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Investigating the Impact of Fly-Ash Additive on Viscosity Reduction at Different Temperatures: A Comparative Analysis

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Abstract: The viscosity of lubricating oils is influenced by fly-ash additives and temperature, as they play a crucial role in regulating the viscosity of oils. Fly-ash additives are added to lubricating oils to improve oxidation resistance and prevent deposit formation, which may reduce viscosity loss at high temperatures. This study aimed to investigate the impact of fly-ash additives and temperature on the viscosity of oils B, C, and A. The experimental methodology involved comparing the viscosity of these oils with and without the addition of a 0.5% fly-ash additive. Viscosity measurements were taken at different temperatures. The results showed significant changes in viscosity after incorporating the fly-ash additive. At 25 °C, oils B, C, and A exhibited viscosity increases of 6.2%, 8.1%, and 13.8%, respectively, compared to the samples without the additive. Similarly, at 75 °C, the viscosity increments were 10.2%, 11.5%, and 22.8% for oils B, C, and A, respectively. At 85 °C, the corresponding increments were 11.1%, 16.6%, and 32.8%. These findings highlight the effectiveness of fly-ash additives in reducing the impact of temperature on oil viscosity, with oil A demonstrating the highest efficacy. By adjusting the viscosity of the oil at different temperatures, the fly-ash additives contribute to maintaining stable lubricating performance. Understanding the influence of fly-ash additives and temperature on oil viscosity is crucial for optimizing the performance of lubricants across various temperature conditions. Additionally, this knowledge assists in selecting the appropriate additive ratios for specific applications, thereby ensuring optimal lubricant performance.

Keywords: fly-ash additive; shear stress; temperature; viscosity

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1. Introduction

Rheological properties play a crucial role in the characteristics of lubrication oil. These properties determine the viscosity of the fluid, which in turn affects the shear stress, tensile stress, and lubricative properties of the fluid, as well as its application capability [1–3]. Over the past century, rheology has been extensively studied to enhance the characteristics of lubrication oil and improve its application potential.

Nanoparticles have found wide-ranging applications and have demonstrated significant benefits. Researchers have investigated the use of nanoparticles to enhance various properties, such as the strength of composite materials and reinforcement capabilities [4–7]. Aluminum oxide, known for its lightweight, hardness, wear resistance, thermal conductivity, high strength, stiffness, and resistance to acid and alkali attack at elevated temperatures, has been extensively studied for applications in electrical and thermal conduction, machine parts, and composite compounds. It is believed that the addition of nanoparticles significantly improves the lubricative properties of oil [8]. Therefore, numerous studies have focused on enhancing the lubricative properties of nanoparticle additives, and several dispersing techniques have been proposed to achieve uniform nanoparticle dispersion in substrates [9–12]. Among these techniques, ultrasonic sonication baths, ultrasonic probe dispersing, ultrasonic cavitation, and ultrasonic resonance vibration dispersal techniques [12,13] are commonly employed for nanoparticle dispersion. The ultrasonic resonance vibration dispersal technique, in particular, is a powerful method for achieving uniform dispersion of nanopowders in colloidal systems [13].

Lubricating oil serves as a cushioning layer between the moving surfaces of machine parts, reducing friction and wear, while providing cooling and abrasion resistance. It plays a critical role in increasing machine efficiency, longevity, and reliability. However, during operation, lubricating oil faces challenges such as temperature variations, oil aging, and external environmental factors, which can impact its lubricating ability and service life. The demand for lubricants is substantial, with a typical additive ratio ranging from 0.5% to 1%. The thermal stability of lubricants can be assessed by examining their viscosity and viscosity index, which are crucial quality criteria. To enhance load-carrying capacity and viscosity index properties, lubricant manufacturers have introduced a range of additive packages. Several studies have examined the effects of nano Al_2O_3 additives on the lubricating properties of oils [14,15]. The addition of Al_2O_3 nanoparticles to lubricants induces changes in the oil's rheological properties. Various commercial lubricating oils have been supplemented with Al_2O_3 nanoparticles (approximately 80 nm in size) [14]. The studies have provided evidence that incorporating nano aluminum oxide into the oil enhances its lubricating properties and heat resistance. This improvement is attributed to the small size of Al_2O_3 particles, which facilitate increased separation between the contacting surfaces, thereby reducing friction and minimizing lubricant consumption, consequently extending the oil's lifespan. Furthermore, nano aluminum oxide can enhance the oil's heat resistance by reducing its viscosity at elevated temperatures. Additionally, various studies have been conducted to investigate the rheological properties, specifically dynamic viscosity, of the mixture of nano Al_2O_3 and base oil at different additive ratios and temperatures [15]. The results of these experiments indicated that the addition of nano aluminum oxide had a modifying effect on the dynamic viscosity of the oil. The research also identified suitable ratios and temperatures for incorporating nano aluminum oxide to ensure favorable lubricating properties. Furthermore, the impact of the mixture of lubricant oil and Al_2O_3 on the hydrodynamic pressure and load-carrying capacity of bearings was examined. The experimental results indicated a notable modification in the hydrodynamic pressure curve across the bearing's circumference, resulting in a substantial enhancement of its load-carrying capacity [15].

