

Article

Influence of Glyceryl Monostearate Adsorption on the Lubrication Behavior of a Slider Bearing

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Abstract: Glyceryl monostearate (GMS) was used as an organic friction modifier (OFM) and added to the base oil (PAO10, poly α -olefin) in this study. The film thickness and friction coefficient of the base oil added with GMS (PAO10G) under different slider inclinations and loads were investigated experimentally by using a slider-on-disc contact lubricant film measurement system, and the effect of the adsorption of GMS on the friction behavior of lubricant was studied. Contact angle hysteresis (CAH) was used to evaluate the wettability of the solid–liquid interface, and its correlation with the coefficient of friction was analyzed. The results show that CAH is in good agreement with the wettability of the solid–liquid interface. Compared with the base oil, the wettability of POA10G is weak, which can effectively reduce the coefficient of friction. However, different from the classical lubrication theory, the film thickness of PAO10G is higher than that of PAO10; this unusual phenomenon is preliminarily explained by the interface slippage in this paper.

Keywords: slider-on-disc contact; organic friction modifier; glyceryl monostearate; wettability; film thickness; coefficient of friction; contact angle hysteresis; interfacial slip

1. Introduction

Lubrication technology can effectively reduce friction and wear; the mechanism is that the lubricating medium forms a lubricating film between the two contact surfaces, so the two moving surfaces can be separated by a film with lubricating properties [1]. Adding a friction modifier to the lubricant can improve the lubrication state of the friction surface and achieve the effect of anti-wear and anti-friction. There are two types of friction modifiers: organic friction modifiers (OFMs) and organomolybdenum compounds [2]. Due to the environmental protection properties of OFMs such as no sulfur and no ash, more and more attention has been paid to them [3], so it is of great significance to design more effective OFMs. OFMs generally refer to long-chain surfactants that contain polar groups (such as carboxylic acids, alcohols, esters, amines, amides, and their derivatives). The relevant research dates back to 1915 when Weels and Southcombe [4] discovered that the dissolved trace amounts of fatty acids in mineral oils can improve their lubrication properties. Langmuir [5] found that the monomolecular film of fatty acids deposited on the glass could significantly reduce the friction coefficient. Hardy and Doubleday [6] showed in 1922 that the friction produced by fatty acids and alcohols on glass and steel surfaces gradually decreased as their chain length increased. Many studies have proved that the chain length and functional group of friction modifiers were the key parameters affecting their anti-friction properties [7–10]. Based on these studies, the generally accepted film-forming principle of OFMs was formed: OFMs adsorbed on the friction metal surface to form a single molecular layer, whose shear strength mainly comes from the weak Van der Waals interaction between opposite hydrocarbon chains at the interface. These monolayers are sufficient to limit metal–metal adhesion and prevent direct metal–metal contact, thereby reducing friction [8,11,12]. Many scholars have proved through research



Citation: Xu, Q.; Jing, Z.; Du, S.; Guo, F.; Mu, R. Influence of Glyceryl Monostearate Adsorption on the Lubrication Behavior of a Slider Bearing. *Lubricants* **2024**, *12*, 67. <https://doi.org/10.3390/lubricants12030067>

Received: 17 December 2023

Revised: 15 February 2024

Accepted: 21 February 2024

Published: 23 February 2024



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that glyceryl monostearate (GMS) as an additive has the function of anti-friction and anti-wear. Sánchez et al. [13] experimentally studied the tribological properties of different types of vegetable oil oleogels and found that oleogels with GMS added had better anti-friction function. Campen et al. [14] used glycerol monooleate (GMO) and GMS and their corresponding fatty acids as OFMs and they were added into hexadecane with the same mass fraction. The change in COF with velocity was studied, and the friction generated by GMS was found to be relatively low; the mechanism is that GMS is adsorbed from the solution by the contact surface and forms an ordered close-packed monolayer. Ji et al. [15] used GMS as an additive in water-based mud; the tribological properties were measured by a ball-disk configuration, and the experimental results show that GMS can effectively adsorb on the surface of steel and improve the lubricity of the mud. Nunes et al. [16] found that monoglycerides with longer carbon chain lengths showed better tribological properties performance via further adsorption on metal surfaces. Sönmez et al. [17] verified through experiments that adding light oil and GMS to the mud can obtain higher lubrication properties. Ouyang et al. [18] used GMS as an OFM; the frictional properties of GMS under high pair contact were studied, and it was found that GMS had good properties of anti-friction and anti-wear.

The wettability of lubricant film is an important factor affecting the thickness and friction. To quantify the strength of the solid–liquid interface, different interface parameters have been proposed by researchers, and the correlation between interface parameters and wettability has been discussed theoretically and verified experimentally. Hild et al. [19] found that the viscous force of the hydrophobic surface was significantly lower than that of the hydrophilic surface. Choo et al. [20] found that hydrophobic surfaces with large contact angles can reduce the friction coefficient of solid–liquid surfaces. Joseph and Tabeling [21] proved experimentally that there is no direct relationship between the contact angle (CA) and hydrodynamic lubrication behavior. Yaminsky [22] proposed the concept of contact angle hysteresis (CAH) as a parameter to characterize the solid–liquid interface. Kalin and Polajnar [23] proposed a spread coefficient to describe wettability and proved that the spread coefficient can describe the wettability of lubricant between DLC coating and steel slider better than the contact angle. Guo [24] used CA, CAH, and spread coefficient to characterize the wettability of the interface and compared the experimental results with the above three characterization parameters; it was found that CAH can reflect wettability better. In addition, the slippage between the lubricant and the friction pair can also reduce friction [25]. Pit et al. [26,27] tested the flow velocity of liquid near a solid wall by using TIR-FRAP experimental technology and proved that Newtonian fluid can slip on the wall. Many scholars have carried out studies on the influencing factors of wall slip; Zhu and Granick [28,29] proved that slippage will occur when the shear stress exceeds the yield limit. Many scholars use interface slippage to explain the changes in film thickness and friction during lubrication. Guo et al. [30] proved through experiments that interface slippage caused by weak wettability can lead to a decrease in film thickness. Spikes [31,32] proposed that interface slippage would greatly reduce friction, and thus proposed the “half-wetted bearing” theory.

In the field of tribology, studies on OFMs mainly focus on the state of boundary lubrication. In recent years, scholars have begun to pay attention to the effect of solid–liquid interface slippage on full-film lubrication. Polajnar and Kalin [33] prepared DLC coatings with different surface energies, and the result of the experiment showed that the friction of the EHL contact pair formed on the surface with low surface energy was significantly reduced. The experiment of Björling and Shi [34] also showed similar results to Polajnar. Kalin and Kus [9] used OFM as an additive, which proved to reduce the friction of EHL.

It is better to maintain a certain film thickness of the oil in the lubrication process under normal circumstances. If the film thickness is too thin, the surface of the friction pair will come into contact and cannot be protected effectively, and the friction will increase rapidly and cause unnecessary energy loss. Both Guo et al. [30] and Choo et al. [35] have shown through experiments that when the interface slips, the friction on the surface of

the friction pair decreases, as well as the film thickness. It will be of great significance to reduce the friction and at the same time ensure a high film thickness in the state of full-film lubrication. In this paper, the lubrication characteristics of oil in full-film state were studied by using GMS as an OFM, and the effect of GMS adsorption on tribological properties was investigated.

