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Research article

Lubricant Droplets Can Bounce on Wetted Cylinders

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A B S T R A C T

In this work, the droplet bounce phenomenon of polyalphaolefin, olive oil, silicone oil, and paraffin oil on wetted cylinders was reported. With a uniform oil film with a thickness of 0.06 mm formed on the cylinder, typical categories of spread, maximum, retract, deposit, and bounce existed. The ratio of the maximum spreading diameter and the initial diameter was negatively corrected with the viscosity due to the viscous resistance. The effect of tangential velocity from 0 m/s to 0.75 m/s on the spreading was investigated, which shows a strong promotion for it. The force analysis explained the mechanism of bouncing caused by the compressed air film, and oil droplets would bounce if the support force was larger than the combined force of gravity and inertia force. The findings in the work provide a basic understanding of droplets impact on wetted and rotating surfaces and design concepts for applications in modern industry.

1. INTRODUCTION

Lubricant droplets impacting surfaces is a common phenomenon in nature where droplets show a series of behaviors such as spread, maximum, retract, deposit, and bounce [1, 2]. Generally, the micro-nano structure and low surface energy of superoleophobic surfaces can make oil droplets bounce easily, and it has wide applications because of the simple manufacturing [3,4]. Differing from superoleophobic surfaces, oil droplets can also bounce on wetted surfaces with the support of the compressed air film between oil droplets and the liquid film according to the lubrication theory [5,6]. This relatively natural bounce condition is very common in the industry, especially in the application of oil mist lubrication, where the dynamics of oil droplets on transmission shafts have had a significant influence on lubrication and heat transfer efficiency [7]. However, there are many factors to be considered to manipulate the bounce of oil droplets, not only wettability. For example, the shape of wetted surfaces will change the symmetry of droplets bouncing [8], and increasing the viscosity of droplets will inhibit their bouncing behavior [9]. At present, most of the experimental objects in the literature are water, or the liquid film is static and flat [10,11], whose application scenario has certain limitations.

For the sake of close to real working conditions, that is, lubricating oil droplets impact wetted and rotating cylinders, polyalphaolefin (PAO4), olive oil, silicone oil, and paraffin oil were selected for bounce experiments. Similar bouncing behaviors of four lubricant droplets illustrated that this phenomenon exists widely in lubricants with different physical properties, and the spreading difference caused by viscosity, density, surface tension, and tangential velocity was explored. The findings in the work provide a basic understanding of droplets impact on wetted cylinders and design concepts for applications in modern industry.

2. MATERIALS AND METHODS

All impact experiments were conducted at the ambient temperature of 25 °C and humidity of 40 %. The cylinder with a radius of curvature R_ρ=5 mm was made of 304 stainless steel with a surface roughness *Sa*=0.3 µm, and roughness surfaces were produced via grinding processes. By continuously dripping oil droplets and rotating the cylinder with tangential velocity V_t=0.25 m/s to form a uniform oil film with a thickness of h=0.06 mm, and switching the type of oil film according to the type of oil droplets to maintain the same. The diameter D_0 and impact velocity V of oil droplets were controlled by the diameter and initial height of the syringe, respectively. All the impacting process was recorded via a high-speed camera (i-SPEED 726R, iX Cameras, UK), and the whole apparatus is shown in Fig. 1. The viscosity μ, surface tension γ, and density ρ of four lubricants are shown in Fig. 2.

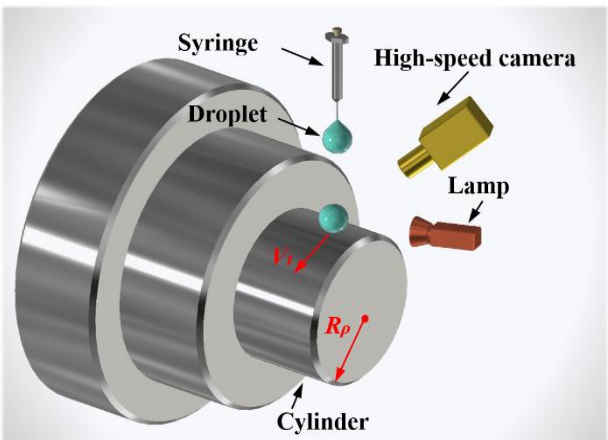

Fig. 1. Experimental apparatus.

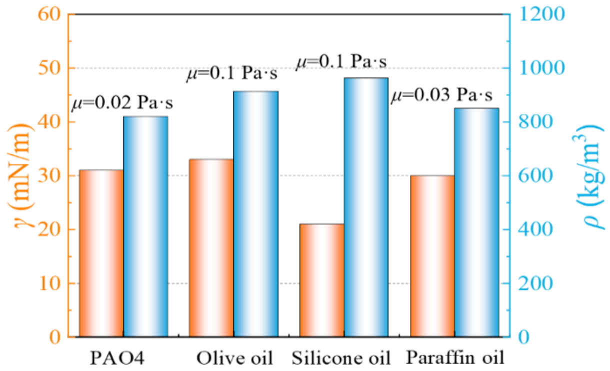

Fig. 2. Physical properties of PAO4, olive oil, silicone oil, and paraffin oil.