Furthermore, numerous studies have been conducted to evaluate the impact of small-sized particulate additives on the lubricating characteristics of oils. Researchers have explored the effects of various proportions of metal oxide nanoparticles, including CuO, Fe_2O_3, NiO, and Al_2O_3, added to lubricating oil, as well as the influence of temperature on oil viscosity. These studies provide valuable insights for developing suitable lubricants that can maintain stable working conditions and contribute to the extension of equipment life. In 2018, Harshkumar Patel et al. conducted a study on the influence of CuO, Fe_2O_3, and NiO nanoparticles, as well as temperature, on the oil's viscosity. The experiments encompassed different ratios of nanometal oxides and temperatures ranging from 27 to 71 °C, with oil viscosities of 77 and 350 Pa·s. The results demonstrated that these factors influenced the viscosity of the oil mixture, resulting in a reduction of 50–70% depending on the ratio of nanometal oxide used [16]. Harshkumar Patel suggested that the viscosity of the heavy oil mixture could decrease by 20–93% depending on the ratio of the emulsion solution blended into the lubricating oil [17]. In a study by Yousef Hamedi Shokrlu et al. in 2014, the authors demonstrated that the decrease in viscosity depends on the density and size of metal particles [18].

According to Yudong Shen et al., SiO_2 nanoparticles can exhibit a micro-bearing effect as rolling elements at the friction interface, leading to friction reduction [19]. Yashvir Singh et al. have developed an eco-friendly oil with improved lubricity by adding SiO_2 nanoparticles to epoxidized Madhuca indica oil [20]. This addition resulted in improved thermo-physical properties and tribological performance, including a reduction in the coefficient of friction and wear rate up to a concentration of 0.8 wt% nanoparticles. Wu et al. conducted a study to investigate the utilization of hard-shelled soft-core composite nanoparticles as a novel additive in grease [21]. Incorporating 1 wt% of these nanoparticles led to a notable decrease in the coefficient of friction and wear scar diameter, creating a composite lubricating film with solid-liquid phases and enhancing the tribological characteristics of conventional greases.

S. Arumugam et al. conducted a comparative study on the tribological properties of chemically modified rapeseed oil using two different anti-wear nano additives, namely TiO_2 and Al_2O_3 [22]. By employing a pin-on-disc tribometer, S. Arumugam et al. observed that the chemically modified rapeseed oil containing spherical TiO_2 nanoparticles displayed a smoother worn pin surface and a lower friction coefficient in comparison to the oil with fibrous nano Al_2O_3 wire. T.F. Ionescu et al. conducted a study to investigate the effectiveness of adding ZnO to rapeseed oil at various concentrations using a four-ball machine. [23]. They observed that adding 1 wt% ZnO did not improve the friction coefficient but reduced the wear rate compared to neat rapeseed oil. The researchers formulated a novel lubricant by incorporating a dispersant (2-methoxyphenol) at a 1:1 ratio to the additive. They then examined the tribological performance of the lubricant based on the obtained results.

Seyedreza Razavi and colleagues conducted a study to assess the influence of calcium carbonate ($CaCO_3$) and silica (SiO_2) nanoparticles on the physical, tribological, and rheological properties of lithium-based grease [24]. The research conducted by Seyedreza Razavi and colleagues demonstrated that the incorporation of calcium carbonate ($CaCO_3$) and silica (SiO_2) nanoparticles into lithium-based grease resulted in enhanced physical, tribological, and rheological properties compared to lithium-based grease. The authors determined that the optimal concentration of calcium carbonate in the lithium-based grease was found to be 1 wt%. At this concentration, the grease exhibited reduced friction and wear, improved resistance to water washing, increased thermal stability, and enhanced tribological behavior.

In a study, Totka Bakalova et al. utilized either TiO_2 or SiO_2 nanoparticles in a cooling lubricant emulsion to address several tribological challenges. The inclusion of these nanoparticles resulted in a significant reduction in the friction coefficient, minimizing wear on the cutting tool, and reducing the variance of measured values, resulting in increased durability during the machining process [25]. The addition of SiO_2 and TiO_2 nanoparticles also resulted in reduced wear without any signs of chipping, cracking, or peeling of the coating. In another study, CuO and TiO_2 nanoparticles were incorporated into a metal-working polymeric lubricant, leading to an overall improvement in tribological properties. The addition of 0.01 wt% TiO_2 and 0.05 wt% CuO demonstrated the highest anti-wear properties with improvements of 77% and 33%, respectively, indicating the potential of nano lubricants for enhancing mechanical component efficiency [26]. Akl et al. examined the tribological properties of CuO nanoparticles in lubricating oil using a pin-on-disc friction and wear tester. The experimental results demonstrated a remarkable reduction of 60.83% in wear rate and 33.1% in friction coefficient compared to the base oil when the concentration of CuO nanoparticles was 0.75 wt%. These findings indicate the potential of CuO nanoparticles as an effective additive in lubricating oils to enhance their tribological performance and reduce friction and wear in various mechanical systems [27].

Other studies have also demonstrated that the presence of metal oxide nanoparticles leads to a decrease in viscosity, as these oxides naturally enter the lubrication area as a result of corrosion. These studies have further explored the impact of nano additives on specific lubricating properties of various industrial oils [28–33]. The results of these investigations suggest that the incorporation of metal oxide additives can enhance the lubricating characteristics of the oil and extend the durability of machine components. However, the impact of these additives on the load-carrying capacity of the oil has not been thoroughly explored. Hence, exploring the load-carrying capability of oil blends containing fly-ash additives may provide a potential solution to modify viscosity or stabilize the operational conditions of machine parts. This is particularly significant when assessing the lubrication effectiveness of heavy-duty machinery operating in demanding industrial environments.

