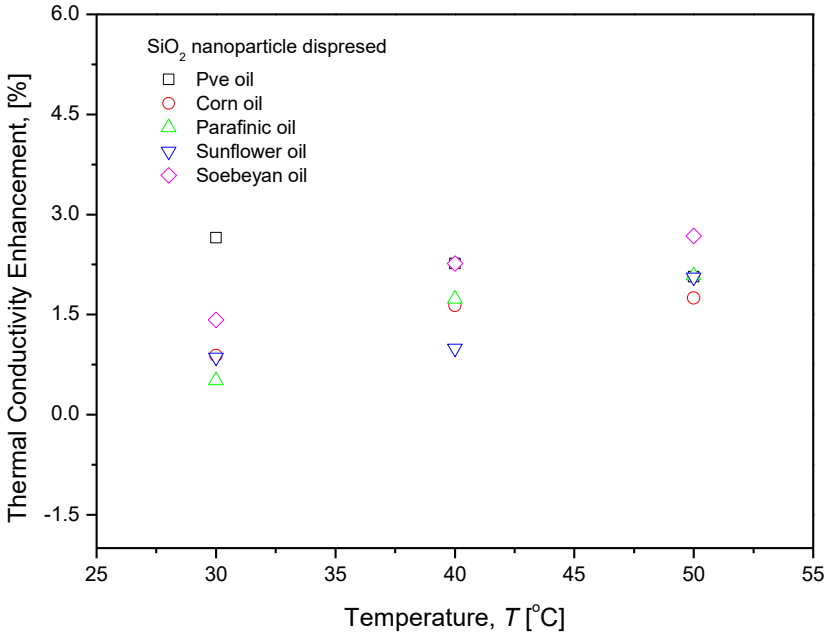

Figure 4. Thermal conductivity enhancement versus previously study using SiO_2 nanoparticle

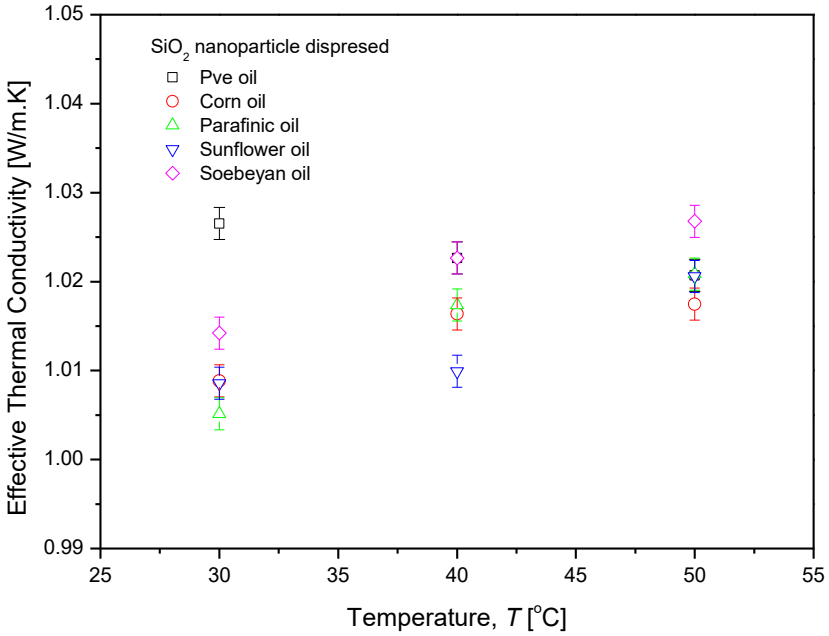

Figure 5. Efective thermal conductivity compared with previously study

CONCLUSION

SiO_2 nanoparticles dispersed into PVE lubricant at a volume concentration of 0.007% showed satisfactory results. This was demonstrated through UV-Vis spectrophotometer observations and investigations of thermal conductivity behaviour over a temperature range of 30°C to 80°C. Comparison of the current study with previous studies also demonstrated improved results. The results showed that the SiO_2/PVE nanolubricant produced 80% absorbance stability, and all SiO_2/PVE nanolubricant samples experienced increased thermal conductivity, with a maximum increase of 2.72% at 80°C. Meanwhile, the correlation of thermal conductivity between

the current study and the previous study showed similar results, with thermal conductivity increasing with increasing temperature. These findings also indicate that SiO_2 nanoparticles dispersed in pure PVE lubricant exhibit significant advantages. Therefore, SiO_2 nanoparticle-based nanolubricants have the potential to improve the performance of lubrication systems. It was concluded that SiO_2/PVE nanolubricants showed significant improvements in thermal stability and conductivity. Given the rapid development of nanotechnology, nanolubricants can be further developed in machining processes and cooling systems. Exploration can focus on the type of nanoparticle, volume concentration, and method of nanoparticle dispersion, with the aim of improving thermophysical and tribological properties, while simultaneously enhancing system performance.

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