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Research Paper

Rheological Behaviour of SiO_2/PAO Nanolubricant for an Electric-Driven Compressor Automotive Air-Conditioning System

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Abstract

Compressor lubricants play a crucial role in refrigeration systems by controlling friction, sealing effectiveness, and heat removal, with lubricant viscosity a key parameter that affects hydrodynamic losses and energy efficiency. This study aimed to systematically characterise the rheological behaviour of silicon dioxide/polyalphaolefin (SiO_2/PAO) nanolubricants under compressor operating conditions. SiO_2/PAO nanolubricants with concentrations of 0.01–0.03% were prepared using a two-step method without the use of surfactants, and dynamic viscosity measurements were conducted over a temperature range of 25 to 100 °C and shear rate from 549 to 4320 s^{-1}. The experimental data were further used to understand the viscosity trends under thermal and shear conditions. Both PAO lubricant and SiO_2/PAO nanolubricants exhibited Newtonian rheological behaviour. The incorporation of SiO_2 nanoparticles led to controlled, concentration-dependent changes in viscosity. The 0.01% SiO_2/PAO nanolubricant exhibited the smallest viscosity change (0.7%) even at high temperatures and shear rates, compared with higher concentrations. The findings show that low-concentration SiO_2/PAO nanolubricants, especially at 0.01%, offer good rheological stability with minimal viscosity penalty, providing an advantage to the electric-driven compressor automotive air-conditioning system (EDC-AAC) by reducing compressor work by 3.5%.

Keywords: SiO_2 nanoparticles; PAO; Nanolubricants; Rheological; Electric compressor; Automotive air conditioning

1. Introduction

Compressor lubricants play a critical role in the operation of refrigeration systems by reducing friction and wear on moving components, providing sealing, and assisting in heat removal as they circulate throughout the system [1], [2], [3]. Lubricants exhibit various properties; viscosity is particularly critical, as it affects hydrodynamic film formation, friction losses, and compressor pumping power [4], [5]. In refrigeration systems, lubricants are constantly exposed to changing conditions, particularly temperature fluctuations. Reduced viscosity can affect lubrication levels, and excessively high viscosity increases mechanical losses and reduces overall system efficiency [2], [4]. This requirement emphasises the importance of understanding lubricant behaviour over a temperature range that coincides with the system's operating temperature.

The principles governing refrigeration lubrication apply to automotive air conditioning

(AAC) systems, where compressor components operate under more dynamic and challenging conditions. Unlike stationary refrigeration systems, AAC compressors experience more frequent load variations, transient operating conditions, and ambient temperature fluctuations [6]. In hybrid and electric vehicles, the use of electrically driven compressors (EDCs) is increasingly common, as compressor operation is independent of engine speed and is powered entirely by the vehicle's electrical system [7]. Experimental investigations have consistently shown that the compressor accounts for a significant portion of energy consumption in AAC systems, making compressor efficiency a major factor influencing cooling performance and overall vehicle energy consumption [6], [7]. Therefore, the lubricant's behaviour in electrically driven compressors for automotive air conditioning (EDC-AAC) directly affects the cooling system's power consumption and efficiency.

In this context, lubricant properties, especially rheological behaviour, are becoming increasingly important to understand. Rheological behaviour governs the relationship between shear stress, shear rate, and viscosity, thereby affecting hydrodynamic drag, oil circulation, and viscous losses in high-speed compressor operation [4], [8], [9]. Although lubricant evaluations often emphasise temperature-dependent viscosity alone, several studies have shown that shear rate can significantly alter apparent viscosity and flow resistance under different operating conditions [8], [10], [11], [12]. A rheologically focused approach that incorporates both temperature and shear-rate dependencies is necessary to gain a more complete understanding of lubricant performance in EDC-AAC systems. To address lubrication flow challenges in refrigeration and AAC systems, advanced lubricants that disperse solid nanoparticles into base lubricants have been increasingly explored [13], [14], [15]. Previous studies have reported that nanolubricants can improve cooling performance, reduce compressor power consumption, and increase the coefficient of performance (COP) in refrigeration system applications [16], [17]. These effects are more likely attributable to improved tribological characteristics, modified thermophysical properties, and changes in rheological behaviour resulting from nanoparticle-lubricant interactions [18].

Despite extensive studies on nanolubricants for automotive refrigeration and air-conditioning applications, there remains a lack of systematic investigations into SiO_2/PAO nanolubricants that comprehensively characterise their rheological behaviour and its impact on EDC-AAC systems. This study presents the first comprehensive rheological investigation of SiO_2/PAO nanolubricants specifically developed for EDC-AAC systems. Furthermore, it establishes the relationship between nanoparticle concentration, rheological behaviour, and the compressor performance of an R1234yf-based EDC-AAC system. These contributions provide new insights into the suitability of SiO_2/PAO nanolubricants for enhancing compressor performance and the reliability of EDC-AAC systems.

2. Materials and Methods

2.1. *Nanolubricant Formulation Strategy*

SiO_2/PAO nanolubricants were prepared using a conventional two-step method [11], [19], [20], [21], with the properties of the nanoparticles and the PAO lubricant summarised in **Table 1** and **Table 2**, respectively. PAO synthetic lubricant, procured from Behr Hella Service GmbH, Germany, was selected as the base lubricant due to its extensive use in automotive refrigeration compressor applications. Commercial SiO_2 nanoparticles supplied by DKNANO (Beijing Deke Daojin Science and Technology Co., Ltd., Beijing, China) were incorporated into PAO lubricant at concentrations of 0.01%, 0.02%, and 0.03%. At the same time, pure PAO was retained as the reference sample. The selected concentration range of 0.01–0.03 vol.% was based on previous studies, which reported that the most significant tribological and system performance improvements in electric-driven compressor air-conditioning systems were consistently achieved within this interval, while maintaining stable nanoparticle dispersion and avoiding the diminished performance and instability commonly associated with higher nanoparticle concentrations [6], [17], [22], [23]. No surfactant or dispersing agent was used in this study to evaluate the intrinsic interaction between SiO_2 nanoparticles and the PAO lubricant.