Fly ash consists of superfine spherical particles composed of silica oxide and other metal oxides, with particle sizes ranging from nano to micro. These nanoparticles are derived from the dust generated in thermal power plants, which is a byproduct of coal combustion in furnaces. To enhance the load-carrying capacity of industrial lubricating oil, a proposal has been made to incorporate a modifying additive sourced from fly ash obtained from thermal power plants. The fly ash additive will be incorporated into the lubricating oil mixture at a concentration of approximately 0.5–1%, leading to the formulation of an industrial lubricant blend enriched with nano/microelements. The optimal dosage of the additive will be carefully examined and optimized to enhance the viscosity, thermal conductivity, and durability of the lubricating oil mixture. Furthermore, this approach aims to reduce emissions of oil residue, contribute to sustainable development, and mitigate the environmental impact associated with oil refining and lubricant waste. In this study, three types of lubricating oils were examined and evaluated for various lubricating properties under different temperature conditions. Additionally, fly-ash additives at a concentration of 0.5% were introduced into these oils to assess the impact of additives on the lubricating characteristics of the oil-additive mixture. Based on these findings, careful consideration and selection of the most suitable oil and additive were made according to the predetermined operating conditions to enhance the oil's viscosity or thermal stability.

2. Materials and Methods

2.1. Experimental Oils

To ensure confidentiality and maintain the reputation of commercial industrial oils, the selected oils for the experiments are referred to as types A, B, and C. The experimental approach involved a comparison of the viscosity of these oils with and without the inclusion of a 0.5% fly-ash additive.

The main technical characteristics of these oils are provided in Table 1. This naming convention allows for the accurate representation of the oils' properties without disclosing specific brand names or proprietary information.

Table 1. Key specifications of experimental oils A, B, and C.

Specification	Test Method	Unit	Oil A	Oil B	Oil C
Specific gravity at 15 °C	ASTM D4052	g/mL	0.852	0.868	0.890
Kinematic viscosity at 100 °C	ASTM D445	mm^2/s	11.9	14.6	18.1
Kinematic viscosity at 40 °C	ASTM D445	mm^2/s	65	126	165
Viscosity index	ASTM D2270	-	183	117	120
Pour point	ASTM D97	°C	−45	-	−24
Cleveland flash point	ASTM D92	°C	234	205	226
Sulfated Ash	ASTM D874	%	1.2	0.88	0.9

In low-temperature environments, lubricating oil tends to thicken, causing challenges in starting machinery due to direct frictional contact without proper lubrication. To address this issue, researchers have incorporated special additive compounds into lubricating oils to reduce their viscosity's dependence on ambient temperature, resulting in the development of multi-grade oils. These multi-grade oils enable engines to start efficiently in low temperatures while ensuring adequate lubrication. It is important to note that the starting process is a relatively short stage in the overall operation of the engine.

During the stable operating stage of the engine, typically between temperatures of 40 °C and 100 °C, the viscosity of the multi-grade oil exhibits a linear relationship with temperature. This linear relationship allows for the determination of the viscosity-temperature relationship of multi-grade oil as a first-order relationship. By understanding and characterizing this relationship, engineers and technicians can effectively optimize lubricant performance across different temperature ranges, ensuring proper lubrication and minimizing friction-related issues during engine operation [34].

2.2. Fly-Ash Additive

Fly ash, derived from thermal power plants, contains metal oxide particles such as SiO_2, Al_2O_3, K_2O, and Fe_2O_3, among others. These particles exhibit a spherical structure with a micrometer-sized particle size. Leveraging the spherical shape and micrometer size of fly ash, it can be employed as an inert additive to enhance the properties of lubricant oil mixtures. By incorporating fly ash as a friction modifier, it is possible to increase viscosity, improve thermal conductivity, extend the service life of lubricant oil mixtures, and mitigate the deposition of sludge in machinery.

In this study, fly ash was chosen as an additive at a concentration of 0.5% in three distinct types of industrial oils, resulting in a mixture of oxide particles and oil. The appropriate concentration of the additive was investigated to optimize viscosity, thermal conductivity, and the service life of lubricant oil mixtures while simultaneously reducing the emission of oil sludge. This research contributes to the pursuit of green development and environmental protection by mitigating the adverse impacts of oil refining and minimizing the generation of lubricant waste.

The fly ash used in the experiments was sourced from a thermal power plant and comprised the main components outlined in Table 2. These components, including SiO_2, Al_2O_3, K_2O, and Fe_2O_3, play a crucial role in determining the efficacy of fly ash as an additive in improving the performance of lubricant oil mixtures.

Table 2. Components of fly-ash additive.

Component	Percentage	Particle Size
SiO_2	57.02%	50 nm–1 µm
Al_2O_3	23.82%	
K_2O	6.56%	
Fe_2O_3	4.69%	

2.3. Rotary Viscometer

To evaluate the viscosity changes of the oil-additive mixture, these fluids were blended and labeled for testing on a rotational viscometer. The operational principle of the rotational viscometer is depicted in Figure 1. For each fluid type, the shear stress values were determined at different rotational speeds. Based on the relationship between shear stress and shear rate obtained from experimental data, an analysis and evaluation were conducted to determine the viscosity of the fluid.