2. Experiment

2.1. Experimental Apparatus

An optical slider-bearing test rig is used to measure the thickness and friction of the slider-on-disc contact in this experiment, which includes a film thickness measuring unit and a friction measuring unit. The principle of the film thickness measuring unit is shown in Figure 1. The friction pairs consist of a stationary steel slider with a fixed inclination angle and a rotating K9 glass disk. When the glass disk rotates at a certain speed, the lubricant is driven into the convergence gap, and an oil film of a certain thickness is formed between the steel slider and the glass disk because of the dynamic pressure effect. The film thickness can be measured based on the method of multi-beam interference [36].

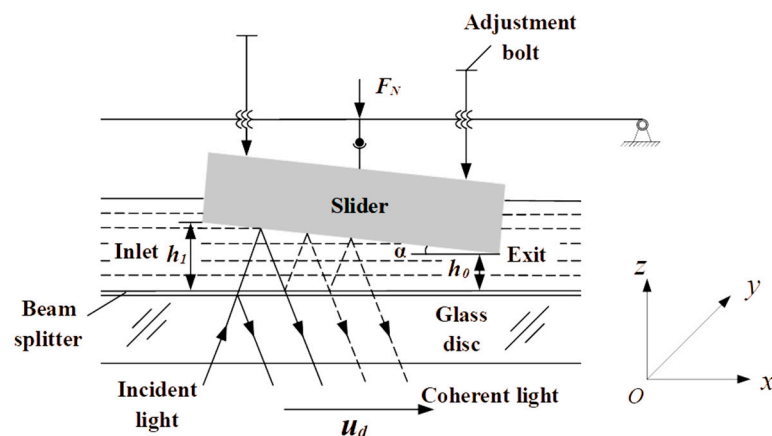


Figure 1. Schematic illustration of the test rig for measuring oil film thickness.

The principle of the friction measuring unit is shown in Figure 2. One loading plate is fixed on the table surface, and the other is used to fix the slider. The two loading plates are connected through the sensor. When the glass disc rotates, the shear force of the oil film in the convergence gap is transmitted to the slider, which causes the deformation of the bridge strain gauge of the sensor, resulting in the change in output voltage, which is converted into friction force through the relationship between voltage and force value.

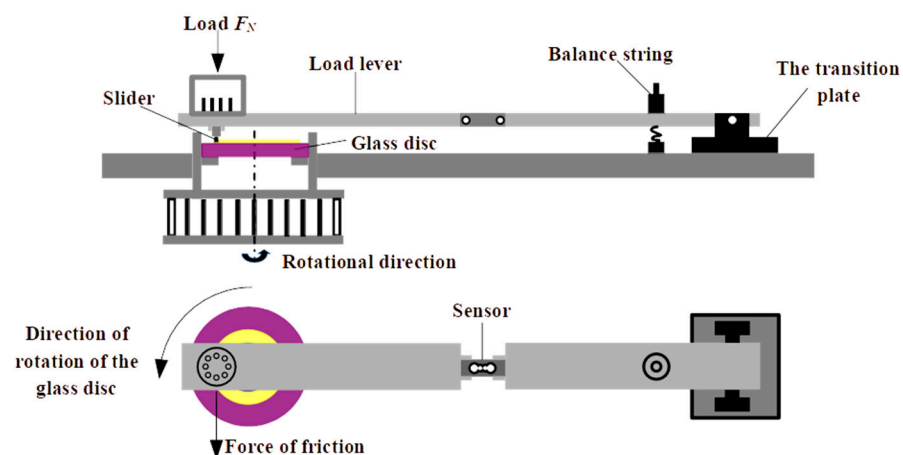


Figure 2. Schematic illustration of the test rig for measuring coefficient of friction.

2.2. Test Samples Lubricants

A K9 glass plate coated with chromium film and silicon dioxide film ($\text{Gr} + \text{SiO}_2$) is used in the experiment, and the surface roughness, R_a , is approximately 4 nm. The reflectance of the chromium film is about 20% to obtain a high-contrast image. The material of the slider used in the experiment is bearing steel GCr15, with a sliding plane size of 4 mm $\times$ 4 mm ($B \times L$), and its roughness R_a is 10 nm.

The base oil used in the experiment is polyalphaolefin synthetic oil (PAO 10), and the OFM is glyceryl monostearate (GMS, Shanghai Aladdin Biochemical Technology Co., Ltd., (Shanghai, China) Concentration: 99%), whose molecular structure formula is $\text{C}_{21}\text{H}_{42}\text{O}_4$, and its molecular weight is 358.56. GMS is a type of monoglyceride. Monoglycerides can be categorized according to the main fatty acid components, such as glyceryl monostearate (GMS), glyceryl monolaurate (GML), and glyceryl monooleate (GMO) [37]. As shown in Figure 3, GMS is a white powder at room temperature, which is mostly used in the food and cosmetics industry and is often used as a surfactant for emulsification, dispersion, defoaming, etc. The GMS molecule has two hydrophilic hydroxyl groups and one long lipophilic carbon chain with a carbon chain length of 18. Three base oils containing 0.05 wt%, 0.1 wt%, and 0.3 wt% GMS (PAO10G) were prepared, and each mixture was heated at 75 °C for 10 h, stirred with multi-head magnetic stirrers for 3 h after being cooled to room temperature, and then stood still at room temperature for a week. The preparation is successful as there is no precipitation.

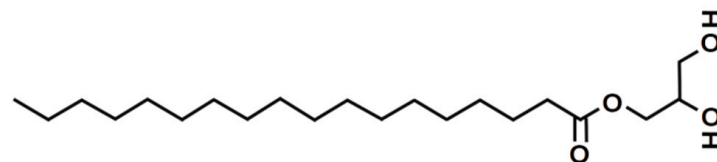


Figure 3. Molecular structures of GMS.

2.3. Characterization of Lubricants

2.3.1. Basic Characteristics of Test Oils

The properties of the four test oils are shown in Table 1. It can be found that there are little differences between the dynamic viscosity and refractive index of the four oils, so it can be confirmed that the addition of GMS has little influence on the properties of base oils.

Table 1. Properties of lubricants used in the tests.

Lubricant	Dynamic Viscosity η /(mPas@22 °C)	Refractive Index n
PAO10	117.3	1.4635
PAO10G _{0.05}	117.4	1.4637
PAO10G _{0.1}	116.9	1.4635
PAO10G _{0.3}	117.1	1.4635

2.3.2. Characterization of GMS Adsorption

To verify the adsorption of GMS on the surface of the contact pair, the contact angle (CA) and contact angle hysteresis (CAH) on the surface of the steel slider were measured as follows:

The cleaned sliders were soaked in four kinds of test oils, and the sample was heated at 75 °C for 30 min to form an adsorbed film on the surface of the sliders. The sliders were washed with n-heptane to remove excess lubricants after cooling to room temperature. Subsequently, the sliders were ultrasonically cleaned in deionized water for 5 min, and then the sliders were blown dry with nitrogen for contact angle experiments.

The suspension drop method was used to test the CA between the surface of the coated sliders and the water. During the measurement, the temperature was controlled at 22 °C $\pm$ 1 °C, humidity was kept at 30% $\pm$ 2%, and the amount of lubricant was 2 μ L. The experiment was repeated five times, and each set of data was measured within 20 min.

The dynamic sessile drop method was adopted, and the volume of droplets used for measurement was 2 μL . Each oil was measured 5 times and averaged to obtain the value of CAH. The CA and CAH are shown in Table 2 and Figure 4.