3. RESULTS AND DISCUSSION

Similar to the conventional oil droplets impacting the dry surface, oil droplets show spreading, maximum, and retracting in turn, but the final result is very different. It can be seen from Fig. 3 that all lubricants droplets would bounce from the wetted cylinder rather than deposit on it under different conditions. This is because when the oil droplet impacts the oil film, the air film between them will be compressed and makes the oil film sag [12]. According to Bernoulli's principle

$$p + \frac{\rho V_l^2}{2} + \rho g h_l = \text{Constant} \tag{1}$$

where p is the pressure at the chosen point, v_l is the fluid flow speed at a point, h_l is the elevation of the point, and g is the gravity acceleration, the decrease in fluid speed will make the increase in pressure, which implies that a greater velocity intensity at both sides of the bottom of the oil droplet produces a higher local pressure that provides sufficient support for it to bounce.

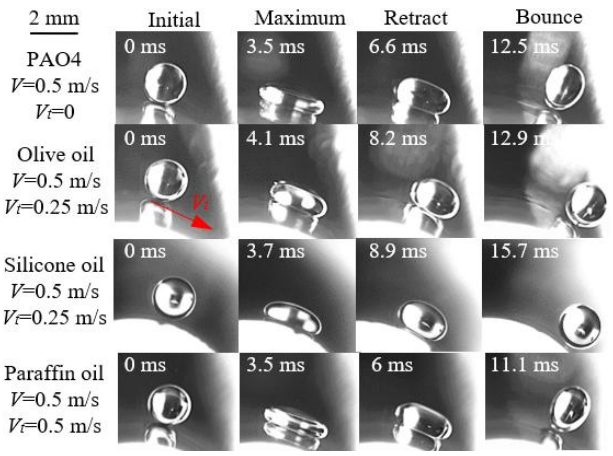

Fig. 3. Impact behaviors of four lubricants with different conditions.

To quantify the impact process of oil droplets, the evolution of the spreading diameter D_s on the cylinder with h=0 mm, V=0.5 m/s, and V_t=0.25 m/s is shown in Fig. 4. It can be seen that all oil droplets have experienced a trend of increasing, stabilizing, and shrinking in diameter. The main difference between static and rotating cylinders is the existence of tangential force. When the oil droplet deposit on the rotating cylinder, the increase in V_t will make the oil droplet to be significantly elongated, while the relationship between V_t and the ratio of the maximum spreading diameter D_{max} and D_0 are 0.25V_t +1.55 (PAO4), 0.56V_t +1.38 (olive oil), 0.63V_t +1.3 (silicone oil), and 0.88V_t +1.46 (paraffin oil), as shown in Fig. 5.

Obviously, both D_{max}/D_0 and D_s/D_0 show that paraffin oil > PAO4 > olive oil > silicone oil, which is due to the rank of μ. With the increase of μ, the resistance of oil droplets during spreading increases which consumes a lot of initial kinetic energy [13]. After wetting the cylinder, D_{max}/D_0 and V_t show a relationship of 0.08V_t+1.54 (PAO4), 0.044V_t+1.4 (olive oil), 0.11V_t+1.4 (silicone oil), and 0.03V_t+1.51 (paraffin oil). It can be seen that the slope is greatly reduced because the oil droplet completely bounces off the oil film, so the tangential force has little influence on it, as shown in Fig. 6.

In the horizontal direction, oil droplets will suffer the aerodynamic force F_{af} and the lubricant force F_l powered by the air film, which are

$$F_{af} \sim \rho_a V_t^2 D_0^2 \tag{2}$$

$$F_l \sim \frac{\mu_a V_t\ D_{max}^2}{\delta} \tag{3}$$

where ρ_a=1.2 kg/m³ is the density of air, μ_a =18e-6 Pa·s is the viscosity of air, and δ is the air film thickness which can be described as

$$\delta \sim R_0 St^{-2/3} \tag{4}$$

where R_0 is the initial radius and St is the Stokes number [14, 15]

$$St = \frac{\rho V R_0}{\mu_a} \tag{5}$$

Therefore, under the action of aerodynamic force and lubrication force, the probability of oil droplets bouncing from the oil film is greater. Considering the capillary length

$$l_c = \sqrt{\frac{\gamma}{\rho g}} \tag{6}$$

where the l_c of PAO4, olive oil, silicone oil, and paraffin oil is 2 mm, 2 mm, 1.5 mm, and 2 mm in turn, which does not meet the condition that is much larger than the diameter of the oil droplet, so gravity cannot be ignored. In the vertical direction, the gravity F_g and inertial force F_{if} play a key role in the spreading of the oil droplet [16], which are