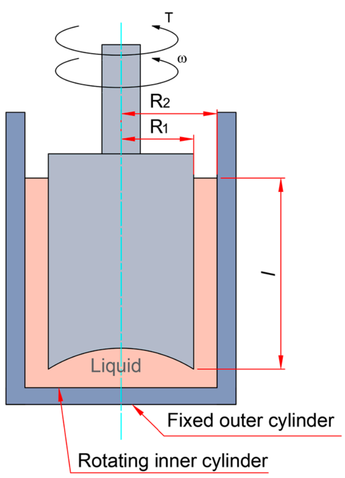


Figure 1. Principle operation of a Rotary Viscometer.

As we know, for Newtonian fluids, the relationship between shear stress and shear rate is approximately linear, and the viscosity of the fluid corresponds to the slope of this characteristic curve. In this study, the relationship between shear stress and shear rate at each experimental temperature was examined to assess the influence of operating conditions on the lubricating properties of the oil.

To ensure stable temperature conditions during the experiments, the measuring head was placed in a temperature-controlled device and maintained at a consistent temperature using a water thermostat. Three types of oils were selected for this study, with the addition of a 0.5% fly-ash additive, and experiments were conducted at different temperatures, namely 25 °C, 40 °C, 65 °C, 75 °C, and 85 °C, to evaluate the effects of temperature and the additive on the oil's viscosity.

The dynamic viscosity of oil was carried out by a rotary viscometer which is described in Figure 1. This rheometer will measure the shear strength of lubricated oil, then the dynamic viscosity of the oil is calculated by the following equations:

$$D_r = \omega \frac{R_1}{R_1 - R_2} \left(\mathrm{s}^{-1}\right) \tag{1}$$

where D_r is the shearing deformation speed; ω is the spindle speed (rpm); R_1 is the radius of measurement spindle; and R_2 is the radius of measurement cup.

The rotary viscometer used in this study is a rheometer (Rheotest RV2 with spindle is S/S_1, which has R_1/R_2 = 0.98).

Then shear stress of oil is calculated by the equation:

$$\tau = Z.\alpha \; \left(\mathrm{N/m^2}\right) \tag{2}$$

where τ is the shearing stress; Z is the measurement equipment index; α is the difference of angle between the measurement spindle and measurement cup (reading from measurement equipment).

Finally, the dynamic viscosity of the oil is calculated by the equation:

$$\eta = \frac{\tau}{D_r} \left(\mathrm{Ns/m^2}\right) \tag{3}$$

where η is dynamic viscosity.

The liquid sample needs to be thoroughly mixed using an ultrasonic sonication bath to eliminate any trapped air bubbles. After that, the liquid is poured into a cup and placed onto the viscosity measuring instrument. The instrument's parameters are adjusted accordingly to meet the experimental requirements. The device is then started, and the measurements are recorded for further analysis and evaluation. Additionally, the use of a temperature control device, such as a water bath, is crucial to maintain a stable temperature throughout the testing process, ensuring accurate and reliable measurements.

3. Results and Discussion

As mentioned in the previous section, experiments were conducted with three types of oils under two conditions: with and without the additive. These experiments were performed at temperatures ranging from 25 °C to 85 °C using the Rhotest VR2 viscometer with appropriately selected parameters to simulate real-world operating conditions for these oils. The measured shear stress values for the different oils and oil-additive mixtures at various rotational speeds are listed in Tables 3–5, corresponding to industrial oils A, B, and C, respectively. Both cases with the additive (at 0.5% concentration) and without the additive were tested and recorded comprehensively.

It can be observed that for each type of industrial oil, the shear stress varies with the corresponding shear rate. The changes in shear stress with temperature can be explained by variations in the viscosity characteristics of the oils. As the temperature increases, the molecular motion within the oil accelerates, leading to a decrease in viscosity and changes in load-carrying capacity. Consequently, the shear stress decreases at higher temperatures. However, these changes differ at each experimental temperature, especially with noticeable differences between the cases with and without the additive. When the additive is introduced, the shear stress increases correspondingly, particularly at any given temperature where the shear stress in the additive-containing case is higher than the case without the additive. The presence of the fly-ash additive can impact the structure and properties of the oil, altering its viscosity and load-carrying capacity.

Table 3. Share stress of oil A with temperature (N/m^2).

Shear Rate (s^{-1})	**0% Fly-Ash Additive**					**0.5% Fly-Ash Additive**				
	25 °C	**40 °C**	**65 °C**	**75 °C**	**85 °C**	**25 °C**	**40 °C**	**65 °C**	**75 °C**	**85 °C**
47.10	567	-	-	-	-	-	-	-	-	-
70.65	2268	-	-	-	-	1134	-	-	-	-
78.50	3402	567	567	-	-	2835	567	-	-	-
117.75	8505	3969	1701	567	567	7371	3969	2268	1134	567
141.30	11,907	6237	2835	1701	1701	10,206	5670	4536	2835	2268
211.95	17,010	11,907	10,773	5103	5103	16,443	10,206	8505	7371	5103
235.50	22,113	14,742	12,474	8505	7371	21,546	14,175	11,907	10,773	9072
353.25	27,216	23,247	16,443	13,041	11,340	31,752	22,113	17,010	15,309	11,907
423.90	34,587	30,051	23,247	18,711	17,577	38,556	31,185	27,216	23,247	20,412
635.85	47,061	37,989	29,484	22,680	20,412	51,597	44,793	33,453	27,783	23,247
706.50	-	44,793	34,587	28,917	22,680	-	-	40,257	35,721	28,917
1271.70	-	-	53,865	44,226	37,989	-	-	-	54,999	50,463

