STUDY OF DROPLET MOTION AND WATER FILM FLOW CHARACTERISTICS ON SUPERHYDROPHOBIC SURFACES UNDER AIRFLOW SHEARING

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Abstract

Commercial aircraft are typically equipped with icing protection systems to solve the icing problem, and thermal protection systems are the most common icing protection systems. The thermal protection systems are typically in a wet anti-icing condition, where unevaporated liquid water flows as a water film over the surface under the shear of the airflow. With the widespread use of superhydrophobic materials, researchers are increasingly interested in the use of superhydrophobic materials and thermal protection systems together for anti-icing purposes. The water film flow on superhydrophobic surfaces is quite different from that on conventional surfaces, and the study of droplet motion and water film flow processes on superhydrophobic surfaces can enhance the understanding of the anti-icing mechanism on such surfaces. The test platform for studying droplet motion and water film flow was constructed using a small wind tunnel. A high-speed camera was used to record the droplet motion and water film flow process on the surface of various materials, while the wind speed was adjusted using a variable frequency fan. In the droplet motion test, the droplet motion morphology of the superhydrophobic surface showed minimal difference from the initial state. The total droplet motion time significantly decreased with increasing droplet volume in the range of 10μL to 40μL, while the difference in total droplet motion time significantly decreased with increasing droplet volume in the range of 40μL to 80μL. In the water film flow test, the water film on the superhydrophobic surface cannot completely cover the test surface. In the low-flow state, the water film thickness was greater and clustered in the middle position due to the weak airflow shear force. After the wind speed gradually increases, the airflow shear force intensifies, causing the water film on the superhydrophobic surface to only sustain a small continuous water film at the initial position, which will quickly break during the development process. Due to the low adhesion of water on superhydrophobic surfaces, the process of water film rupture causes droplets to detach from the water film and break into smaller droplets when exposed to airflow, accelerating them away from the surface. The significant difference in the water film flow characteristics between superhydrophobic surfaces and conventional surfaces is the large number of droplets flying away. The research results can provide a reference for further research on the anti-icing characteristics of superhydrophobic surfaces.

Keywords: Aircraft icing; superhydrophobic surface; droplet motion; water film flow; fluctuation characteristics

1. Introduction

When an aircraft is flying in clouds, icing occurs when supercooled droplets in the clouds hit the surface. Icing can lead to reduced lift and increased drag, seriously threatening flight safety.

In the research of aircraft anti-icing, the wet anti-icing method of thermal protection system is widely used. Supercooled water that has not completely evaporated will flow along the surface under the influence of airflow and form a water film on the surface. The water film ruptures into streams or droplets under the combined effect of airflow shear, surface tension, and surface wetting characteristics. After the water film ruptures, the anti-icing surface is divided into wet and dry surfaces, which directly affects the surface heat transfer characteristics and the prediction of anti-icing energy consumption. In recent years, with the advancement of superhydrophobic materials, the research on the anti-icing mechanism of superhydrophobic and electrothermal composites has gained significant attention[1]. The motion characteristics of water films and droplets on superhydrophobic surfaces differ significantly from those on traditional hydrophilic surfaces, which urgently need to be studied in depth.

Early studies on water film flow mainly focused on falling film studies. Liu et al. [2] used a fluorescence imaging system to investigate the gravity-driven liquid film instability. Chang et al. [3] used planar laser-induced fluorescence to analyze the thickness and wave characteristics of the water film. Hu et al. [4,5] developed the digital streak projection (DFP) technique and the digital image projection (DIP) technique to achieve non-invasive thickness measurement of transient flow during water film motion. Zhao et al. [6] investigated the characteristics of water film flow on various rough surfaces and summarized the effect of roughness on surface flow according to the experimental results. In the study of droplet motion, J. Fan [7] considered both experimentally and analytically the surface droplet motion of a droplet driven by a shear airflow. S.C. Fu [8] investigated the deformation and separation of droplets on three different solid surfaces in a fully developed turbulent channel. The study showed droplet compression or elongation induced by the turbulence but did not analyze the dynamic changes in contact angle. The experimental study of droplet motion conducted by Wang et al.[9] on surfaces with various wetting characteristics characterized the evolution of the droplet motion process into four stages but did not investigate droplet flow on superhydrophobic surfaces.