Table 1. Properties of nanoparticles [24]

Property	SiO_2
Color	White
Purity, %	99.9
Structure	Spherical
Density, g/cm³	2.22
Average size, nm	30
Molecular mass, g/mol	60.08
Specific heat, J/kg.K	745
Thermal conductivity, W/m.K	1.4

Table 2. Properties of PAO lubricant [25]

Property	Unit	PAO Lubricant
Density	g/cm³	0.838 (15 °C)
Kinematic viscosity	mm²/ s	65.6 (40 °C), 10.0 (100 °C)
Refractive index		1.44
Pour Point	°C	-50
Flash point	°C	>250

Among various nanoparticle materials, SiO_2 has attracted attention due to its chemical inertness and thermal stability, with several studies showing that SiO_2 helps in the aspect of relatively low viscosity increase compared to other metal oxide nanoparticles, and good effect on dielectric behaviour suitable for electrical compressor conditions [8], [18], [24], [26]. At the same time, PAO lubricants have emerged as the base lubricant for electric compressors due to their non-hygroscopic nature, good thermal stability, and good viscosity characteristics compared to POE and PAG lubricants [7]. However, existing studies increasingly emphasise the need to limit the concentration of nanoparticles used in AAC systems to low levels to avoid excessive increases in viscosity and energy loss [17], [27], [28].

The required mass of SiO_2 nanoparticles, calculated using Eq. (1) [8], was accurately weighed using a five-decimal digital balance, and the corresponding volume of PAO lubricant was measured using a measuring cylinder. The nanoparticles were first dispersed into the PAO lubricant and magnetically stirred for 30 min at ambient conditions without external heating. The resulting mixtures were then homogenised for 1 h to ensure uniform nanoparticle dispersion [20].

$$\phi = \frac{\left(\frac{m}{\rho}\right)_{SiO_2}}{\left(\frac{m}{\rho}\right)_{SiO_2} + \left(\frac{m}{\rho}\right)_{PAO}} \times 100 \qquad (1)$$

For stability evaluation, 15 ml of each nanolubricant sample was reserved for visual observation using the photo-capturing method; however, due to the low optical opacity of SiO_2 nanoparticles in the transparent PAO lubricant, this approach alone was insufficient to assess dispersion stability reliably, and zeta potential analysis was therefore employed for quantitative evaluation using an additional 5 ml of each sample. The morphological images of spherical SiO_2 nanoparticles with an average size of 30 nm were examined and confirmed using Transmission Electron Microscopy (TEM), as shown in **Figure 1**.

Visual observations of the SiO_2/PAO nanolubricant immediately after preparation (**Figure 2a**) and after 30 days of storage (**Figure 2b**) revealed no visible sedimentation or phase separation, indicating excellent dispersion stability throughout the observation period. The SiO_2/PAO nanolubricant, with a zeta potential of 144.1 mV (**Figure 3**), showed excellent stability

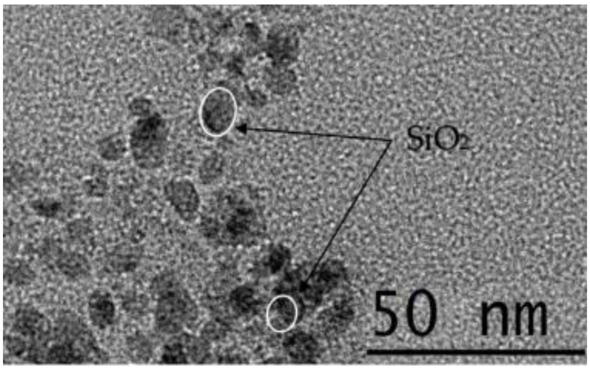

Figure 1. Morphological characteristics of SiO_2 nanoparticles by TEM analysis

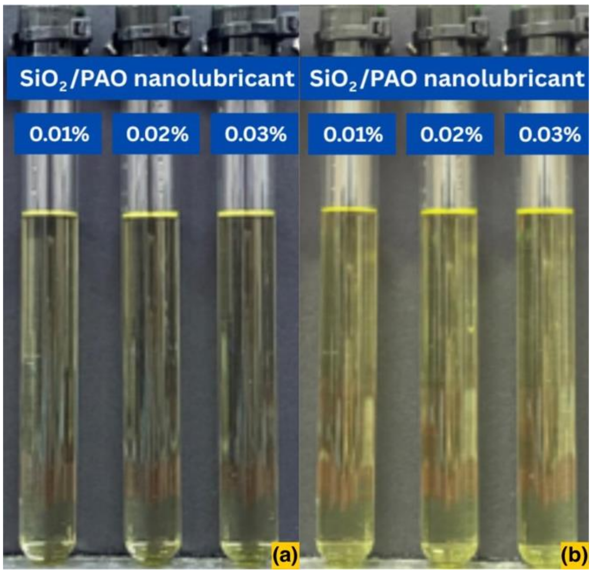

Figure 2. Visual stability of the SiO_2/PAO nanolubricant: (a) iImmediately after preparation and (b) After 30 days of storage