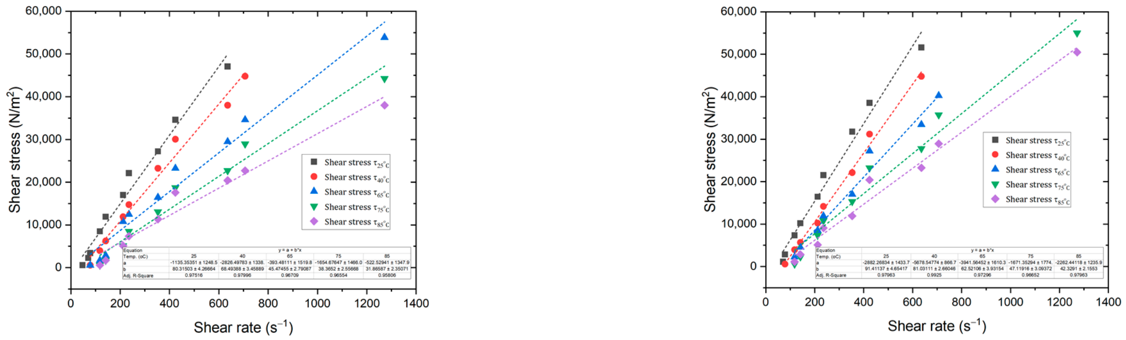
Table 4. Share stress of oil B with temperature (N/m^2).

Shear Rate (s^{-1})	**0% Fly-Ash Additive**					**0.5% Fly-Ash Additive**				
	25 °C	**40 °C**	**65 °C**	**75 °C**	**85 °C**	**25 °C**	**40 °C**	**65 °C**	**75 °C**	**85 °C**
26.17	3402	-	-	-	-					
39.25	6237	-	-	-	-	5103	567	-	-	-
47.10	9072	1701	1134	-	-	7938	3402	-	-	-
70.65	15,876	5670	4536	3402	2835	15,876	6804	4536	3402	2835
78.50	18,711	9639	7938	6237	5103	18,711	9072	5670	4536	3969
117.75	23,247	14,175	11,907	10,773	8505	22,680	16,443	11,340	8505	7938
141.30	27,216	22,680	17,010	14,175	11,907	27,216	22,680	16,443	12,474	11,340
211.95	33,453	27,783	22,113	19,845	15,309	34,020	28,350	22,680	19,845	15,309
235.50	37,989	32,319	23,814	22,680	17,577	39,690	32,886	27,783	23,247	20,412
353.25	50,463	43,659	32,886	29,484	22,680	54,432	44,226	34,020	30,051	26,082
423.90	-	51,597	39,123	34,020	27,216	-	-	44,226	35,721	30,618
635.85	-	-	-	43,659	34,587	-	-	-	45,927	37,989
706.50						-	-	-	-	43,092

For Newtonian fluids, the relationship between shear stress and shear rate is linear. From the experimental results, empirical regression equations can be determined by linearizing these relationships. The results of the shear stress-shear rate relationship for oils A, B, and C at different temperatures are shown in Figures 2–4, respectively. In these figures, both cases without the additive and with the 0.5% additive are depicted in detail. It can be observed that these linear curves have different slopes, which characterize the viscosity of the corresponding fluids. As known, the viscosity of a fluid is the tangent of the slope of these linear curves. Thus, as the temperature increases, this slope decreases. This phenomenon holds true for both cases with and without the additive. Additionally, the empirical regression equations have R-Square values greater than 0.95, ensuring the reliability of the empirical regression equations.

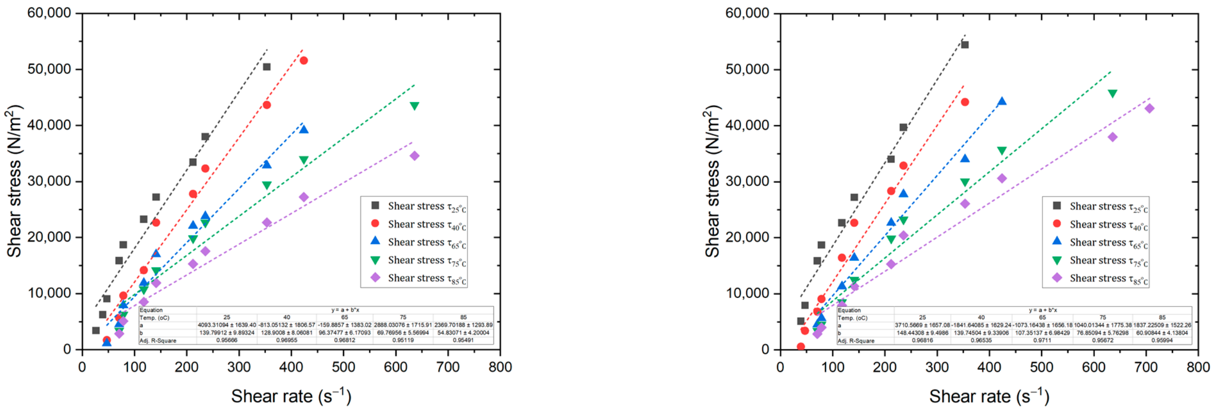
Table 5. Share stress of oil C with temperature (N/m^2).

