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How supercooled superhydrophobic surfaces affect dynamic behaviors of impacting water droplets?

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ABSTRACT

Water droplet icing on the supercooled surface is ubiquitous and presents gigantic harmfulness on the power transmission lines, aircraft and outdoor equipment. Therefore, a good understanding of droplet impact and freezing process on the supercooled superhydrophobic surface is crucial. In this paper, aluminium sheet was adopted as the substrate to prepare the superhydrophobic (SH) surface. A high-speed camera was applied to explore the dynamic behaviors of a water droplet impacting on the SH surface with various supercooling degrees visually. Moreover, the droplet spreading factor, dimensionless height, characteristics time, rebounding energy and mass fraction of the secondary droplets were adopted to reflect the dynamic behaviors. The results indicate that the dynamic behaviors of a droplet (with an initial temperature of 15 °C, equivalent diameter of 2.94 mm and impacting velocity of 0.99 $m \cdot s^{-1}$) impacting on the SH surface (160° in static contact angle) with a lower supercooling degree is consisted of three regimes: spreading, retraction and rebounding. Whereas, the retraction and rebounding regime are limited at -17 °C and -24 °C, respectively. Moreover, in the retraction regime, the governing factor of the droplet frozen onset time transforms from the interface heat transfer ability into incubation time at the surface temperature below -34.4 °C. Furthermore, the droplet separating and rebounding are prevented once the remaining energy at the end of the retraction regime is lower than 35% of the droplet initial energy.

1. Introduction

Water droplet icing on supercooled surface is ubiquitous, especially in high latitude and altitude localities. However, it shows gigantic harmfulness on the power transmission lines, aircraft and outdoor equipment [1–3]. Specifically, ice accretion will rip down the powder transmission lines, which could cause large area blackouts and huge economic loss. Moreover, ice accumulation on the aerofoils can cause hazardous air flow conditions, degrading the controllability of an aircraft and causing a crash in a severe case [4]. At present, surface heating, coatings with anti-icing chemicals and superhydrophobic (SH) surface are adopted to solve these problems [4–6]. Among them, the SHS is the most effective and energy saving one, owing to the outstanding water repellency. However, the supercooling degree shows a significant effect on the impact and freezing processes of droplets on the supercooled SH surface [7]. On the SH surface with a small degree of supercooling, a long incubation time is essential for the droplets to freeze [8]. That means, slight shake or natural wind may be adequate to drive the droplets away from the SH surface during the incubation period [9]. Whereas, the droplets icing problem is inevitable once the supercooling degree of the SH surface is quite great [10]. Therefore, a good understanding of the droplet impact and freezing process on the supercooled SH surface is crucial.

Up to now, extensive investigations on the dynamic behaviors of water droplets on the SH surface have been reported [6]. Generally, water droplets impact on the SH surface defined three scenarios, including spreading, retraction and rebounding [6]. Moreover, the effects of impact velocity [11–13], surface microstructure [14–16] and impact angle [17–19] etc. on such impingements have been explored deeply. For instance, Yang et al. [12] explored the effect of impact velocity on a water droplet impacting a SH surface with the static contract angle of 156°. The experimental results showed that the spreading diameter of droplet and the velocity of three-phase contract line increased with an increase in the impact velocity. Moreover, three groups of satellite droplets were generated in the spreading and retraction processes once the impact velocity was greater than 2.63 $m \cdot s^{-1}$.

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Moreover, the effect of impact velocity on the Cassie-to-Wenzel wetting transition was researched by Lee et al. [13]. It illustrated that the transition firstly presented in the retraction process, then it appeared in the spreading process with the impact velocity increasing. Furthermore, Hao et al. [15] investigated the impact behaviors of a water droplet on the micropillar-like SH surface with various geometrical parameters. It indicated that the critical impact velocity inducing Cassie-to-Wenzel wetting transition was mainly governed by the single micropillar perimeter and the air trapped area between the repeated micropillar. In addition, the water droplet impact and rebounding behaviors on an oblique SH surface was experimentally studied by Yeong et al. [17]. The results revealed that the contact time of droplet on the SH surface was independent from the oblique angle. Similarly, the oblique angle had no obvious effect on the impact and rebounding behaviors at low impact velocities. Whereas, at a higher impact velocity, the maximum spreading diameter was controlled by the oblique angle, which could be related to asymmetry and more complex outcomes. However, most of these researches were carried out in a room temperature. It has to point out that the temperature of the SH surface showed a significant effect on the droplet viscosity [20,21]. That means, the dynamic behaviors of a droplet impacting on a supercooled SH surface was quite different from that on a room temperature surface, owing to heat transfer between the water droplet and the supercooled surface [10].