In the study of water film flow and droplet motion, the main focus is on conventional hydrophilic surfaces, while the investigation of water film flow and droplet motion on superhydrophobic surfaces is relatively limited. In this paper, an experimental study is conducted to investigate the motion of droplets and the flow of water film under the shear effect of airflow. The flow state and flow characteristics are then analyzed. It has a significant guiding value for the in-depth understanding of the anti-icing and icing mechanisms on superhydrophobic surfaces.

2. Experimental method

The superhydrophobic material used in this study was prepared using the ultrafast laser method on the surface of 0.3mm thick 6061 aviation aluminum alloy material. The material was chemically modified to create a superhydrophobic surface, as shown in Figure 1. The average contact angle on the surface of the test sample is 158.6°, with forward and backward contact angles of 159.8° and 154.7°, respectively, and the average rolling angle is 6.63°.

Figure 1 - Superhydrophobic Materials

The droplet motion experiment is conducted using a small wind tunnel, which consists of a centrifugal blower, a settling chamber, a contraction section, an experimental section, and an expansion section. The maximum airflow speed is 55 m/s. The middle structure at the bottom of the experimental section is detachable, which makes it easy to replace the test board. In the water droplet experiment, a hole is set on the top glass cover plate to facilitate water droplet generation, and a high-speed camera is used to record images of water droplet motion.

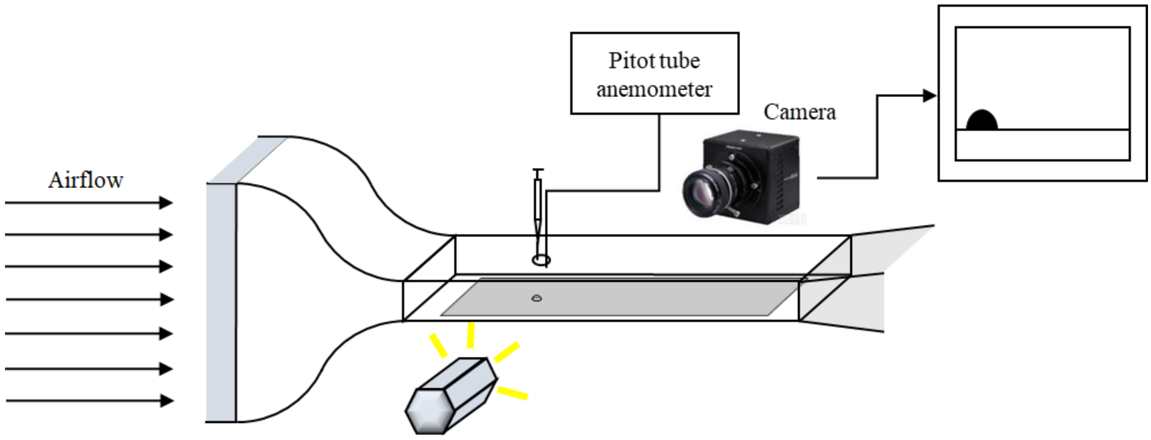


Figure 2 - Schematic diagram of droplet motion experimental device

The main system of the wind tunnel for water film flow experiment is the same as the above device. The aluminum test board at the bottom of the experimental section has a water film outlet seam, and the working fluid is injected by a submersible pump. Then the initial water film is formed by entering the experimental section through a slot distributor with a width of 8cm.The water flow rate is measured by a pre calibrated rotor flowmeter with an accuracy of 5%.At the end of the test board, the liquid is collected in a collection vessel through a groove, which is filled with absorbent sponge material to capture water and prevent the inhalation of air.