Shear Rate (s^{-1})	0% Fly-Ash Additive					0.5% Fly-Ash Additive				
	25 °C	40 °C	65 °C	75 °C	85 °C	25 °C	40 °C	65 °C	75 °C	85 °C
23.55	6237	-	-	-	-	1701	1134	-	-	-
26.17	8505	2835	-	-	-	2268	1701	1134	1134	-
39.25	11,340	5103	2268	1701	1134	6237	5670	3402	2268	-
47.10	15,309	9072	4536	3402	2835	9639	6804	6237	5103	4536
70.65	18,711	11,907	9639	6237	4536	15,876	14,742	10,773	9639	8505
78.50	22,113	17,577	12,474	10,206	5670	19,278	17,010	14,742	13,608	11,907
117.75	25,515	22,113	17,577	14,175	9639	23,814	22,113	18,711	17,577	15,876
141.30	33,453	25,515	21,546	17,577	13,041	29,484	28,350	23,814	22,113	19,278
211.95	41,391	34,587	28,917	22,680	16,443	39,690	36,855	32,886	27,216	23,247
235.50	-	39,690	33,453	26,649	19,845	45,360	40,257	35,154	31,185	26,082
353.25	-	-	43,659	36,288	25,515	-	-	48,195	39,690	31,752
423.90	-	-	-	39,690	31,752	-	-	-	45,360	38,556
635.85	-	-	-	-	39,690	-	-	-	-	52,731



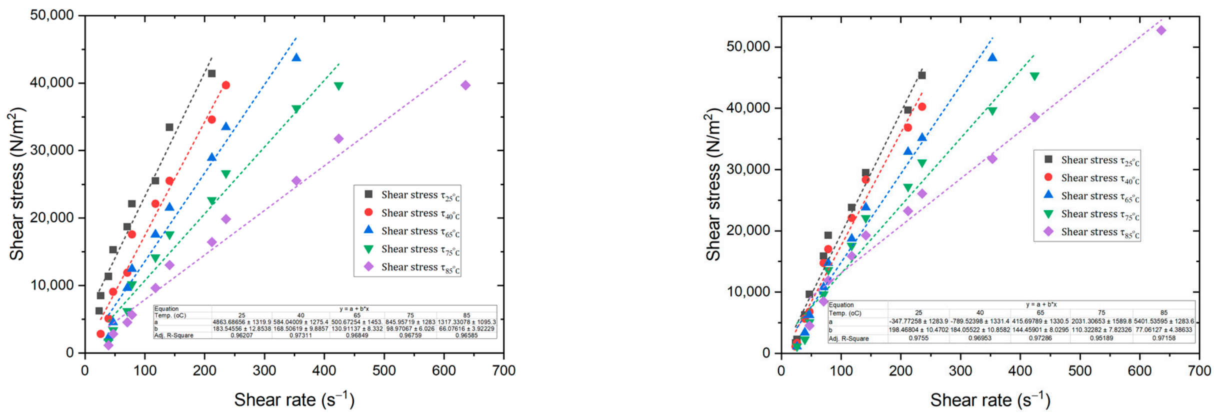
(**a**) (**b**)

Figure 2. Shear stress with different temperature of oil A. (**a**) 0% fly-ash additive. (**b**) 0.5% fly-ash additive.



(**a**) (**b**)

Figure 3. Shear pressure with different temperature of oil B. (**a**) 0% fly-ash additive. (**b**) 0.5% fly-ash additive.



(**a**) (**b**)

Figure 4. Shear pressure with different temperature of oil C. (**a**) 0% fly-ash additive. (**b**) 0.5% fly-ash additive.

Furthermore, it can be understood that as the temperature rises, the oil or additive molecules increase their motion, resulting in a decrease in the viscosity of the fluid. The viscosity values of the oils in both cases, with and without the additive and at different experimental temperatures, are listed in Table 6. To observe and evaluate more visually, these results are presented in Figure 5, depicting the relationship between the viscosity of the tested oils A, B, and C at various temperatures. From these results, we can have a visual understanding of the influence of temperature ranges on the viscosity of the oils. Accordingly, within the temperature range from 25 °C to 65 °C, the viscosity of the oil decreases with a lower magnitude compared to the range from 65 °C to 85 °C. This is reflected in the slopes of the graphs in Figure 5. In the case of the additive at a concentration of 0.5%, the trend of viscosity reduction with temperature occurs similarly to the case without the additive. However, for oil A, the magnitude of viscosity reduction within this temperature range is smaller, as indicated by a smaller slope. This could be attributed to the fact that oil A initially has the lowest viscosity among the three oils, and the additive enhances the effectiveness of viscosity reduction more in oils with higher initial viscosities. An appropriate amount of additive helps enhance the lubricating properties of the base oil. In this case, the additive has reduced the impact of temperature on the viscosity of the oil. The additive consists of high-hardness metal oxide particles that act as better thermal conductors than base oil.

Table 6. Viscosity vs. temperature (mPa.s).