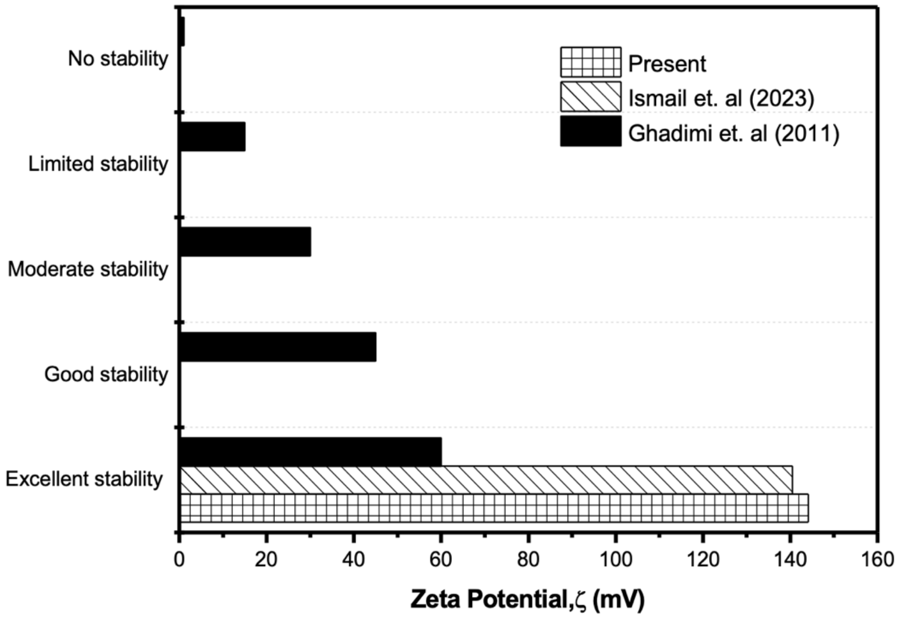

Figure 3. Zeta potential stability assessment of SiO_2/PAO nanolubricants in comparison with stability criteria and previous studies

(>60 mV) according to the classification by Ghadimi *et al*. [29]. Repeated measurements confirmed the high zeta potential obtained, consistent with previous studies reporting zeta potentials exceeding 140 mV for highly stable synthetic PVE nanolubricant systems after optimised ultrasonication [30]. This result indicates strong electrostatic repulsion between SiO_2 nanoparticles in the PAO lubricant matrix. It confirms that they remain well dispersed, thereby reducing agglomeration and ensuring stable rheological and system performance. Previous work has emphasised that good dispersion stability is crucial for achieving more consistent viscosity in PAO-based nanolubricants, especially over long-term operation [31], [32], [33].

2.2. *Measurement of Rheological Properties*

The measurements were performed according to ISO 3219:1993, with each sample of PAO lubricant and SiO_2/PAO nanolubricant at concentrations of 0.01, 0.02, and 0.03 vol% being tested for dynamic viscosity in triplicate to ensure reproducibility using a high-precision rotational rheometer (RheolabQC, Anton Paar). The measurements were performed over a temperature range of 25 to 100 °C and shear rates of 549 to 4320 s^{-1}, with temperature precisely controlled using an integrated Peltier system with air counter-cooling. The rheological behaviour of the PAO lubricant across a range of temperatures and shear rates was examined, and the resulting experimental results were compared with established industrial data and previous research to ensure consistency and reliability.

The ratio of the measured dynamic viscosity of the SiO_2/PAO nanolubricant, $\mu_{\mathrm{SiO_2/PAO}}$ to the PAO lubricant, μ_{PAO} under the same operating conditions, also known as relative viscosity μ_r expressed in Eq. (2).

$$\mu_r = \frac{\mu_{NL}}{\mu_L} = \frac{\mu_{\mathrm{SiO_2/PAO}}}{\mu_{\mathrm{PAO}}} \qquad (2)$$

This evaluation enables a direct assessment of the viscosity modification resulting from the incorporation of SiO_2 nanoparticles, independent of the PAO's absolute lubricant viscosity. In addition, the viscosity change, $\Delta\mu$ is measured in terms of percentage deviation relative to the PAO lubricant using the viscosity difference, which is calculated using Eq. (3).

$$\Delta\mu\ (\%) = \frac{\mu_{\mathrm{NL}} - \mu_{\mathrm{L}}}{\mu_{\mathrm{L}}} \times 100 = (\mu_{\mathrm{r}} - 1) \times 100 \qquad (3)$$

where, μ_{NL} represent the dynamic viscosity SiO_2/PAO nanolubricant and μ_{L} is the dynamic viscosity of PAO lubricant, at the same temperature.

2.3. *Experimental Procedure*

The experimental evaluation of the performance of SiO_2 nanolubricants was conducted using an electric-driven compressor automotive air conditioning (EDC-AAC) test rig, designed in accordance with SAE J2765 (**Figure 4**), in line with the performance evaluation requirements of automotive air conditioning systems. All experiments were conducted under controlled conditions, with room temperature between 25–26 °C and relative humidity between 50–60%, to minimise environmental effects on the performance of the EDC-AAC system. The EDC-AAC system was run for 20 minutes to reach stability, and data were collected for the next 10 minutes. The thermal performance was evaluated with special focus on the compressor inlet and outlet temperatures (T_1 and T_2) and the corresponding compressor work in the EDC-AAC system using SiO_2 nanolubricants. The compressor inlet (T_1) and outlet (T_2) temperatures were measured using K-type thermocouples. These measured pressure and temperature parameters were used to determine the specific enthalpy values at the compressor inlet (h_1) and outlet (h_2) using Engineering Equation Solver (EES), based on the measured pressure–temperature data for R1234yf refrigerant. The compressor work, $\dot{W}_{comp}$ was then calculated from the enthalpy rise across the compressor, as expressed in Eq. (4) [34], [35].

$$\dot{W}_{comp} = \dot{m}(h_2 - h_1) \tag{4}$$

where, $\dot{m}$ is the refrigerant mass flow rate. All measurements were repeated three times under identical operating conditions to ensure repeatability, and the averaged values of T_1, T_2, and compressor work were used for analysis. The measuring ranges and corresponding uncertainties of the instruments used throughout the experimental investigation are summarised in **Table 3** to demonstrate the reliability and accuracy of the acquired data.