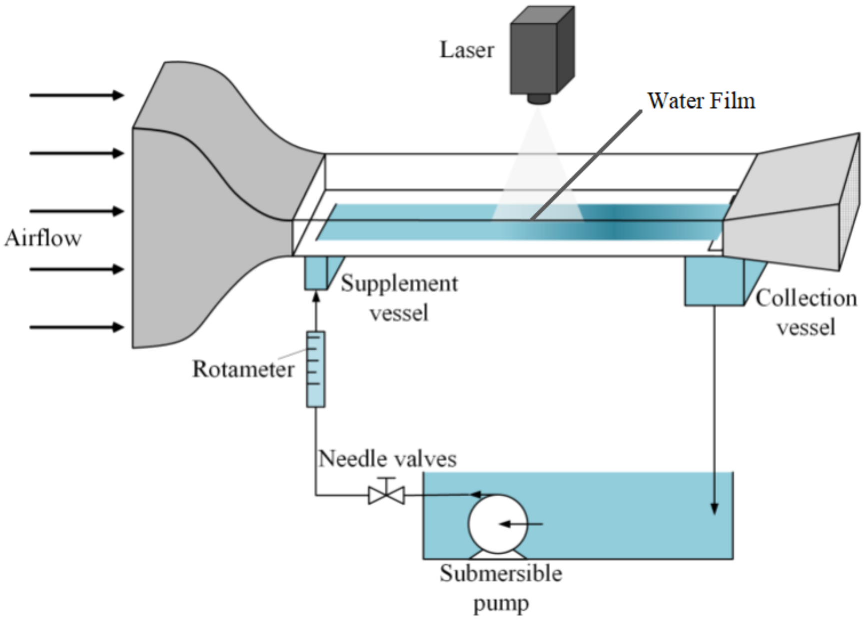


Figure 3 - Schematic diagram of water film flow experimental device

3. Results and Discussion

3.1 Superhydrophobic surface droplet motion experiment

The droplet volumes in this experiment are: 10μL, 20μL, 40μL, 60μL, 80μL. Starting from a state of stillness, the variable frequency fan is controlled to provide a shear airflow. The target wind speed of the fan is 25 m/s, and the movement of droplets of different volumes on the superhydrophobic surface is shown in Figure 4.

On superhydrophobic surfaces, there is no significant change in the contact angle of droplets as they move across the surface. The shape of droplets remains consistent with the initial droplet shape during movement. Droplet size ranges from 10μL to 40μL. As the droplet size increases, the total movement time of the droplet decreases significantly. When the droplet reaches 40μL to 80μL, the total movement time of the droplet changes very little as the droplet size increases.