Oils	0% Fly-Ash Additive					0.5% Fly-Ash Additive				
	25 °C	40 °C	65 °C	75 °C	85 °C	25 °C	40 °C	65 °C	75 °C	85 °C
A	80.315 ± 4.266	68.494 ± 3.459	45.475 ± 2.791	38.365 ± 2.557	31.866 ± 2.351	91.411 ± 4.654	81.031 ± 2.660	62.521 ± 3.931	47.119 ± 3.094	42.329 ± 2.155
B	139.799 ± 9.893	128.901 ± 8.061	96.375 ± 6.171	69.769 ± 5.569	54.831 ± 4.200	148.443 ± 9.498	139.745 ± 9.339	107.351 ± 6.984	76.851 ± 5.763	60.908 ± 4.138
C	183.545 ± 12.854	168.506 ± 9.886	130.911 ± 8.332	98.970 ± 6.026	66.076 ± 3.922	198.468 ± 10.470	184.055 ± 10.858	144.45901 ± 8.029	110.323 ± 7.823	77.061 ± 4.386

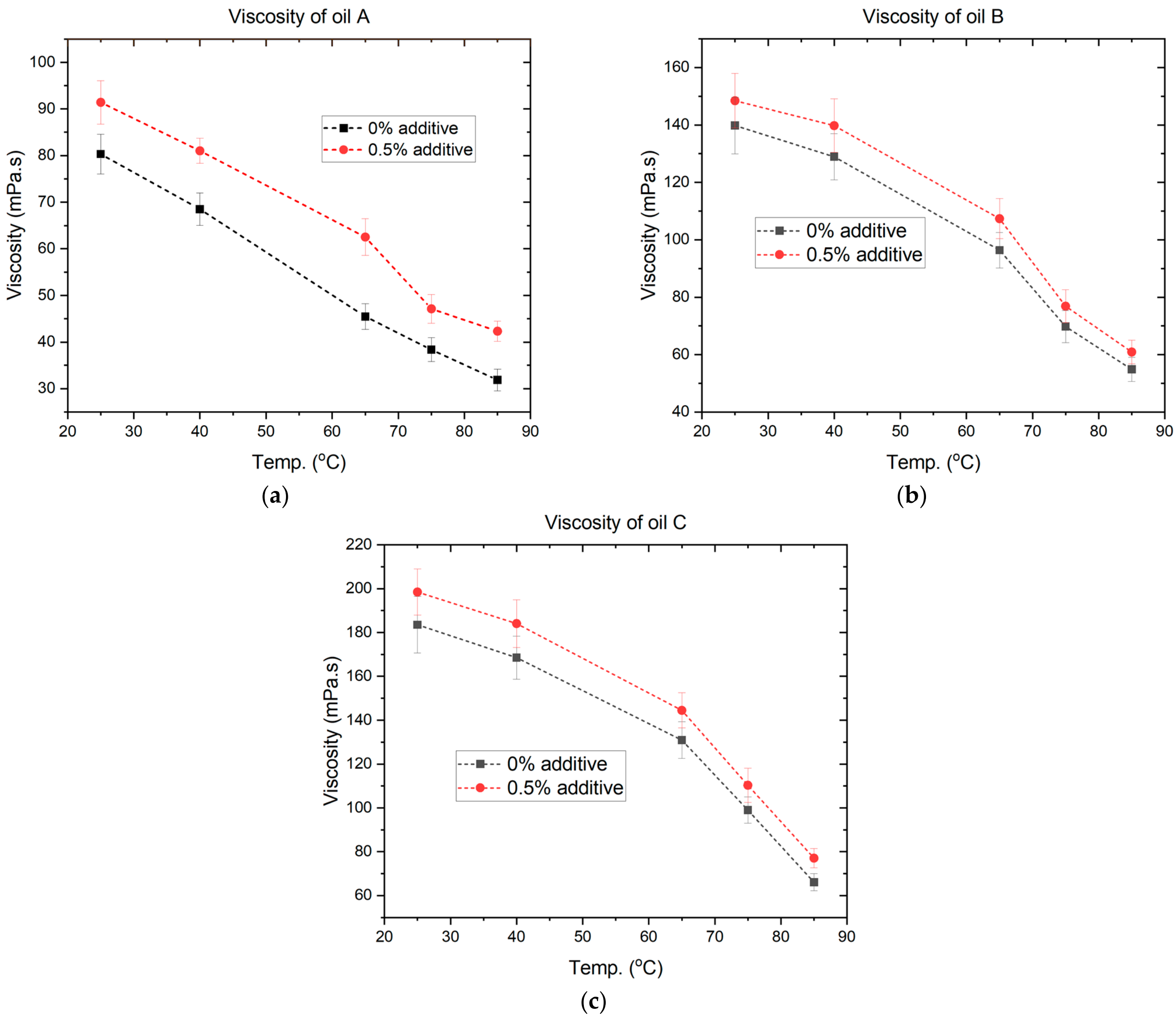


Figure 5. Viscosity of oils with and without additive at different temperatures: (**a**) for oil A; (**b**) for oil B; (**c**) for oil C.

Figure 5a illustrates that the viscosity of oil A decreases from 80.315 mPa.s to 31.866 mPa.s as the temperature changes from 25 °C to 85 °C, whereas without the additive, the viscosity changes from 91.411 mPa.s to 42.329 mPa.s when the temperature increases from 25 °C to 85 °C. Thus, at 25 °C, the viscosity increased by 13.8% with the addition of the 0.5% additive. In contrast, at 85 °C, this value increased by 32.8% compared to the case without the additive. It can be observed that the additive played an important role in increasing the viscosity of the oil by enhancing the load-carrying capacity of the lubricating oil. Particularly, under high-temperature working conditions, the additive helps reduce the influence of temperature on viscosity reduction, contributing to maintaining more stable working conditions compared to the case without the additive.