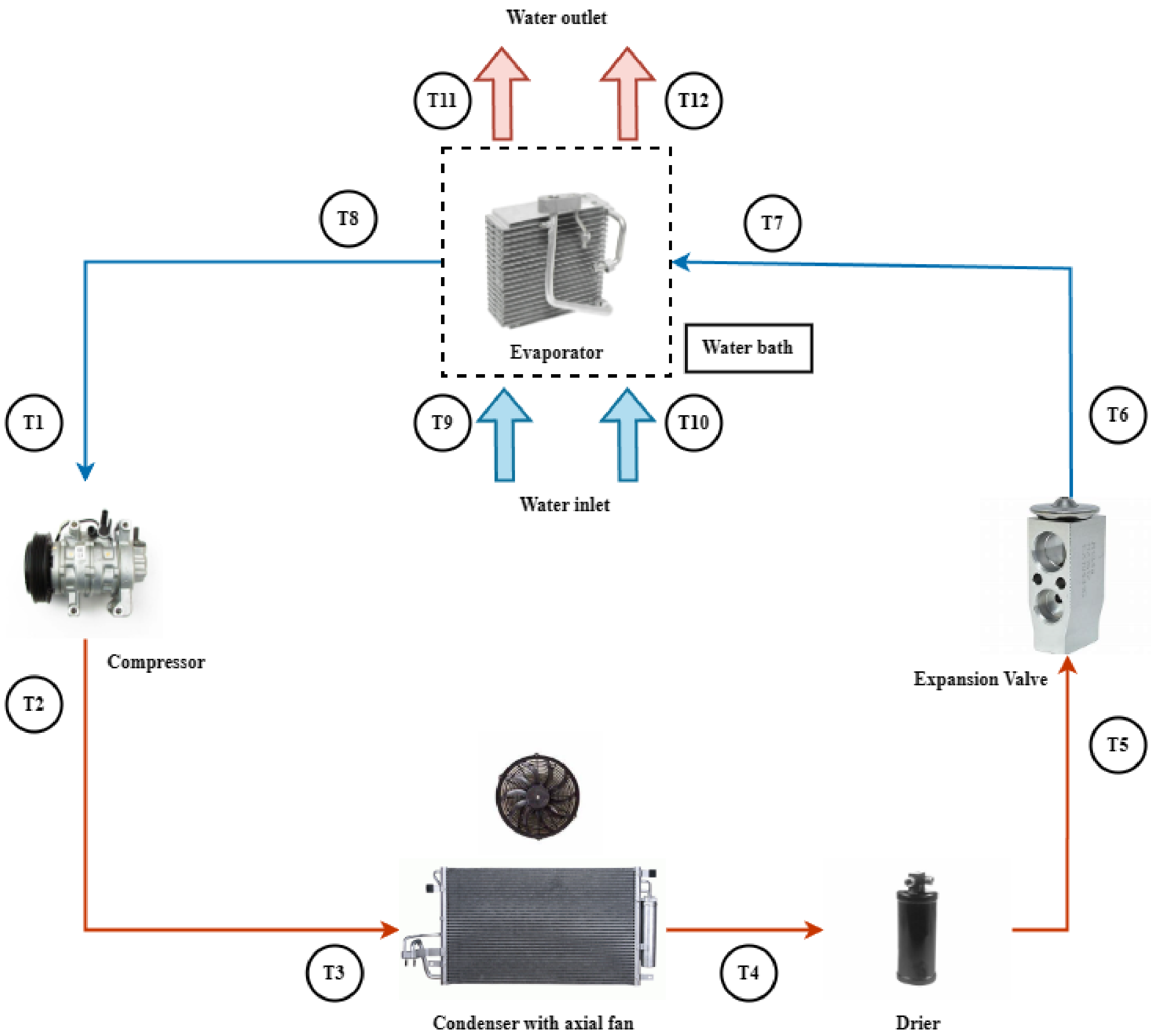

Figure 4. Schematic layout of EDC-AAC experimental test rig

Table 3. Instrument ranges and uncertainties

Instrument	Unit	Measuring Range	Uncertainty (%)
Weight balance	g	0 – 200	±0.0001
Zeta potential	mV	-600 – 600	±0.1
Dynamic Viscosity	Pa.s	0.001 – 0.109	±0.0001
Temperature	°C	-50 – 250	±0.1
Pressure	MPa	0 – 6.5	±0.001

3. Results and Discussion

3.1. *Effect of Temperature and Concentration on Viscosity*

Figure 5 illustrates the variation in the dynamic viscosity of the PAO lubricant with temperature, comparing the present measurements with industry data and previously reported literature. A clear decrease in viscosity with increasing temperature is observed across all datasets. The current results follow the reported trends, with an error of ±5% over the temperature range studied [24], [25]. At lower temperatures, PAO lubricant exhibits high viscosity due to stronger intermolecular interactions and reduced molecular mobility. As temperatures rise, thermal energy weakens cohesive forces and increases molecular motion, reducing resistance to flow. Temperature-dependent viscosity behaviour observed for PAO lubricant. The consistency confirms the reliability of the current experimental technique, validates the use of PAO as a reference lubricant, and further evaluates the rheological performance of SiO_2 nanoparticle additions.

Figure 6a depicts the temperature-dependent dynamic viscosity of SiO_2/PAO nanolubricants at different nanoparticle concentrations, while Figure 6b measures the corresponding viscosity change compared to the PAO lubricant. In general, all the SiO_2/PAO nanolubricant samples showed a decrease in dynamic viscosity with increasing temperature, similar to the behaviour of PAO lubricant, due to weakened intermolecular forces and increased molecular mobility at high temperatures. The SiO_2 nanoparticles led to a measurable increase in viscosity relative to the PAO lubricant, with the effect becoming more pronounced at concentrations of 0.01% to 0.03%, as shown in Figure 6a. This behaviour was attributed to the formation of nanoparticle-lubricant interaction networks and increased hydrodynamic resistance resulting from the well-dispersed SiO_2 nanoparticles in the PAO lubricant.

A similar trend was observed in previous studies using SiO_2 nanoparticles dispersed in POE and PAG lubricants, where the viscosity decreased consistently with increasing temperature and increased with the addition of SiO_2 nanoparticles [8], [36].