Table 2. Contact angle and contact angle hysteresis on the surface of steel slider by four lubricants.

Slider	Lubricant	Contact Angle, CA/(°)	Contact Angle Hysteresis, CAH/(°)
Steel	PAO10	55 ± 2.2	26 ± 1.5
Steel	PAO10G _{0.05}	71 ± 2	20.5 ± 1
Steel	PAO10G _{0.1}	77 ± 0.5	18.6 ± 0.5
Steel	PAO10G _{0.3}	77.5 ± 0.2	17.5 ± 0.6

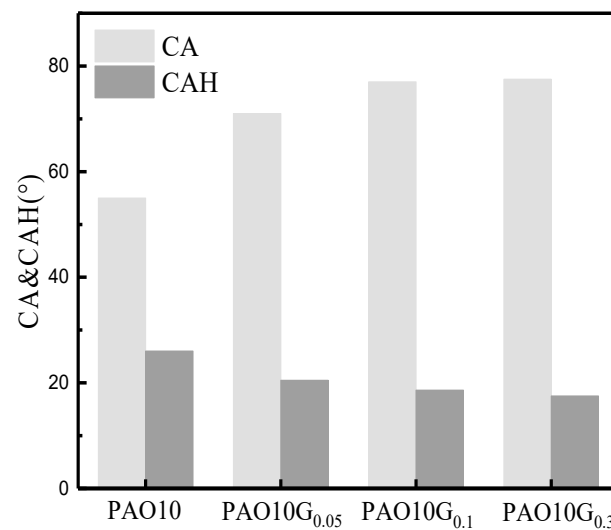


Figure 4. CA and CAH of the surface of the steel slider.

In Table 2, it can be seen that the CA of the steel slider soaked in PAO10G is larger than that of the steel slider soaked in PAO10, indicating that GMS is adsorbed on the surface of the steel slider. The CA of the steel slider soaked with different concentrations of PAO10G is also different, indicating that the concentration of GMS will affect its adsorption on the steel slider. The CA and CAH of PAO10G are higher than those of PAO10, indicating that compared with PAO10, PAO10G has weaker wettability and better hydrophobicity. For PAO10G with different mass concentrations, the CA and CAH are different: while the CA of PAO10G increases with an increase in the mass fraction of GMS, the CAH is just the opposite.

2.4. Characterization of Lubricants

Under the conditions of constant temperature (22 ± 1 °C) and relative humidity (RH30 $\pm$ 2%), the film thickness and friction coefficient of experimental oils were tested. The load was 2 N and 6 N, the velocity changed from 1.69 mm/s to 67.75 mm/s, the slider inclination α was 5.6×10^{-4} rad, and the oil supply was 10 μL . Each experiment was repeated at least 5 times.

3. Results

Figure 5 shows the interference diagram of PAO10G_{0.05} as a lubricant at different speeds. It indicates that the inclination angle of the slider can remain unchanged, and the stripes are relatively parallel under different speeds, which proves that the relative position of the disc and the slider remains stable during the experiment. In this experimental condition, the optical interference fringe is complete and there is no oil starvation in the entrance area, indicating that the experiment is in the state of full-film lubrication.

It can be seen from Figure 6a,c that under the same load, the film thickness of PAO10G has the same change trend as that of PAO10, which gradually increases with an increase in speed. The pressure in the contact area increases with an increase in load at the same speed, resulting in a thinner film thickness, which conforms to the classical theory of lubrication. At the same speed, the film thickness of PAO10G is generally thicker than that of PAO10, indicating that the film-forming capacity of PAO10G is better than that of PAO10. Under the load of 2 N, the film thickness of PAO10G increases by 6.6% on average and 17.8% on average under the load of 6 N. The differences in film thickness under high speed and heavy load are larger compared with low speed and light load. When the load is 6 N and the speed is 67.75 mm/s, the film thickness of PAO10G_{0.1} is 0.38 μm higher than that of PAO10.

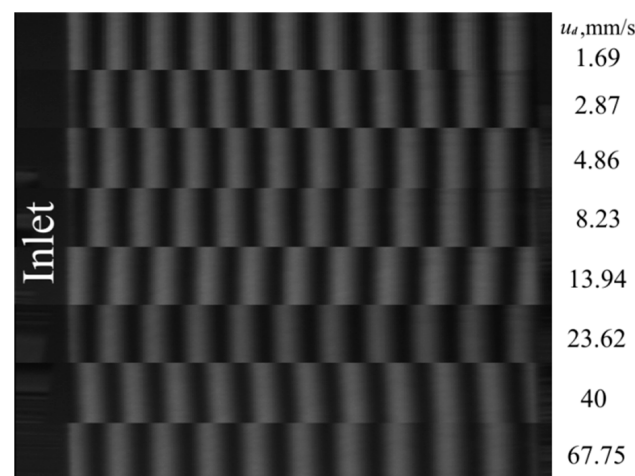


Figure 5. Interference fringes at different disc speeds (PAO10G_{0.05}, $F_N = 2\text{ N}$, $\alpha = 5.6 \times 10^{-4}\text{ rad}$).

It can be seen in Figure 6b,d that under the load of 2 N, the coefficient of friction (COF) of both PAO10 and PAO10G tends to increase with an increase in speed, and the lubricants are in a state of hydrodynamic lubrication. Under the load of 6 N, the COF decreases first and then increases. The friction of the two contact surfaces under the load of 6 N is higher than that under the load of 2 N, but the COF is smaller. The COF of PAO10G is lower than that of PAO10 under the same experimental conditions, which is reduced by 11.8% on average when the load is 2 N, and reduced by 16.5% on average when the load is 6 N. Similar to the film thickness, the anti-friction effect of PAO10G is more obvious under high-speed and heavy load conditions.

It can be analyzed from Tables 1 and 2 that the differences in film thickness and COF between PAO10 and PAO10G under the same working conditions are related to the differences in CA and CAH, which are the relevant indicators of the wettability of oil film. Table 2 shows that the CA of PAO10G with various mass fractions is higher than that of PAO10, and the CAH is lower than that of PAO10. It can be preliminarily judged that the lubricant with larger CA and smaller CAH has better friction performance.

By adjusting the inclination of the sliders to $2.7 \times 10^{-4}\text{ rad}$ and $8.2 \times 10^{-4}\text{ rad}$, the film thickness and COF of different lubricants are shown in Figures 7 and 8, respectively. It can be seen that under different inclinations and loads, the film thickness of PAO10G is higher than that of PAO10, and the relationships between the film thickness, load, and speed are the same as that under the inclination of $5.6 \times 10^{-4}\text{ rad}$ of the lubricants. Under the same experimental condition, the effect of the anti-friction of PAO10G is also better than that of PAO10.

Taking PAO10G_{0.3} as an example, the changes in film thickness and COF with speed under different inclinations are studied, as shown in Figure 9. It can be found that under the three slider inclinations set in the experiment, when the load is the same under the condition of low speed, the film thickness increases with a decrease in the inclination of the slider. The film thickness with a smaller inclination of the slider increases slowly with

an increase in speed, while the film thickness with a larger slider inclination increases faster. With the increase in speed, the film thickness with a larger slider inclination exceeds that of the small slider inclination, showing the opposite phenomenon at low speed. With the increase in load, when the film thickness of the larger slider inclination exceeds the film thickness of the smaller slider inclination, the corresponding velocity node will shift back. Figure 10 shows the relationship between the dimensionless bearing capacity W and $\mu B/h_0$ (COF) and convergence ratio K , respectively, of PAO10G_{0.3} under loads of 2 N and 6 N at different slider inclinations. The film thickness in Figure 9a,b corresponds to the dimensionless bearing capacity in Figure 10a,b. When the dimensionless bearing capacity of the lubricant is stronger, the film thickness is larger. The COF in Figure 9c,d corresponds to the $\mu B/h_0$ in Figure 10c,d.