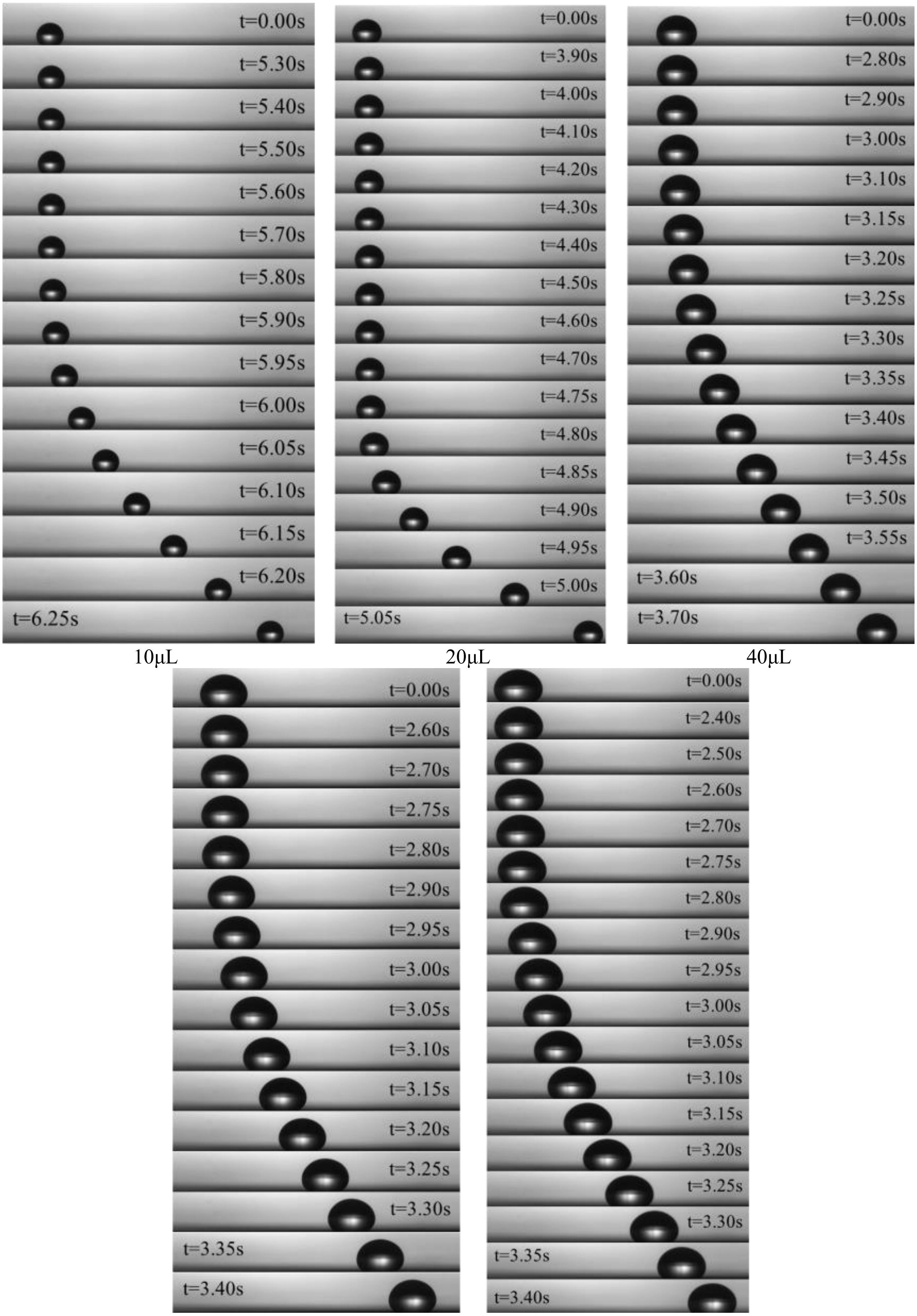


Figure 4 - Motion process of droplets on superhydrophobic surfaces

3.2 Superhydrophobic surface water film flow experiment

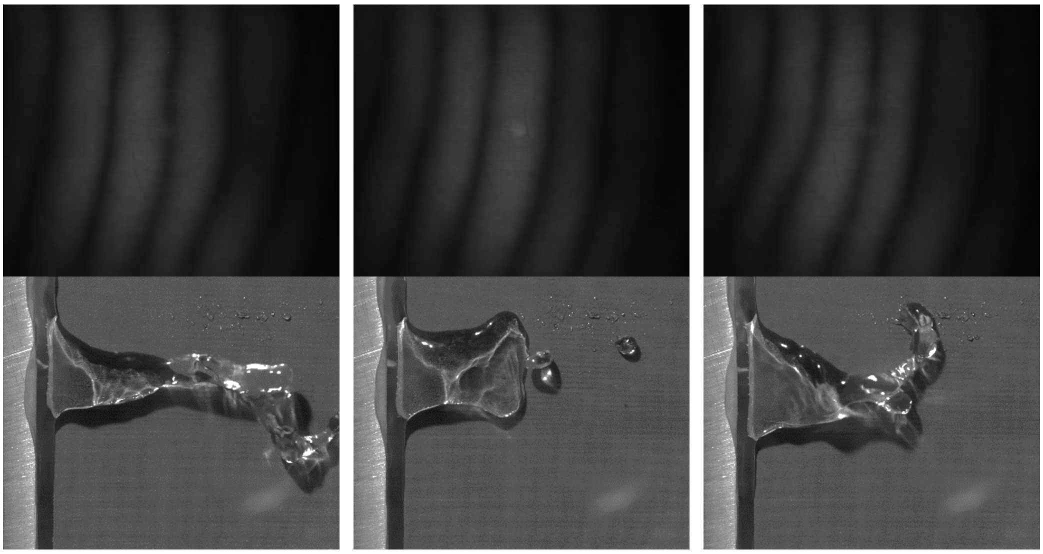
In the water film flow experiment, the water film Reynolds number Re_L is introduced as Q/wv_l, where Q, w, and v_l represent the liquid volume flow rate, film width, and kinematic viscosity, respectively. To compare the differences between hydrophilic surfaces and superhydrophobic surfaces, several typical experiment states of hydrophilic surfaces were selected for research. The experiment conditions are shown in Table 1.