The trends in viscosity change in Figure 6b further clarify the combined influence of temperature and nanoparticle concentration. At low temperature (25 °C), the viscosity change is most significant, increasing from 1.69% at 0.01% to 2.43% at 0.03%, indicating strong particle–particle and particle–fluid interactions under reduced thermal agitation. As the temperature increases to 40 °C and 60 °C, the viscosity changes decrease overall but remain concentration-dependent, suggesting that thermal motion progressively disrupts nanoparticle interaction structures. At the same time, higher loadings still maintain noticeable reinforcement effects. At higher temperatures (80–100 °C), the viscosity change for 0.01% becomes negligible, reaching 0% at 100 °C, whereas higher concentrations (0.02% and 0.03%) continue to exhibit measurable changes in viscosity. This behaviour indicates that at elevated

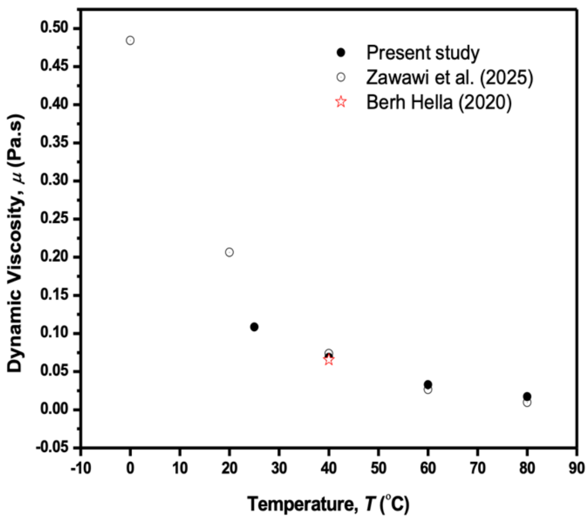

Figure 5. Temperature-dependent dynamic viscosity of PAO lubricant compared with literature and industry data

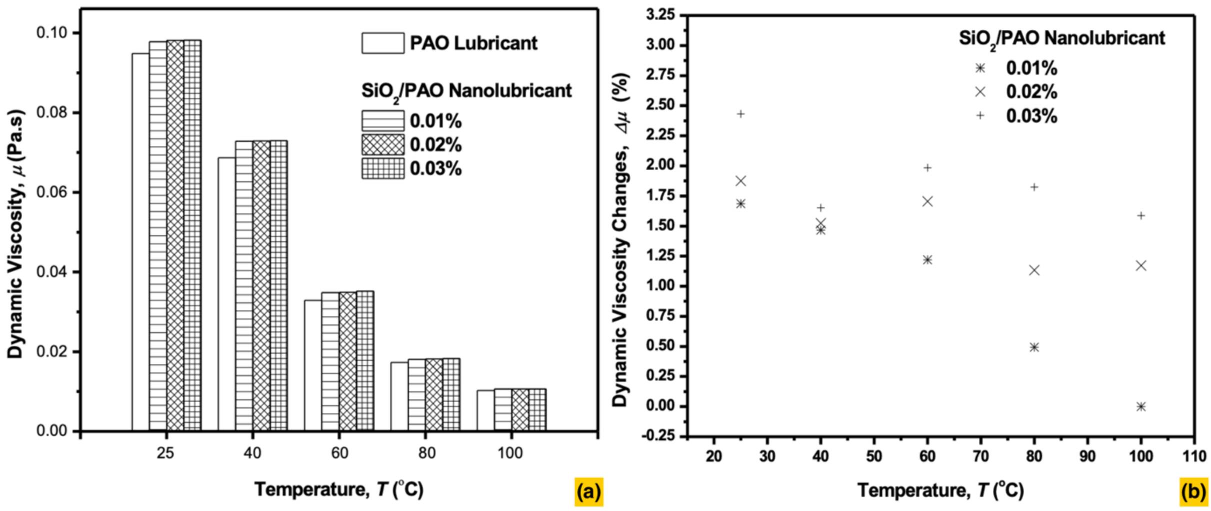

Figure 6. Effect of temperature and SiO_2 nanoparticle concentration on the dynamic viscosity of SiO_2/PAO nanolubricants: (a) Dynamic viscosity variation; (b) Dynamic viscosity change

temperatures, the base lubricant dominates the flow behaviour at low nanoparticle loading. In contrast, higher concentrations maintain sufficient interfacial interactions and an effective volume fraction, thereby influencing the rheological response. The results demonstrate that the viscosity modification induced by SiO_2 nanoparticles is strongly temperature-sensitive and concentration-dependent, with more pronounced effects at lower temperatures and higher nanoparticle loadings.

3.2. Shear-rate Rheological Behaviour

Figure 7a presents the shear-rate-dependent dynamic viscosity of the PAO lubricant at different temperatures, while Figure 7b extends the comparison to SiO_2/PAO nanolubricants with concentrations of 0.01%, 0.02%, and 0.03%. As observed in Figure 7a, at 25 °C, the PAO lubricant and SiO_2/PAO nanolubricant exhibit a relatively high viscosity level that remains constant over the entire investigated shear-rate range, indicating Newtonian behaviour. The absence of significant shear-rate dependence suggests that the molecular structure of the PAO lubricant is stable under applied shear at low temperatures, with viscous resistance governed primarily by intermolecular interactions rather than by flow-induced structural changes. Although the viscosity exhibited an initial development in the low shear-rate region at 40 °C, a plateau was subsequently attained, resulting in an essentially constant viscosity over the investigated shear-rate range. This behaviour confirms that the PAO lubricant and the SiO_2/PAO nanolubricant retain Newtonian characteristics at moderate temperatures,