Base on this, the effect of the surface supercooling degree on the impacting behaviors of water droplet was studied by some scholars [10,22–24]. Roisman et al. [22] found that the maximum spreading diameter was independent from the SH surface temperature. Whereas, Li et al. [24] and Mishchenko et al. [10] confirmed that the retraction speed and the maximum retraction height undergone significant decreases with increasing the supercooling degree of the SH surface, which attributed to the decrease of droplet temperature in the retraction process. Moreover, Mishchenko et al. [10] observed that the rebounding process was inhibited (icing transition) once the surface temperature below −25 °C. Furthermore, they confirmed that initial temperature of water droplet showed no obvious effect on the icing transition. In addition, the activation energy of heterogeneous nucleation is significantly decreased by the roughness asperities on the solid surface [25]. That is, the heterogeneous nucleation instead of homogeneous nucleation plays a dominant role on the icing process of a droplet impacting on the supercooled surface. Unfortunately, up to now, only a few researchers focused on dynamic behaviors of a water droplet impacting on a supercooled SH surface. Moreover, the complex influences of droplet impact dynamics, heat transfer at the interface (between the droplet and the supercooled SH surface) and heterogeneous ice nucleation on the dynamic behaviors were still unclear.

In this paper, aluminum substrate was adopted to prepare the SH surface. A high-speed camera was applied to explore the dynamic behaviors of a water droplet impacting on the SH surface with various supercooling degrees visually. Therefore, the evolutions of droplet spreading factor, dimensionless height, characteristics time, rebounding energy and mass fraction of the secondary droplets under various surface temperatures were experimentally investigated. These results may provide theoretical guidance for the design of anti-icing surface.

2. Experimental section

2.1. Surface fabrication and characterization

In the present experiment, the smooth aluminum sheet (7075, 50 mm in length, 25 mm in width, 5 mm in thick) was adopted to fabricate a SH surface. Moreover, three holes (1.5 mm in diameter, 10 mm in depth, 15 mm in interval) were taken along the width direction near the top surface of the aluminum sheet, so as to place thermocouples. Then, the top surface of the smooth aluminum sheet was ablated by a infrared laser (5 W in power, 10 μm in laser beam diameter, 50 μm in ablation depth). After that the laser-ablated aluminum sheet was washed with acetone and deionized water subsequently using an ultrasonic bath and then dried in a vacuum drying chamber (70 °C) for 5 h. Eventually, a heptadecafluorodecyltrimethoxysilane ($C_{13}H_{13}F_{17}O_3Si$, PTES) solution was prepared by dissolving PTES (1 wt%) in methanol. Thereafter, the laser-ablated aluminum sheet was dipping in the PTES coating solution for 1 h at 70 °C, to ensure the surface was coated with a cross linked PTES layer. The SH surface was produced after 5 h of drying in a vacuum drying chamber (70 °C).

The morphologies of the smooth surface, laser-ablated surface and laser-ablated surface with PTES coating were obtained using a scanning electron microscope (SEM, model S-4800, Hitachi, Japan) and shown in Fig. 1a–c, respectively. One can notice that, aluminum sheet was relatively smooth and only few scratch-like defects can be observed (Fig. 1a). By contrast, the smooth surface turned to a porous one after the laser ablation (Fig. 1b). Specifically, the micropore diameter and the space between the adjacent micropores were 10 and 15 μm in average. Moreover, the porous surface was fully covered with urchin-like microspheres with a diameter of 100–500 nm. In Fig. 1c, one can see that the porous surface was evenly covered with the PTES coating, including the inner wall surface of the micropores. In addition, to obtain the wettability of the prepared surface, an image of a sessile millimetric water drop on the surface (25 °C, 50% in humidity) was taken using a CMOS camera (GS3-U3-41C6M-C, PointGray) and shown in Fig. 1d. It is noted that the prepared surface presented an excellent hydrophobic property. Moreover, the static contact angle (θ), advancing angle (θ_A) and receding angle (θ_R) were measured using a optical angle meter (XG-CAMC33, China). To verify the uniformity of the prepared surface, more than 15 tests were carried out at various positions of the surface, we confirmed that the θ, θ_A and θ_R was 160°, 152.9° and 151.2°, respectively, the maximal error was 1°. That is, the prepared surface was a SH one.

2.2. Experimental system and method

Fig. 2 displays the schematic of the experimental setup in the current research. To obtain a higher supercooling degree on the SH surface, the liquid nitrogen (LN_2) was adopted as the cooling medium, which was served in a stainless container (200 mm in diameter, 200 mm in height) with an insulation layer. Moreover, the SH surface was placed on the upper surface of a red copper column (200 mm in diameter, 250 mm in height) which was set in the container. A stainless capillary tube (0.8 mm in inner diameter, 100 mm in length) was positioned at a controlled distance (50 mm) above the SH surface, which was connected to a syringe pump (TYD01, China) via a flexible tubing. Besides, a perspex shell (90 mm in diameter, 100 mm in height) was used to cover the SH surface during the experiments. Prior to the experiment, the nitrogen (N_2) was imported into the perspex shell to remove air and reduce the relative humidity (below 10%), then, the liquid nitrogen was poured in the container. Moreover, four thermocouples (type K, a diameter of 0.3 mm and accuracy of ±0.1 °C) were placed in the perspex shell and the SH surface. Furthermore, the environmental temperature in the perspex shell (T_f) and temperature of the SH surface (T_s) were acquired by a data logger (Agilent Instruments, model 34972A) and shown on the screen of computer 1. During the cooling process, to prevent frosting on the SH surface and icing in the capillary tube, the T_f and T_w (deionized water temperature inside the capillary tube) were controlled at about 15 °C by adjusting