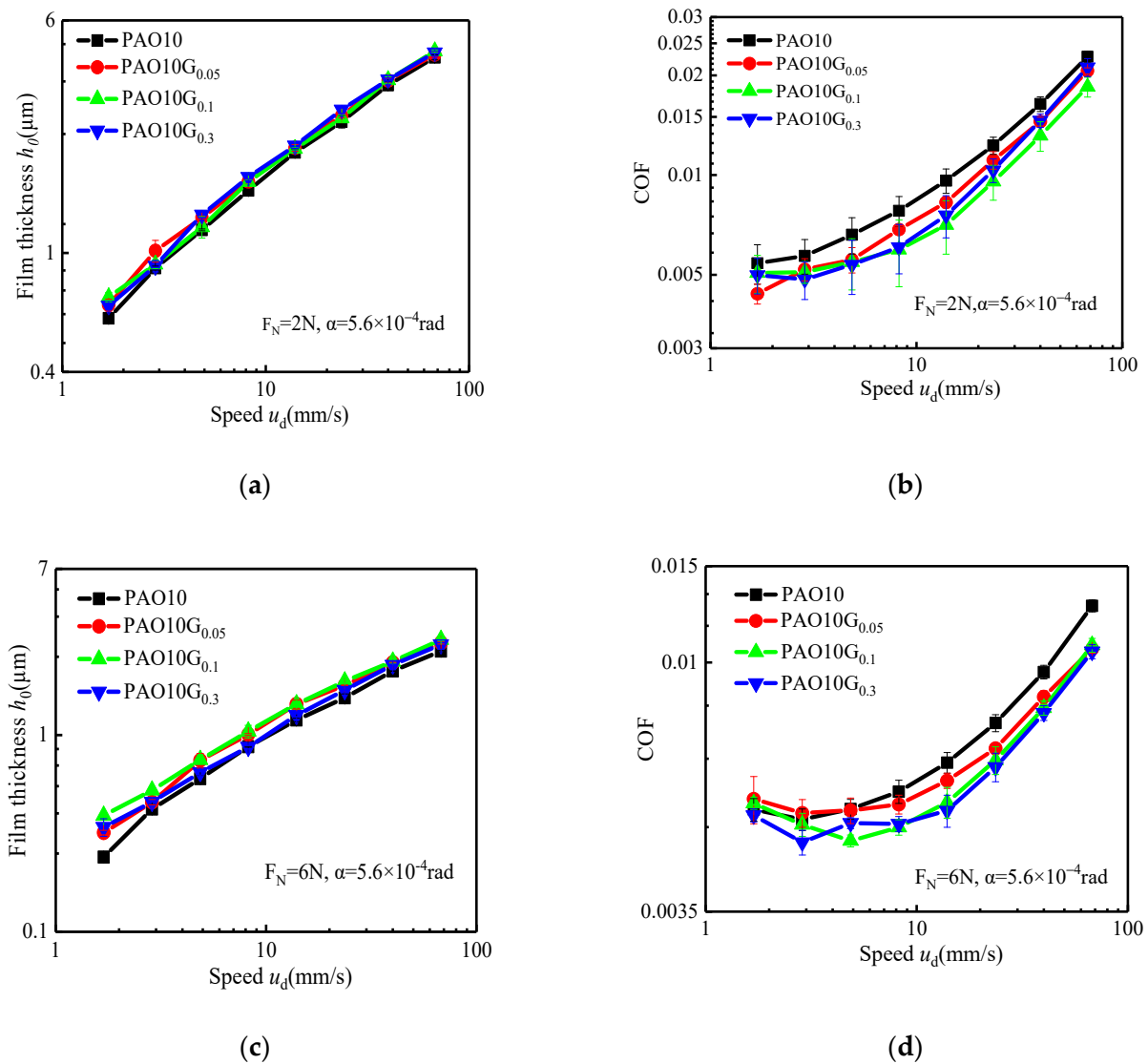


Figure 6. Film thickness and COF of steel sliders using PAO10 and PAO10G under various loads at $\alpha = 5.6 \times 10^{-4}\text{ rad}$. (a) film thickness at $F_N = 2\text{ N}$; (b) COF at $F_N = 2\text{ N}$; (c) film thickness at $F_N = 6\text{ N}$; (d) COF at $F_N = 6\text{ N}$.

The contact surface of the slider is coated with a solution of PAO10G_{0.05}; taking PAO10 as a lubricant, the experiment of film thickness is carried out under the load of 2 N, and other conditions remain unchanged. Figure 11 shows the film thickness comparison at speeds of 4.86 mm/s, 23.62 mm/s, and 40 mm/s using three different combinations of steel slider-PAO10, steel slider coated with PAO10G_{0.05}-PAO10, and steel slider-PAO10G_{0.05}. It

can be found that compared with the untreated slider, the film thickness of the lubricant after GMS plating on the surface of the slider is higher, but the film thickness of the GMS slider-PAO10 is lower than that of the slider-PAO10G. The results fully show that GMS as an OFM has the effect of increasing the film thickness. When the surface of the slider is coated with GMS, according to the generally recognized mechanism of OFMs, GMS is adsorbed on the surface of the friction pair through polar hydroxyl groups, which improves the working environment of the friction pair and increases the film thickness [38]. When PAO10G is used as a lubricant, the GMS in the lubricant can be absorbed on the surface of the steel slider and the surface of the glass plate at the same time, and the effect of adsorption is better than that of the coating GMS on the steel slider alone, so the film thickness of slider-PAO10G is thicker than that of GMS slider-PAO10.