Similarly, for oil B, the viscosity-temperature relationship in both cases with and without the additive is depicted in Figure 5b. The viscosity changes from 139.799 mPa.s to 54.831 mPa.s corresponding to a temperature increase from 25 °C to 85 °C. With 0.5% additive, these values change from 148.443 mPa.s to 60.908 mPa.s as the temperature changes from 25 °C to 85 °C. Thus, in the case of the additive, the viscosity increases by 6.2% and 11.1% at 25 °C and 85 °C, respectively. For oil C, this result is shown in Figure 5c, where the viscosity of the oil increases by 8.1% and 16.6% at 25 °C and 85 °C, respectively.

From these results, it can be seen that the fly-ash additive added to the base oil at a 0.5% weight ratio plays an important role in reducing the influence of temperature on viscosity. Moreover, the additive is particularly effective with oil A, increasing the viscosity by 32.8% at 85 °C. This can be understood as the base oil of oil A having the lowest viscosity among the tested oils. Therefore, when adding an appropriate amount of additive, the lubricating properties of the oil are significantly improved compared to the case without the additive. However, the optimal amount of additive is still under research. In this study, the focus was only on testing with a 0.5% additive ratio. This will serve as a basis for further research to find the most suitable additive ratio, ensuring better lubricating properties than the base oil.

Indeed, for oil A, the viscosity increased from 38.365 mPa.s to 47.119 mPa.s, which is approximately a 22.8% increase compared to the case without the additive. In contrast, at this temperature, the viscosity of oil B increased by 10.2% with the additive. In the case of oil C, the viscosity also increased by approximately 11.5% compared to the case of using the base oil. From these results, it can be observed that the additive improves viscosity when operating at 75 °C, with oil A showing the most significant improvement, followed by oil C and oil B. At different temperatures (40 °C and 65 °C), the influence of the additive on the viscosity reduction follows a similar pattern as the results analyzed above. This overall view of the viscosity reduction's dependence on temperature in the presence of the additive at these temperatures can be observed in Table 6 and Figure 5. Therefore, based on the analyzed results, it can be inferred that if the base oil has a higher viscosity, the impact of the additive on enhancing viscosity under different temperature conditions is not as effective as in oils with lower viscosity. The presence of the metal oxide additive can be interpreted as forming a material layer that transforms sliding friction into rolling friction on the surface of the friction pairs. It acts as a medium that enhances the heat dissipation process, thereby reducing the influence of temperature on viscosity.

Thus, this study focused on investigating the effects of an additive, specifically fly ash, on the viscosity and load-carrying capacity of three industrial oils (A, B, and C) at different temperatures. The experiments were conducted using a viscometer under realistic operating conditions, and shear stress measurements were recorded for both the oils with and without the additive.

The results demonstrated that the shear stress varied with the shear rate for each type of oil, and the changes in shear stress were attributed to variations in the viscosity characteristics of the oils. As the temperature increased, the viscosity decreased due to increased molecular motion within the oil, leading to a decrease in shear stress. However, these changes differed at each experimental temperature, especially when comparing the cases with and without the additive. The introduction of the fly-ash additive resulted in an increase in shear stress, particularly at higher temperatures. The presence of the additive impacted the structure and properties of the oil, altering its viscosity and load-carrying capacity.

Empirical regression equations were derived from the experimental data to characterize the shear stress-shear rate relationship for the different oils at various temperatures. The viscosity values were calculated from these equations, and it was observed that as the temperature increased, the viscosity of the oils decreased. The additive also influenced the viscosity-temperature relationship, with a smaller magnitude of viscosity reduction for oil A compared to the other oils. The additive enhanced the lubricating properties of the base oil by reducing the impact of temperature on viscosity, as the additive particles acted as better thermal conductors.

Therefore, this study provided valuable insights into the effects of temperature and the fly-ash additive on the viscosity and load-carrying capacity of industrial oils. The findings highlight the potential benefits of using such additives to improve the performance of lubricating oils under varying operating conditions, particularly at higher temperatures. Further research can focus on exploring the long-term effects and optimizing the concentration of additives for different types of oils.

4. Conclusions

The research and experimentation conducted have shown that both fly-ash additives and temperature have a significant impact on the viscosity of lubricating oils. Fly-ash additives are utilized to enhance oxidation resistance and prevent deposit formation in the oil, effectively reducing viscosity loss at high temperatures. Temperature also plays a crucial role in regulating oil viscosity, as increased temperatures tend to decrease viscosity, affecting lubrication capability and friction resistance. This can result in increased wear and damage to machine components. However, with the appropriate application of fly-ash additives, it is possible to adjust oil viscosity at different temperatures and maintain good lubricating performance.

Experimental results demonstrated that at a temperature of 25 °C, the addition of a 0.5% fly ash additive led to viscosity increases of 6.2%, 8.1%, and 13.8% for oils B, C, and A, respectively, compared to the case without the additive. Similarly, at 75 °C, the viscosity increments were 10.2%, 11.5%, and 22.8% for oils B, C, and A, respectively, while at 85 °C, the corresponding increments were 11.1%, 16.6%, and 32.8%. These findings indicate that fly-ash additives effectively mitigate the impact of temperature on oil viscosity, with the highest efficacy observed in oil A.

In summary, the combination of fly-ash additives and temperature control is crucial for maintaining stable viscosity in lubricating oils. These additives minimize viscosity loss, thereby improving equipment performance and longevity. Understanding the influences of fly-ash additives and temperature is essential for optimizing lubricant performance in various temperature conditions and selecting the appropriate additive ratios for specific applications. Continued research and implementation of this technology will significantly contribute to the advancement of lubrication science and industrial applications.

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