$$F_g = \frac{\pi \rho g D_0^3}{6} \tag{7}$$

$$F_{if} = \frac{\pi \rho D_0^2 V^2}{6} \tag{8}$$

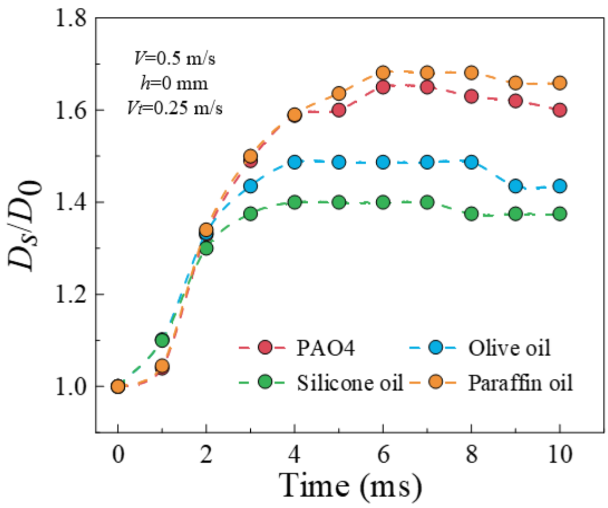

Fig. 4. Changing trends of D_s/D_0 with h=0 mm, V=0.5 m/s, and V_t=0.25 m/s.

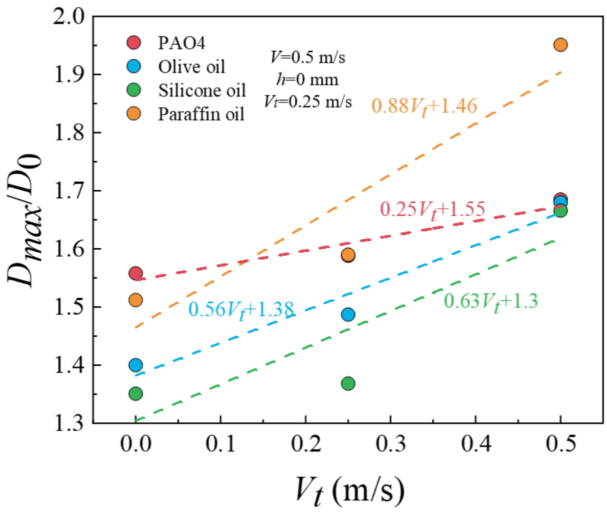

Fig. 5. Changing trends of D_{max}/D_0 under different V_t with h=0 mm.

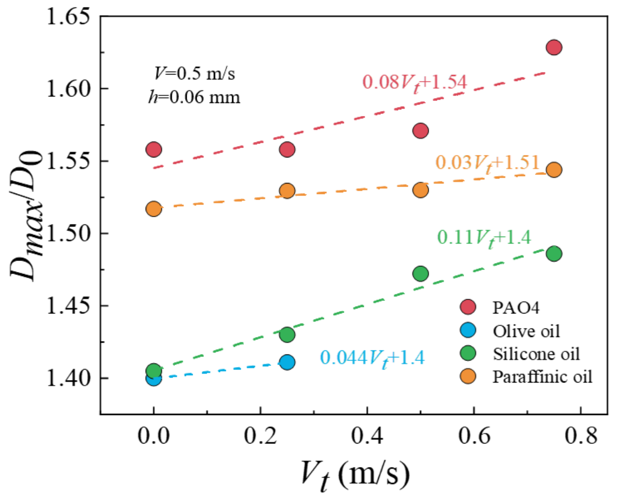

Fig. 5. Changing trends of D_{max}/D_0 under different V_t with h=0.03 mm.

So, the combined forces of F_g and F_{if} acting on PAO4, olive oil, silicone oil, and paraffin oil are 592.6 μN, 414.4 μN, 436.8 μN, and 385.4 μN with V=0.5 m/s, respectively. Conversely, the support force F_a of the compressed air film is competing with F_g and F_{if}. With the relative pressure ΔP of the air film induced by the impact scales as ρV^2, there is $F_a=\Delta PS$, where S is the contact area of the oil droplet and the air film [5]. Therefore, oil droplets will bounce off once $F_g+F_{if} < F_a$, while depositing when $F_g+F_{if} > F_a$.

4. CONCLUSION

In this work, the impact behaviors of four lubricants on wetted cylinders were highlighted. Similar to conventional droplets impact phenomenon, spreading, maximum, retracting, depositing, and bouncing existed. Comparing the impact behaviors of four lubricant droplets, it can be seen that the viscous force has a strong restrictive effect on the spread of oil droplets. Due to the existence of tangential force, the maximum spreading diameter of oil droplets on dry and rotating cylinders increases significantly after increasing the tangential velocity, but it was not obvious on wetted and rotating cylinders. Force analysis was used to explain the mechanism of bouncing, and oil droplets would bounce if the support force is larger than the combined force of gravity and inertia force. The findings provide a basic understanding of lubricant droplets impact on wetted cylinders and design concepts for applications in modern industry.

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