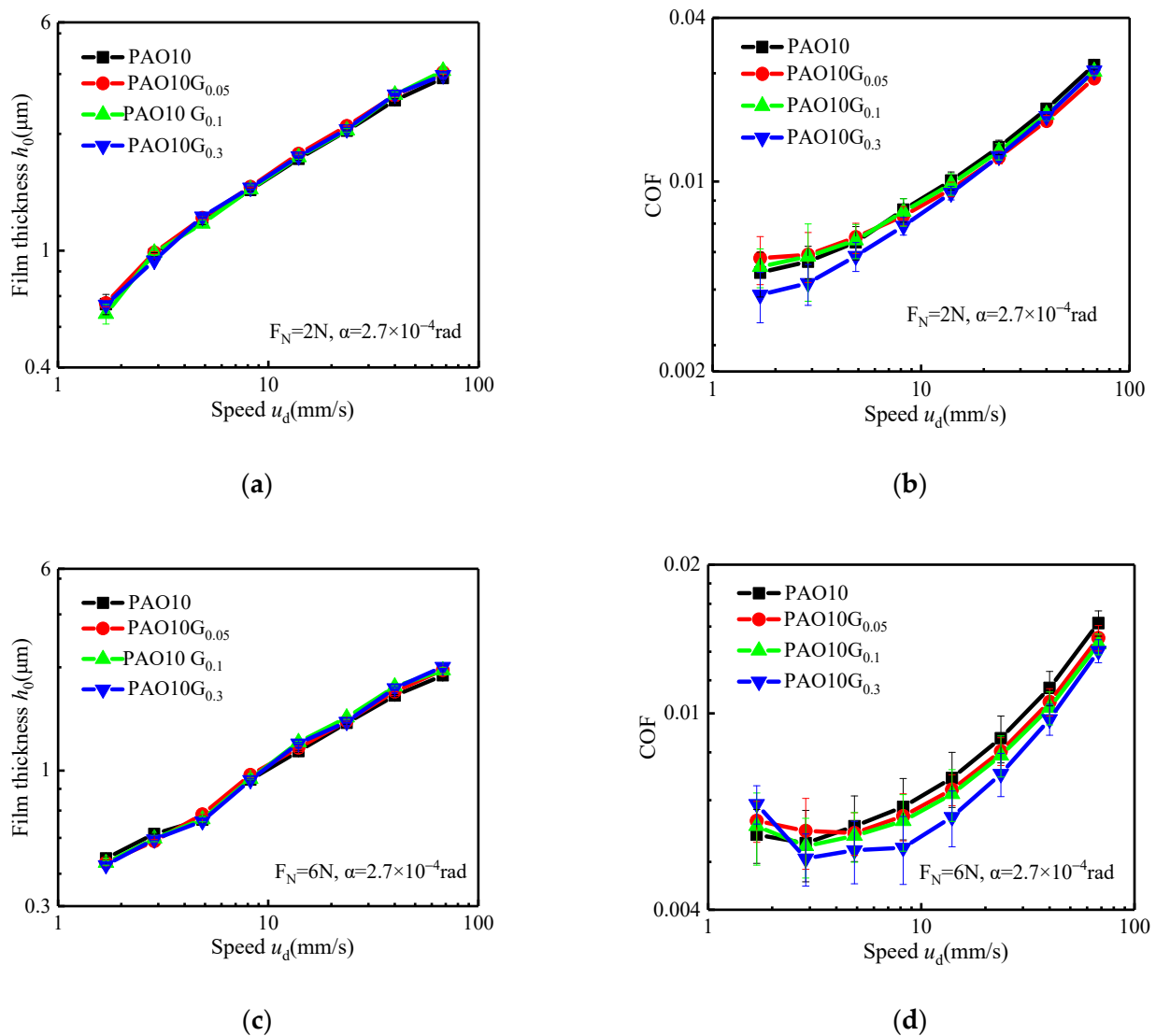
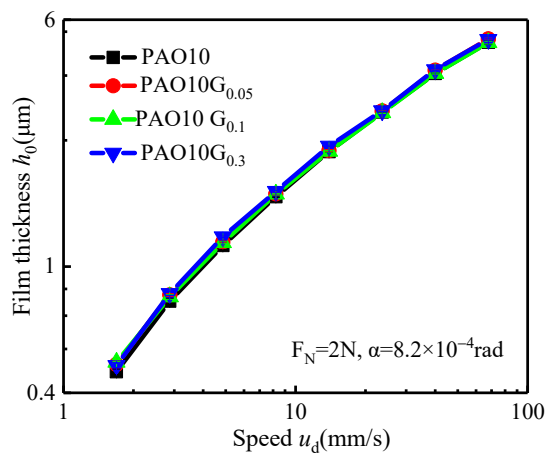
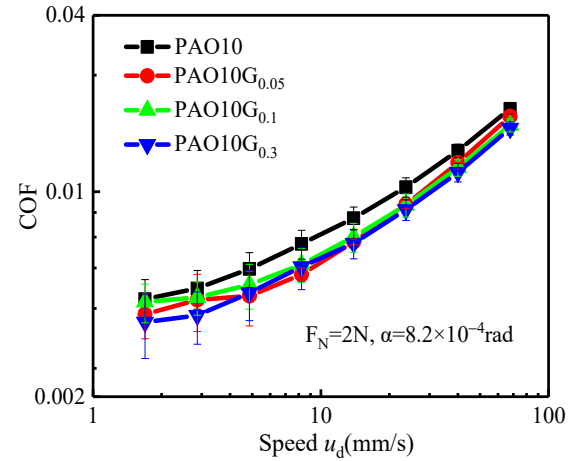


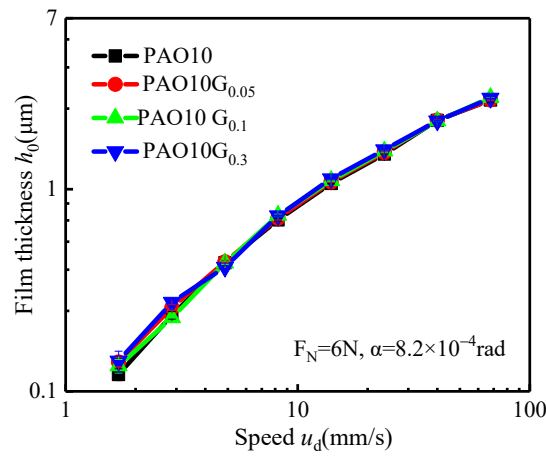
Figure 7. Film thickness and COF of steel sliders using PAO10 and PAO10G under various loads at $\alpha = 2.7 \times 10^{-4}\text{ rad}$. (a) film thickness at $F_N = 2\text{ N}$; (b) COF at $F_N = 2\text{ N}$; (c) film thickness at $F_N = 6\text{ N}$; (d) COF at $F_N = 6\text{ N}$.



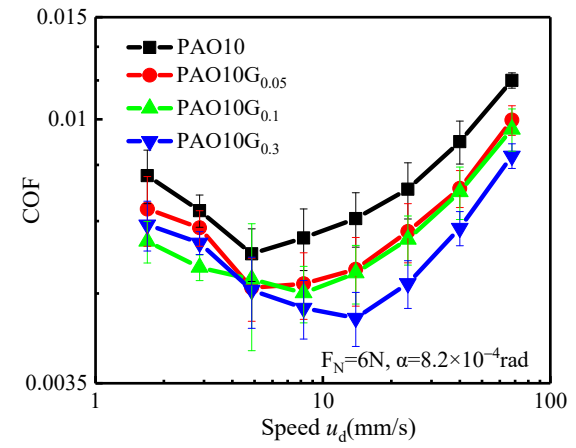
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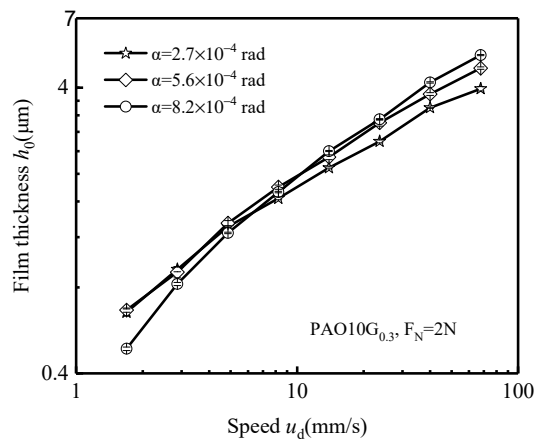


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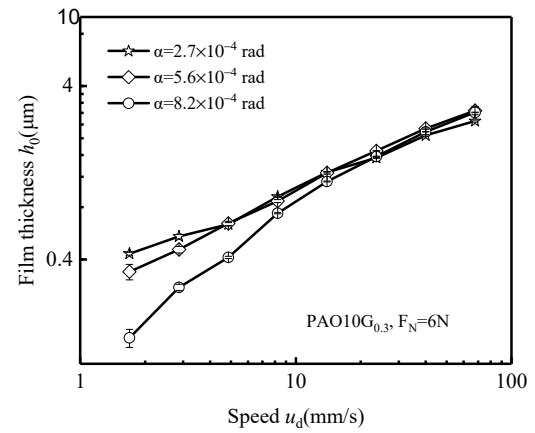


(d)

Figure 8. Film thickness and COF of steel sliders using PAO10 and PAO10G under various loads at $\alpha = 8.2 \times 10^{-4}$ rad. (a) film thickness at $F_N = 2$ N; (b) COF at $F_N = 2$ N; (c) film thickness at $F_N = 6$ N; (d) COF at $F_N = 6$ N.