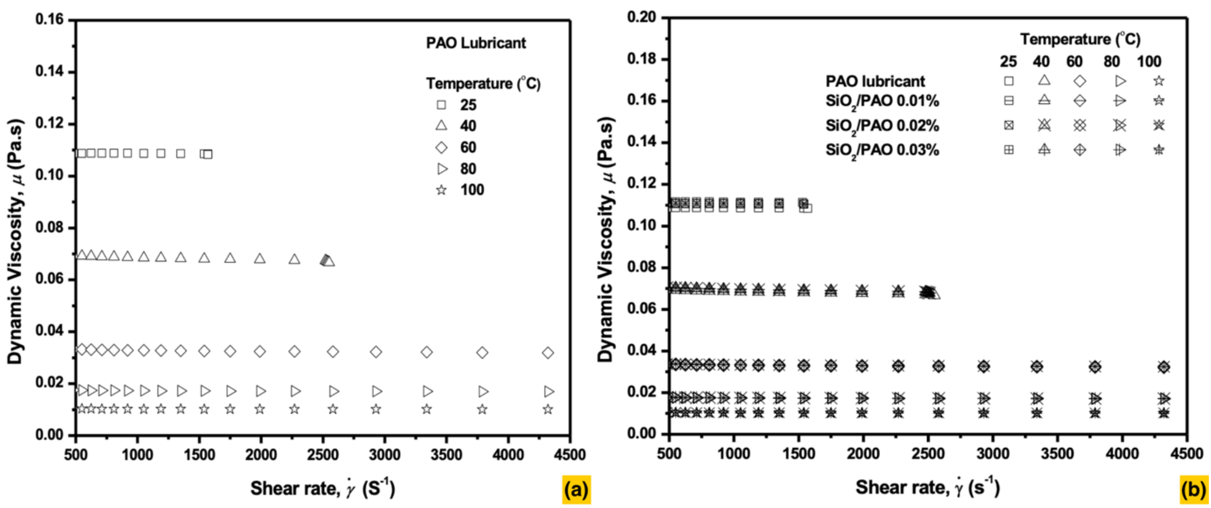

Figure 7. Effect of shear rate and elevated temperature on the dynamic viscosity: (a) PAO lubricant; (b) Comparison of PAO lubricant and SiO_2/PAO nanolubricants with different nanoparticle concentrations

with a decrease in viscosity attributed to enhanced molecular mobility and reduced cohesive forces due to thermal excitation. Minor viscosity variations were observed at lower shear rates at 40 °C; these trends are consistent with those reported for PAO lubricants in the literature [20], [37]. At 60 °C, the viscosity decreases further but remains essentially independent of shear rate, indicating that temperature continues to dominate the rheological response over shear effects.

At elevated temperatures of 80 °C and 100 °C, the dynamic viscosity reaches its lowest values and exhibits minimal variation with shear rate across the full measurement range. This outcome confirms that the PAO lubricant and the SiO_2/PAO nanolubricant maintain stable Newtonian behaviour even under high shear conditions at elevated temperatures. The combined effects of increased thermal energy and reduced internal resistance facilitate molecular alignment and flow without inducing shear-dependent changes in viscosity.

As shown in **Figure 8a** at 25 °C, all SiO_2/PAO nanolubricants exhibit relatively higher viscosity changes at low shear rates, with values of approximately 1.6–2.1% for 0.01%, 1.8–2.4% for 0.02%, and up to about 3.0% for 0.03%, indicating the dominance of particle–particle and particle–fluid interaction networks under weak deformation conditions. As the shear rate increases, a gradual reduction in viscosity is observed across all concentrations, suggesting a partial disruption of weak-interaction structures and progressive molecular alignment. For the SiO_2/PAO nanolubricant 0.01%, the viscosity change decreases steadily to approximately 1.63–1.67% at shear rates above 3000 s^{-1}, while for the SiO_2/PAO nanolubricant 0.02%, the values decline from 2.4% at low shear rates to approximately 1.85–1.90% at high shear rates. The SiO_2/PAO nanolubricant 0.03% nanolubricant consistently exhibits the highest viscosity change across the entire shear-rate range, decreasing from 3.0% at low shear rates to about 2.35–2.40% at the highest shear rates. At medium-to-high shear rates, the viscosity change curves tend to stabilise, indicating the establishment of steady-state flow conditions. At 40 °C (**Figure 8b**), the viscosity changes of SiO_2/PAO nanolubricants exhibit a shear-rate-dependent trend similar to that observed at 25 °C, but with reduced magnitude and narrower variation. At low shear rates, the viscosity changes range from approximately 1.4–1.6% for 0.01%, 1.5–1.9% for 0.02%, and 1.7–1.8% for 0.03%, indicating that particle–fluid and particle–particle interactions remain active under weak deformation conditions. Compared to 25 °C, the overall viscosity changes at 40 °C are lower, reflecting the influence of increased thermal energy in weakening interaction structures. With increasing shear rate, viscosity changes for all concentrations exhibit minor fluctuations but remain within relatively narrow bands. At higher shear rates, the viscosity changes stabilise at approximately 1.45–1.50% for 0.01%, 1.48–1.51% for 0.02%, and 1.65–1.69% for 0.03%, indicating the establishment of steady-state flow conditions.

The viscosity change of the SiO_2/PAO nanolubricant shows a different shear-rate dependence than at the previous temperature, with a higher overall value and larger fluctuations across the shear-rate range at 60 °C in **Figure 8c**. At low shear rates, the viscosity change ranges from approximately 1.3–1.6% for the 0.01% SiO_2/PAO nanolubricant, 1.6–1.8% for the 0.02% SiO_2/PAO nanolubricant, and 2.0–2.1% for the 0.03% SiO_2/PAO nanolubricant, indicating that the nanoparticle-related interactions remain significant despite the increased thermal agitation. As the shear rate increases, the viscosity change across all concentrations shows a moderate fluctuation. For the 0.01% nanolubricant, the viscosity change generally remained in the range of 1.22–1.33% at moderate to high shear rates, while the 0.02% sample stabilised around 1.70–1.80%. The 0.03% nanolubricant consistently exhibited the highest viscosity change throughout the shear rate range, with values largely maintained between 2.00–2.16% at higher shear rates. **Figure 8d** shows the results at 80 °C; the viscosity of the SiO_2/PAO nanolubricant decreases continuously, reflecting the stronger influence of thermal effects on the rheological behaviour. The viscosity change ranges from about 0.3–0.9% for 0.01%, 0.8–1.3% for 0.02%, and 1.0–2.1% for 0.03%, indicating that nanoparticle-related interactions persist but are partially weakened at high temperatures. With increasing shear rate, the viscosity change at all concentrations shows significant fluctuations, reflecting the competition between shear-induced alignment and thermally activated particle motion. At moderate to high shear rates, the viscosity changes significantly for the 0.01% SiO_2/PAO nanolubricant, stabilising mostly below 0.50%, while the 0.02% sample is in the range of 1.00–1.15%. In contrast, 0.03% nanolubricants consistently maintained higher viscosity changes, generally in the range of 1.80–1.90%.