Table 1 - Water film flow experiment conditions

Condition	Water supply flow rate (mL/min)	Reynolds number of water film	Velocity（m/s）	Reynolds number of airflow
Case 1	100	21	15	8.7×10^{5}
Case 2	100	21	35	2.01×10^{6}
Case 3	300	62	30	1.73×10^{6}
Case 4	700	144	25	1.15×10^{6}
Case 5	700	144	35	2.01×10^{6}

Hydrophilic surfaces

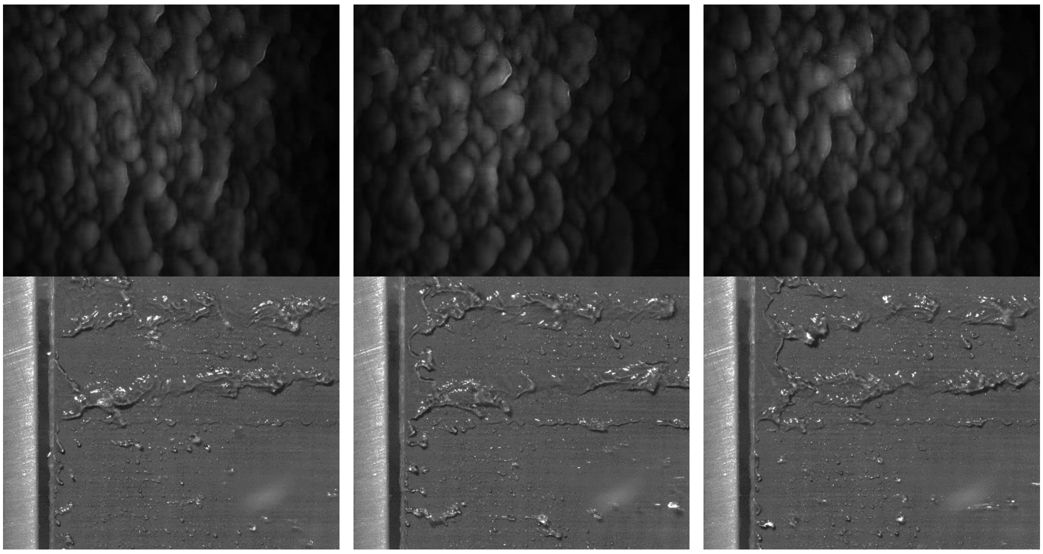
Superhydrophobic surfaces



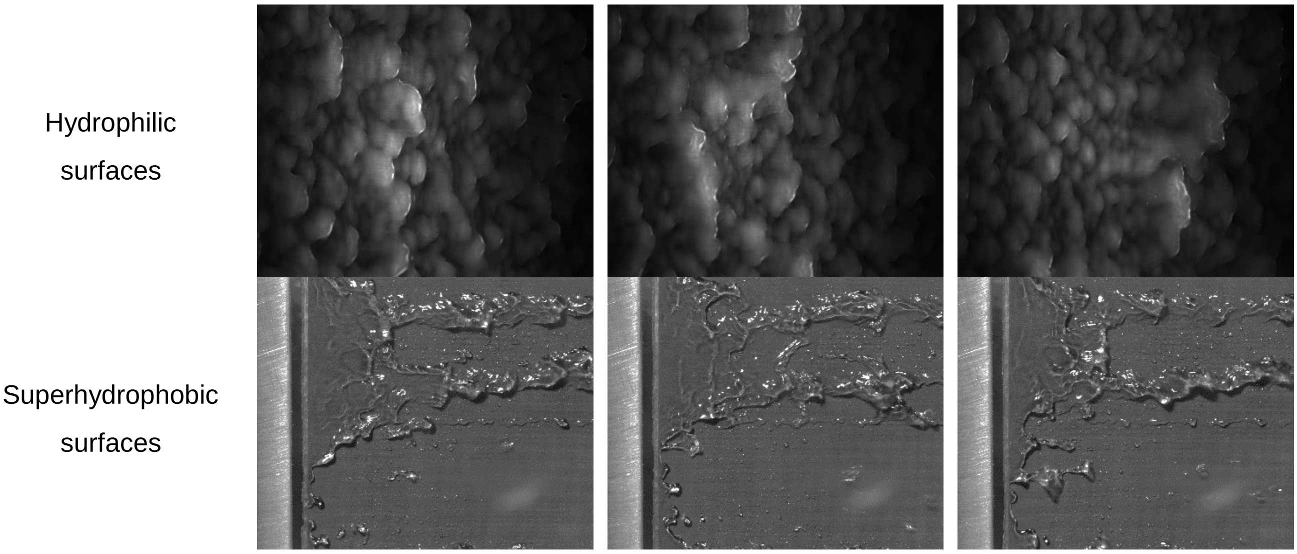
Case 1

Hydrophilic surfaces

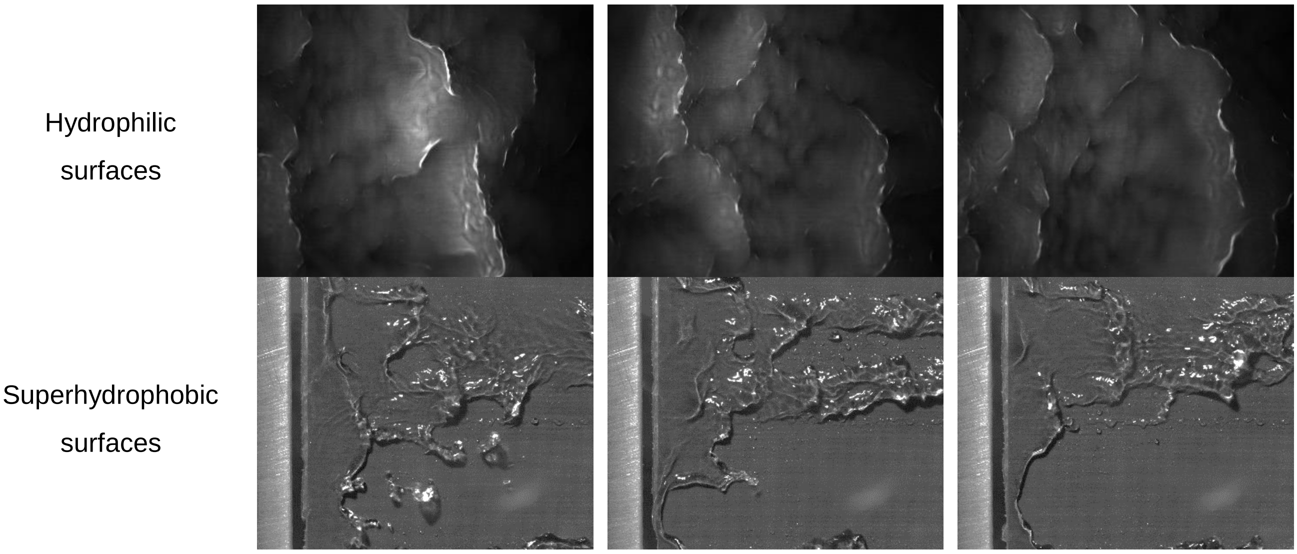
Superhydrophobic surfaces



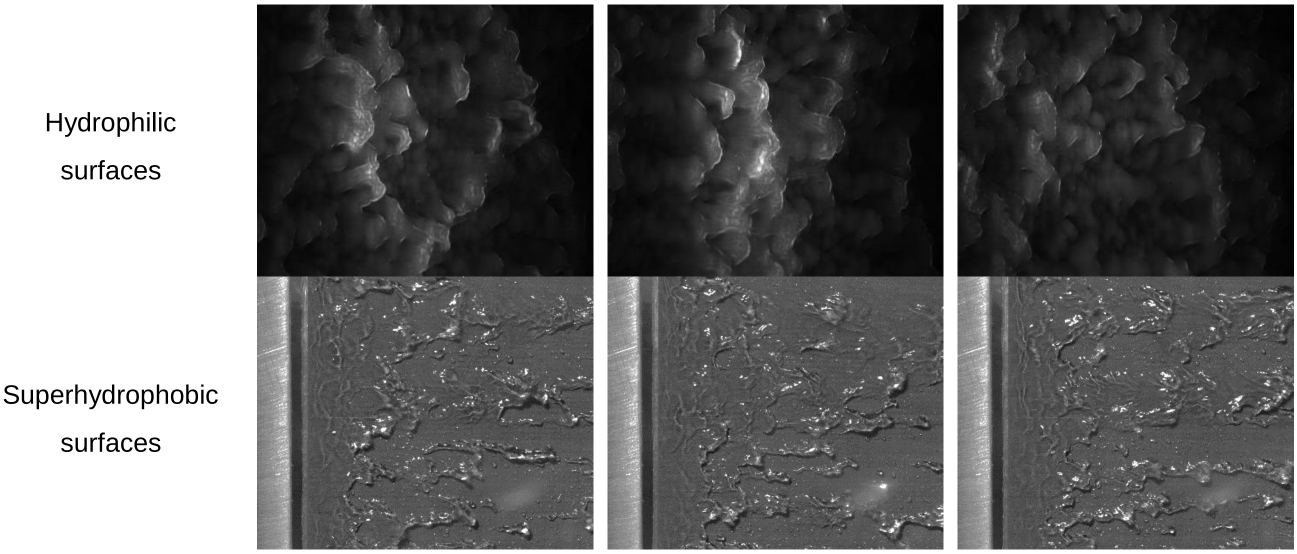
Case 2



Case 3



Case 4



Case 5

Figure 5 – Comparison of water film flow characteristics in typical experimental conditions of hydrophilic and superhydrophobic surfaces

In Case 1, the fluctuation amplitude of the hydrophilic surface water film interface is relatively low, exhibiting clear periodicity and uniform distribution along the entire water film spreading direction. Due to the large contact angle of superhydrophobic surfaces, the water film does not fully cover the surface within the field of view. Instead, it contracts and converges to a certain point on the outlet, forming a continuous water flow. In Case 2, the waveform of the hydrophilic surface water film interface exhibits obvious three-dimensional wave characteristics, presenting a surface covered with pebbles. The water film on the superhydrophobic surface is discontinuous and