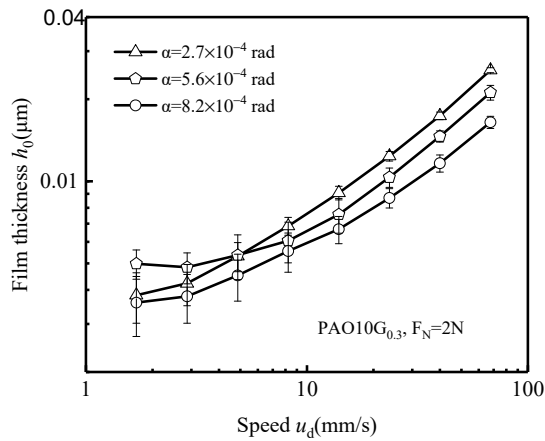


(a)

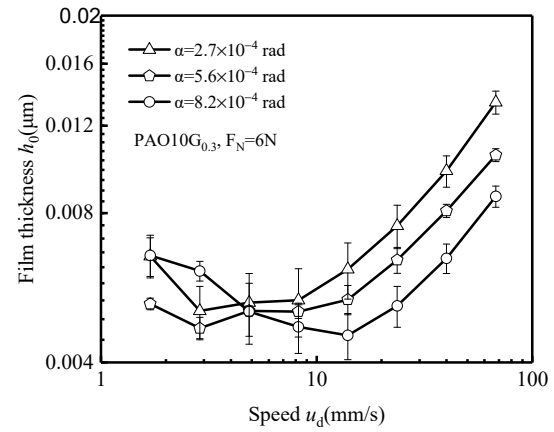


(b)

Figure 9. Cont.

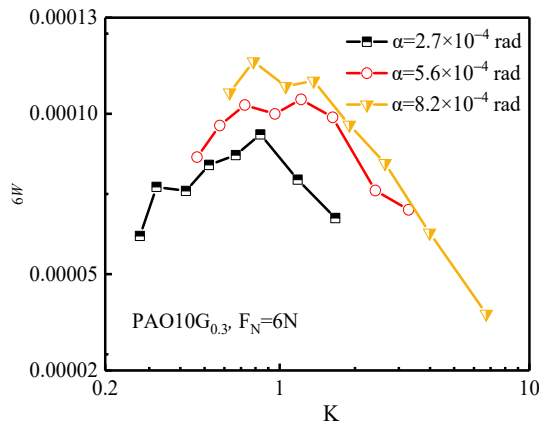


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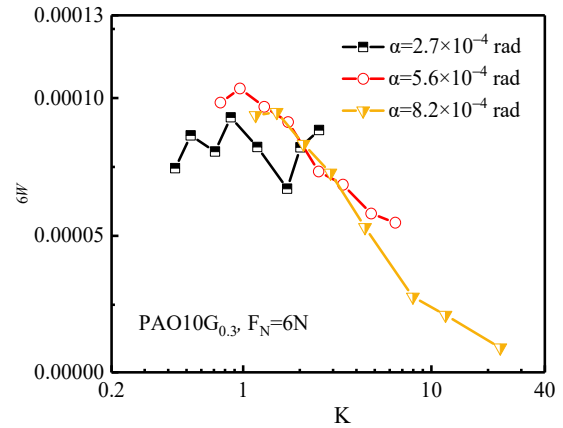


(d)

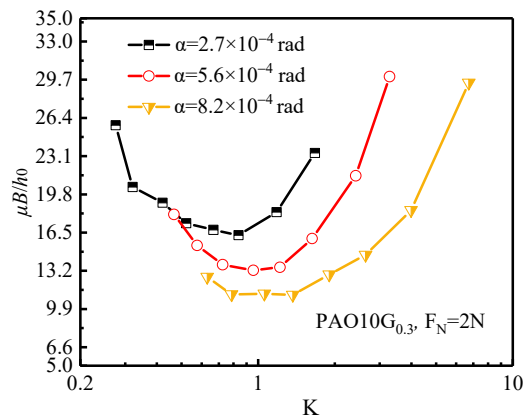
Figure 9. Film thickness and $\mu B/h_0$ (COF) of steel sliders using PAO10G_{0.3} under different slider inclinations. (a) film thickness at $F_N = 2$ N; (b) film thickness at $F_N = 6$ N; (c) $\mu B/h_0$ at $F_N = 2$ N; (d) $\mu B/h_0$ at $F_N = 6$ N.



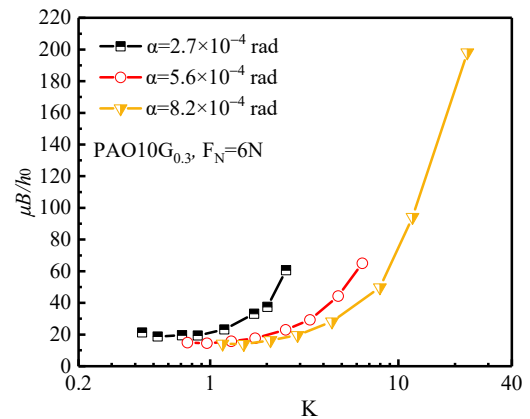
(a)



(b)



(c)



(d)

Figure 10. The dimensionless bearing capacity W and $\mu B/h_0$ of PAO10G_{0.3} under different slider inclinations. (a) the dimensionless bearing capacity at $F_N = 2$ N; (b) the dimensionless bearing capacity at $F_N = 6$ N; (c) $\mu B/h_0$ at $F_N = 2$ N; (d) $\mu B/h_0$ at $F_N = 6$ N.

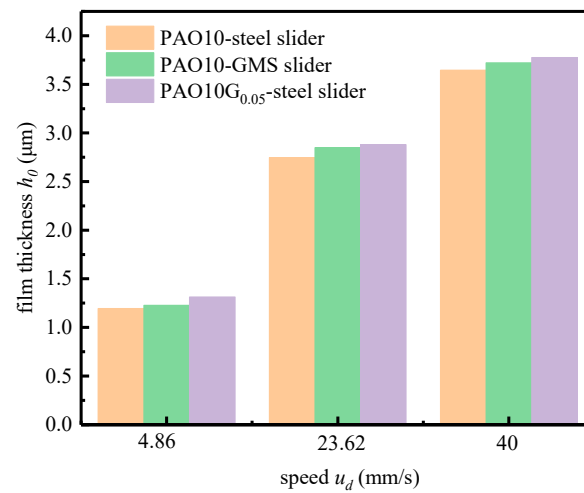


Figure 11. Film thickness versus three speeds with three different combinations of steel sliders and lubricants.