The viscosity of the SiO_2/PAO nanolubricant showed the smallest overall change and the most pronounced spread at 100 °C, as shown in **Figure 8e**

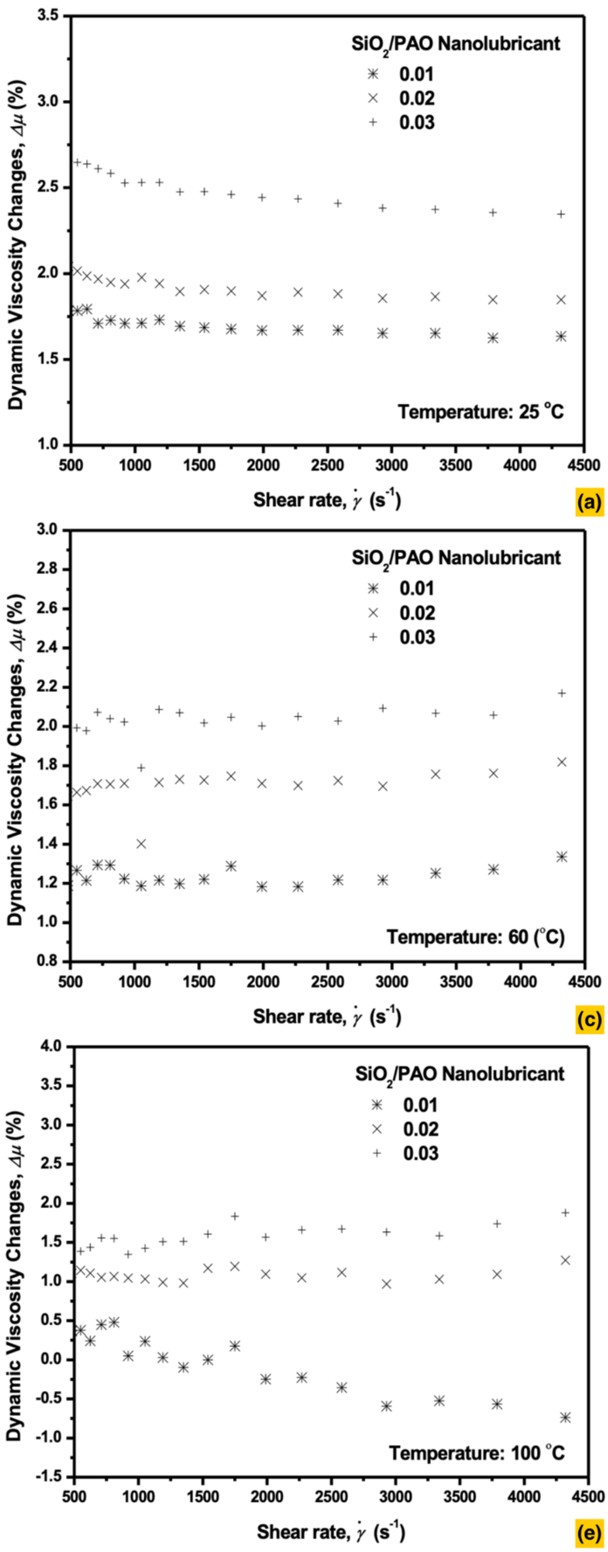

Figure 8. Effect of shear rate on viscosity change of SiO_2/PAO nanolubricants at different temperatures. (a) 25 °C (b) 40 °C (c) 60 °C (d) 80 °C (e) 100 °C

across the range of shear rates studied, highlighting the dominant influence of high temperature on the rheological behaviour. At low shear rates, the viscosity change ranged from approximately -0.7% at 0.01%, -0.9% at 0.02%, and -0.6% at 0.03%, indicating that nanoparticle-related interactions persisted but weakened as temperature increased. With increasing shear rate, the viscosity change for the 0.01% SiO_2/PAO nanolubricant decreased significantly and reached the viscosity of the PAO lubricant, with some values becoming negative at higher shear rates, indicating that the rheological response of the viscosity was slightly less than that of the PAO lubricant. In contrast, the 0.02% SiO_2/PAO nanolubricant maintained a relatively stable viscosity change around 1.00–1.27%, and the 0.03% SiO_2/PAO nanolubricant consistently exhibited the highest viscosity change, generally increasing towards 1.60–1.88% at high shear rates, indicating that the higher nanoparticle concentration maintained a controlled rheological influence even at high temperatures.

3.3. *Compressor Temperature and Work Analysis*

Figure 9 shows the operating temperatures at the inlet and outlet of the electric compressor components of the EDC-AAC system for the PAO lubricant and the SiO_2/PAO nanolubricant at different nanoparticle concentrations. This figure connects the rheological results discussed in Sections 3.1 and 3.2 and provides insight into the practical operating temperatures of the nanolubricants formulated in the EDC-AAC system. At the compressor inlet, the operating temperatures remain within a relatively narrow range (28–31 °C) for all lubricants, with only minor differences observed between the PAO lubricant and the SiO_2/PAO nanolubricant. The outlet temperature of the electric compressor for SiO_2/PAO nanolubricants is 75–84 °C. The reduction in inlet and outlet temperatures of the electric compressor with the SiO_2/PAO nanolubricant, compared to the PAO lubricant, is attributed to improved heat dissipation and reduced viscous dissipation in the suction region, resulting from the nanolubricant's rheological properties.