is pinched off by the airflow to form small water droplets. In Case 3, the hydrophilic surface water film flow exhibits a rolling wave state with multiple forms of coexisting waves. The distribution range of superhydrophobic surface water film widens, leading to the formation of small water droplets due to pinching. In Case 4, the range of hydrophilic surface rolling waves expands. The distribution of water film on the superhydrophobic surface widens, and the water film is sandwiched, forming small water droplets under the action of airflow shear. Continuous water film coverage reduces the performance of superhydrophobicity. In Case 5, the rolling wave is accompanied by the phenomenon of peak breaking during its development. On superhydrophobic surfaces, a continuous water film is observed at the outlet. At a distance from the outlet, the water film transforms into entrained small water droplets under the airflow shear.

4. Conclusion

The following conclusions have been derived from experimental research in this article.

1) The droplet morphology during the motion on superhydrophobic surfaces is not significantly different from the initial droplet morphology. From the patterns of droplets of different sizes, it can be seen that droplets vary from 10μL to 40μL. As the droplet size increases, the total movement time of the droplet significantly decreases. When the droplet reaches 40μL to 80μL, the total movement time of the droplet changes very little as the droplet size increases.

2) The water film cannot completely cover the superhydrophobic surface. At low flow rates, the airflow shear force is weak, the water film thickness is thick, and it gathers in the middle position. As the wind speed gradually increases, the shear force of the airflow also increases. The superhydrophobic surface can only sustain a small continuous water film at its initial position, which will quickly break as it moves backward. Due to the low adhesion of water on the superhydrophobic surface, the process of water film rupture can cause droplets and water masses to detach from the wall. These droplets break into smaller droplets when exposed to airflow, which accelerates their detachment from the wall.

3) In some areas where superhydrophobic surfaces fail, the wall maintains a high adhesion force to the water film or droplets, making it difficult for water to detach from the wall. In the region where the superhydrophobic surface typically operates, there is a layer of bubbles that forms between the water and the superhydrophobic surface, acting as a barrier, and the adhesion force of water to the surface is relatively low. The difference in adhesion is a key factor in distinguishing the flow state between superhydrophobic surfaces and hydrophilic surfaces.

5. Copyright Statement

6. Acknowledgements

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