4. Discussion

4.1. Analysis of COF

4.1.1. Trends of COF Variation with Velocity

The interference fringes of all experiments were similar to those in Figure 5, and the interference fringes were straight, indicating no elastic deformation. There was no oil starvation in the experiments, and it was concluded that the experiments involved in this paper were in a state of hydrodynamic lubrication. Figure 12 shows the variation in dimensionless bearing capacity with convergence ratio when the inclination of the slider is 5.6×10^{-4} rad and the load is 6 N. It can be seen that the curve of dimensionless bearing capacity obtained in the experiment accords with the trend of theoretical change, so the experimental data obtained in this experiment can be verified to be correct. However, in the COF change curve shown in Figure 6d, it is found that at a low speed, with an increase in speed, the COF decreases first and then increases, leaving a minimum COF. According to Newton's law of viscosity,

$$\tau = \eta \dot{\gamma} = \eta \frac{du}{dh_0} \quad (1)$$

where τ is the shear stress, η is the dynamic viscosity of the fluid, and $\dot{\gamma}$ is the shear strain rate.

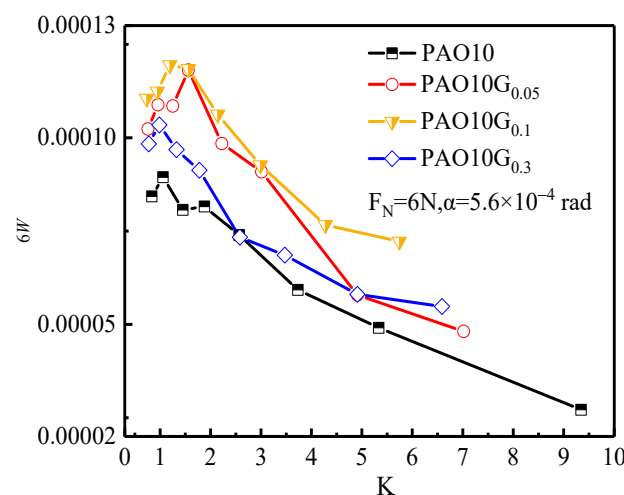


Figure 12. Measurement of dimensionless load-carrying capacity using PAO10 and PAO10G ($\alpha = 5.6 \times 10^{-4}$ rad, $F_N = 2$ N).

Combined with the film thickness in Figure 6c, it can be seen that at a low speed, the film thickness increases rapidly, and its rate of change is higher than that of speed, so the shear strain rate decreases, resulting in lower friction force and lower COF. With the increase in velocity, the increase rate of the film thickness with velocity becomes smaller, which results in an increase in the shear rate and therefore COF, so the COF shows a trend of first decreasing and then increasing. The same is true for the rest of the slider inclination. As shown in Figure 8d, when the slider inclination is 8.2×10^{-4} rad, the lowest point of the COF is more obvious, and the lowest point is more delayed than that under the condition of a smaller slider inclination.

4.1.2. COF of Various Lubricants with the Same Inclination of the Slider

From the previous analysis, it can be seen that the adsorption of GMS causes a change in the lubricant's wettability to the slider, which changes its frictional properties. Hence, the differences in COF in the experiment have a great correlation with the wettability of the surface of the sliders to different lubricants. To measure the wettability of the solid–liquid interface, the interface parameters proposed mainly include CA, CAH, and expansion coefficient [20,22,23]. Guo [24] has confirmed through experiments that the correlation between CAH and wettability is better. Therefore, CAH is used as an interface parameter to analyze the influence of GMS adsorption on COF in this paper.

There is an adhesion between the liquid and the surface of the solid, so there is an energy barrier, and the liquid molecules will not be able to move on the surface of the solid when the energy of the liquid molecules does not reach the energy barrier. At this time, the shear stress at the interface of solid and liquid increases with an increase in the amount of liquid. When liquid molecules gradually accumulate, the liquid molecules have sufficient energy to break the energy barrier; that is, the liquid will move or slide relative to the solid surface when the interface of the solid and liquid reaches the boundary yield stress, which is called the potential energy barrier. The difference in the potential energy barrier between different solid–liquid interfaces corresponds to the difference in the yield stress at the boundary of the solid–liquid interface. Guo [24] confirmed through experiments that there is a monotonic positive correlation between boundary yield stress and potential energy barrier under hydrodynamic lubrication conditions.

The potential energy barrier can be characterized by two parameters: CA and CAH. Whyman [39] deduced the relation between CAH and potential energy barrier E as

$$E = \frac{\gamma R_0}{2^{7/3}} (CAH)^2 f(\theta) \quad (2)$$

$$f(\theta) = \frac{(1 + \cos \theta)^{1/2}}{(1 - \cos \theta)^{1/6} (2 + \cos \theta)^{4/3}} \quad (3)$$

where γ is the surface tension of the liquid (mN/m), R_0 is the initial radius (m) of the spherical droplet formed before the matrix, and the surface tension of PAO10 [40] is 39.28 mN/m.

By substituting the parameters of the four lubricants into the formula, the comparison of the potential energy barrier obtained is shown in Figure 13. It can be seen that the potential energy barrier of PAO10G is lower than that of PAO10, which corresponds to the difference in COF. It shows that the adsorption of GMS reduces the potential energy barrier between the slider and the glass disc, thus reducing the COF between the friction pair. To reflect the influence of the potential energy barrier on the wettability of lubricant more directly, taking two working conditions as $\alpha = 8.2 \times 10^{-4}$ rad, $F_N = 2$ N, and $\alpha = 5.6 \times 10^{-4}$ rad, $F_N = 6$ N, the relationship between the potential energy barrier and COF of the four lubricants when $u_d = 40$ mm/s is shown in Figure 14. There is a good agreement between COF and potential energy barrier, that is, COF has a greater correlation with CAH. The smaller the CAH of the lubricant, the smaller the potential energy barrier to

be crossed, the smaller the boundary yield stress, and the easier it is to slip; and, the COF is also smaller.

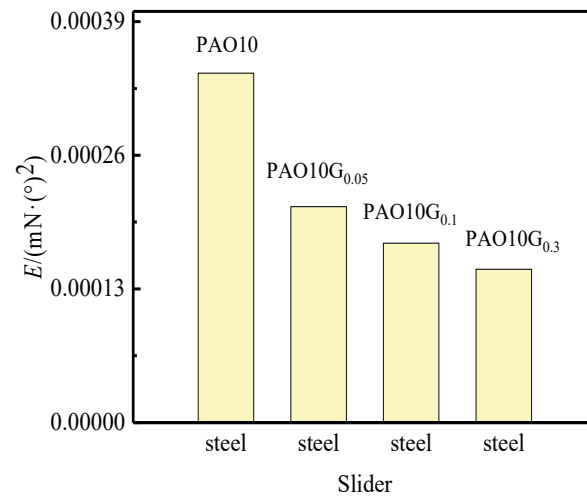


Figure 13. The potential energy barrier of steel slider versus PAO10 and PAO10G.