Figure 10 shows a comparison of the compressor work of the EDC-AAC system operating with PAO lubricant and SiO_2/PAO nanolubricant at different nanoparticle concentrations. The results show that the compressor work increases slightly with the addition of 0.03% SiO_2 nanoparticles, from 43 kJ/kg to 46 kJ/kg, a 7% increase. This increase is due to changes in the viscosity of the nanoparticle concentration, resulting in higher viscous shear resistance in the compressor compression chamber and between the lubricating surfaces. The analysis of variance (ANOVA) was performed on the compressor work data at different SiO_2 concentrations. The analysis yielded an F-value of 496.29 and a p-value of 2.17×10^{-7}, indicating a statistically significant effect of rheological characteristics associated with different SiO_2 concentrations on compressor work ($p < 0.05$). This rheological stability promotes consistent lubricant film formation and minimises excessive frictional losses, thereby contributing to

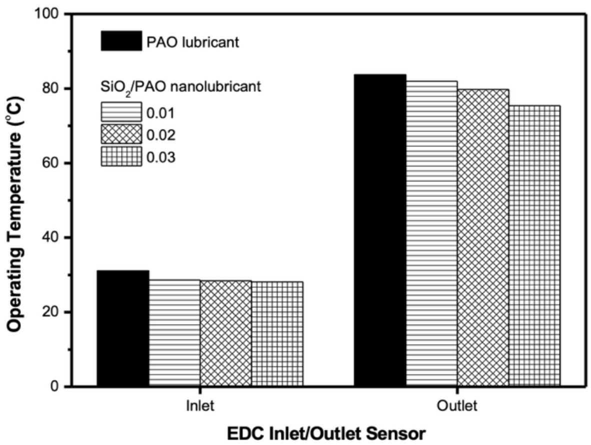

Figure 9. Inlet and outlet temperature characteristics of an electric driven compressor using PAO lubricant and SiO_2/PAO nanolubricants

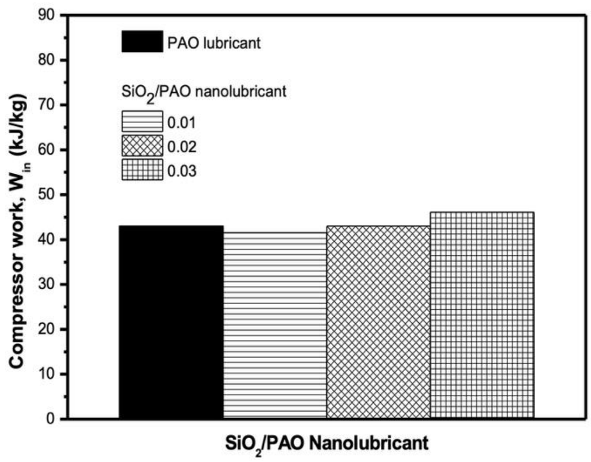

Figure 10. Influence of SiO_2 nanoparticle concentration on compressor work of EDC-AAC system

reliable compressor operation and improved energy efficiency.

As previously shown in **Figure 6** to **Figure 8**, the SiO_2/PAO nanolubricant exhibits higher viscosity than the PAO lubricant, resulting in a slight increase in the mechanical work required for compression. This trend contrasts with the SiO_2/PAO nanolubricant (0.01%), which reduces compressor work by 3.5% compared to the PAO lubricant, demonstrating a clear performance advantage with minimal viscosity modification. This reduction is consistent with the rheological results in **Figure 6** to **Figure 8**, where the SiO_2/PAO nanolubricant (0.01%) exhibits the smallest change in viscosity and maintains stable flow behaviour under high-shear conditions. The improved lubrication flow stability and reduced metal-to-metal contact from the SiO_2 nanoparticles contribute to smoother compression and improved thermal management, which are important for maintaining electrical efficiency and component reliability in EDC-AAC systems [17], [24], [38]. In EDC-AAC systems, such improvements can reduce the electrical load on the battery system, thereby enhancing overall energy utilisation efficiency and potentially extending driving range during vehicle operation.

4. Conclusions

This study comprehensively examined the rheological behaviour of SiO_2/PAO nanolubricants and their effects on the compressor performance of EDC-AAC systems. Based on the experimental results and performance evaluation, the following conclusions can be drawn:

a. Pure PAO exhibits a consistent decrease in viscosity with increasing temperature, confirming the reliability of the experimental measurements and validating PAO as a base lubricant.
b. The addition of SiO_2 nanoparticles at low concentrations (up to 0.03%) results in controlled, temperature- and concentration-dependent viscosity changes, with more pronounced effects at lower temperatures and higher nanoparticle loadings.
c. Both PAO lubricant and SiO_2/PAO nanolubricants maintain Newtonian behaviour across the investigated shear-rate range.
d. The SiO_2/PAO nanolubricant at 0.01% concentration exhibits the lowest viscosity deviation, with viscosity changes limited to approximately 0.7% even at elevated temperatures, compared to higher concentrations.
e. System performance evaluation indicates that the 0.01% SiO_2/PAO nanolubricant reduces compressor work by 3.5%, demonstrating a favourable balance between rheological stability, thermal behaviour, and energy efficiency for EDC-AAC applications.

Despite the promising rheological characteristics observed, the practical implementation of SiO_2/PAO nanolubricants in EDC-AAC systems may present several challenges. Potential concerns include wear due to viscosity changes, potential effects on the electrical insulation requirements of electric compressors, and maintenance requirements under prolonged operating conditions. Therefore, further investigations focusing on durability, electrical compatibility, and long-term system reliability are recommended to support the safe and effective application of nanolubricants in EDC-AAC systems.

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Author's Declaration

Authors' contributions and responsibilities

M.A.A.R.: Conceptualization, Methodology, Investigation, Visualization, Formal analysis, Validation, Writing - original draft. W.H.A.: Supervision, Resources, Funding acquisition, Project administration. A.I. R.: Data curation, Writing - review & editing.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Generative AI statement

During the preparation of this work, the author(s) used Grammarly and ChatGPT to repair grammar errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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