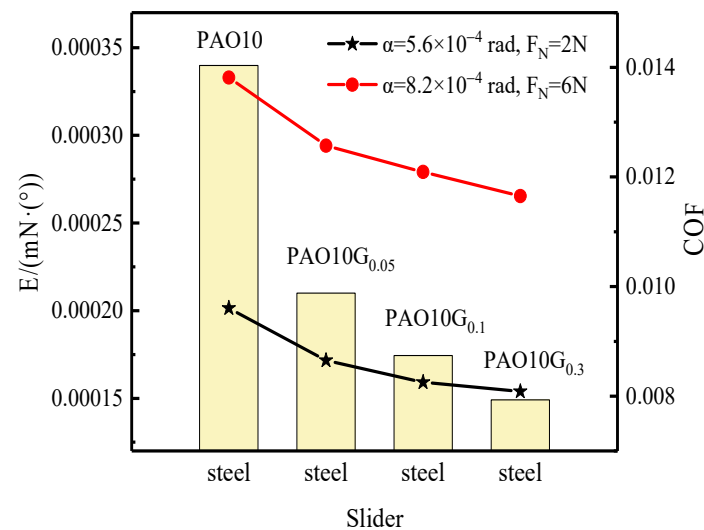


Figure 14. COF changes with the potential energy barrier.

Therefore, at the same slider inclination, the difference in COF in the experiment is due to the adsorption of GMS. The mass fraction of GMS in lubricants is different, resulting in different adsorption amounts of GMS on the surface of the friction pair, which affects the potential energy barrier between the two friction surfaces, and thus affects the COF of the two friction surfaces. Moreover, the mass fraction of GMS is negatively correlated with COF; that is, the more GMS content in the solution, the more GMS will be adsorbed on the friction surfaces, thus reducing the potential energy barrier and reducing COF.

4.1.3. COF of the Same Lubricant with Different Inclinations of the Slider

Li [41] compared the relationship between COF and convergence ratio K at different slider inclinations via experiments. By comparing the relationship between K and film thickness h_0 , it was found that COF increased with an increase in slider inclinations, but as is shown in Figure 9c,d, the COF decreased with an increase in the slider inclinations. The author explained that the reason for this phenomenon is that when the slider inclination increases, the outlet of the contact area of the lubricant is smaller than that of the entrance. In the process of relative sliding between the slider and the glass disc, more GMS molecules accumulate at the entrance [42], more GMS molecules are confined to the contact area

between the slider and the glass disc and cannot leave from the exit area, which increases the concentration of GMS in the local area between the slider and the glass disc, and more GMS molecules are adsorbed on the friction pair in the contact region, further reducing the potential energy barrier, increasing the degree of slip, and reducing the COF. When the lubricants in the contact area partially slip, the COF can also be reduced [43]. It is probable that under different slide inclinations, the degree of slippage and the sliding area of the lubricants in the contact area may be different, resulting in the difference in COF.

4.2. Analysis of Film Thickness

By calculating the potential energy barrier of PAO10 and PAO10G above, it can be concluded that the potential energy barrier of PAO10G is smaller than that of PAO10. Generally speaking, the larger the potential energy barrier, the more difficult it is for the liquid molecules to move on the solid surface, and the liquid molecules continue to accumulate, making the film thickness thicker. Therefore, PAO10 with a larger potential energy barrier should have a thicker film thickness, and the experimental results are exactly the opposite. Under the three slider inclinations, the film thickness of PAO10G is thicker than that of PAO10 regardless of the load. It can be seen from the above that when the interface slips, the film thickness is reduced [30]. It is probable that PAO10G and PAO10 have different degrees of interface slippage that reduce the thickness of the film, which should have been raised. Guo [24] calculated the relation between the boundary yield stress and the film thickness of the slider-on-disc contact under EHL conditions using the scalar method. As shown in Figure 15, it can be seen that there is no single linear relationship between the boundary yield stress and the film thickness of the lubricant. With the increase in the boundary yield stress, the film thickness of the lubricant is unchanged at the beginning and then decreases, and increases gradually after reaching the lowest; finally, it remains unchanged. Zone 1 in Figure 15 corresponds to the state of full slippage, where the film thickness of the lubricant does not change with the change in the boundary yield stress. Zones 2 to 4 correspond to the state of partial slippage, in which the film thickness of the lubricant of zones 2 and 3 is lower than that of the full slippage state. Zone 5 corresponds to the state of no-slippage, in which the film thickness of the lubricant is the highest. It can be speculated that when the boundary yield stress is lower, the film thickness of PAO10G is thicker than that of PAO10 because the degree of slippage of the two lubricants is different, so the slip zones of the two kinds of lubricants are different in Figure 15. PAO10 and PAO10G may be in the indicated zones in Figure 15, but it is necessary to conduct further research to determine which region they are in.

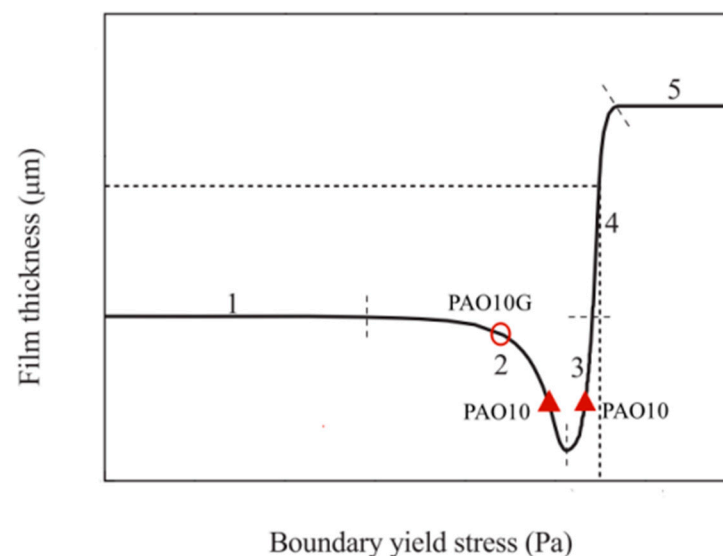


Figure 15. Variation in film thickness with boundary yield stress under certain working conditions.

5. Conclusions

GMS was added to PAO10 as an OFM, and the film thickness and COF of PAO10G were measured using the slider-on-disc contact lubricant film measuring system. The experimental results were analyzed theoretically. The findings are summarized as follows:

1. GMS as an OFM can be effectively adsorbed on the contact surface of the friction pair, improving the lubrication performance of base oil, reducing COF, as well increasing the film thickness.
2. The film thickness and COF of PAO10 and PAO10G under different slider inclinations are compared. The friction performance of PAO10G is better than that of PAO10 under various slider inclinations; under the same working conditions, the film thickness tends to increase with an increase in slider inclinations, while the COF decreases.
3. The relationship between lubricant wettability and potential energy barrier is analyzed. The potential energy barrier and COF have the same variation trend. It is proved that CAH can better characterize lubricant wettability.
4. The reason why the COF of PAO10G decreases while the film thickness increases under full-film lubrication is analyzed, and it is speculated that interface slippage may have occurred.

Author Contributions: Conceptualization, F.G. and Q.X.; methodology, Q.X. and F.G.; validation, Q.X., F.G. and Z.J.; formal analysis, Q.X. and Z.J.; investigation, Q.X., F.G. and S.D.; resources, Q.X.; data curation, Q.X. and Z.J.; writing—original draft preparation, Q.X.; writing—review and editing, F.G.; visualization, F.G.; supervision, F.G. and R.M.; project administration, F.G.; funding acquisition, F.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52175173.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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