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Experimental investigation of the impact and freezing processes of a water droplet on different cold concave surfaces

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ABSTRACT

In the present study, we report the observations of the impact and freezing processes of a water droplet on different cold concave surfaces. During the experiment, the concave surface was put into a cover in which pressurized Argon gas was injected at the same time with a purpose to minimize the desublimation of the vapor. Then, the surface temperature was cooled down to a desirable value by a constant temperature bath circulator. After that, a deionized water droplet was released to impinge the concave surface and its impact and freezing processes were recorded by two cameras. The results showed that, during the impact process of the water droplet, the maximum contact diameter along azimuthal direction was generally smaller than that along axial direction. In addition, during the water droplet recoiling process, the residue of a ring appeared on the cold concave surface and the radius of the concave surface was found to have a minor effect on the spreading factor along axial direction. During the freezing process of the water droplet, the change of the temperature as well as the radius of the concave surface did not lead to an apparent variation of the ice bead shape.

1. Introduction

Under certain weather and flight conditions, ice accretion may occur in the windward surface of the aero-engine, which not only affects the aerodynamic performance and but poses hazards to the safety of the aero-engine [1,2]. Generally speaking, the icing on the fan blades of aero-engine involves the impact and freezing processes of water droplets on cold concave surfaces. Thus, a better understanding of these processes would be very desirable for researchers to predict the ice accretion on the fan blades of aero-engine more accurately.

Over the years, the impact and freezing processes of a water droplet on different cold solid surfaces have been attracting researchers around the world. The commonly studied shapes of the cold solid surfaces include flat surfaces [3–21], cylindrical surfaces [22,23], and spherical surfaces [24].

As for the cold flat surfaces, Li et al. [3] carried out an experimental study to identify the influence of solidification upon the impact process of a single water droplet on aluminum surfaces. The results showed that solidification did not influence the first spreading phase while its suppression on the receding phase was only noticeable for longer receding phases. Xu et al. [4] observed the impact process of a water droplet on a Teflon plate and a stainless-steel plate, the inclined angle of which was 30°. The surface texture of the stainless-steel plate produced by the polishing process had an obvious effect on the droplet dimension retraction. Jin et al. [5–7] carried out a series of experimental studies on the impact and freezing process of a water droplet on different cold inclined surfaces. Their results demonstrated that the freezing time of the water droplets and the shape of the ice beads could be affected by cold surfaces characteristics and surface inclined angle. Moreover, Jin et al. [8] reported the detailed dynamic motions of a water droplet impacting on an ice surface. The results showed that, during the impact process of the water droplet, once the water droplet reached its maximum contact diameter, the contact line of the water droplet was pinned on the ice surface without recoiling. Zhang and Liu [9] conducted experimental studies to determine the effects of droplet size on the thermodynamics for supercooled large droplet impingement on an aluminum flat surface. Through phenomenological reproduction, the rapid-freezing characteristics were observed in diameters of 400, 800, and 1300 μm. Recently, due to the extraordinary water repellency capability of the superhydrophobic surfaces, some researcher have performed the investigations on the impact and freezing processes of water droplets on cold flat superhydrophobic surfaces [10–19]. As for the impact process of the water droplet, when the superhydrophobic surfaces are placed in a dry environment, the water droplets fully retract and bounce off the surface leaving no residue on the cold superhydrophobic surfaces [10]. However, when the superhydrophobic

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surfaces are exposed to ambient air with a relative high humidity, the frost formation significantly compromises the icephobic properties of superhydrophobic surfaces during the water droplet impact process [11]. In addition, some researchers reported nucleation delay of the water droplets on SHSs, which was generally attributed to the insulating effect of the air pockets situated between the topographical features, to reduced solid–liquid contact area, and to an increased free-energy barrier to heterogeneous nucleation [12–19]. More recently, slippery liquid-infused porous surfaces [20] and magnetic slippery surfaces [21] were developed as new icephobic surfaces.

As for the cold cylindrical surfaces, Yang et al. [22] investigated the freezing mechanism of the supercooled water droplet impinging on cold cylindrical metal surfaces and found the phenomena of instantaneous and non-instantaneous freezing. They studied three different metal tube surfaces, which were stainless steel, aluminum, and red copper. The phenomena of instantaneous and non-instantaneous freezing of the supercooled impinging droplet were identified and the conditional boundaries for these two kinds of freezing were found statistically. Recently, Jin et al. [23] investigated the impact and freezing processes of a water droplet on different cold cylindrical surfaces. The results showed that, during the impact process of the water droplet, the maximum contact diameter along azimuthal direction was generally larger than that along axial direction. As for the cold spherical surfaces, Khaled [24] investigated the impact and freezing processes of a water droplet on a super cold spherical surface. Droplet temperature was found to have no effect on the crack formation while the formation of a thin layer of frost on the sphere before the drop impact led to the lateral cracking of the ice.

Even though some researches have been performed on the impact and freezing processes of a water droplet on various cold surfaces in previous studies [3–24], to the authors' best knowledge, the detailed measurement of a water droplet impact and freezing processes on cold concave surfaces with different curvatures have not yet been experimentally investigated. Since the ice accretion on the fan blades of aero-engine usually involves the impact and freezing processes of a water droplet on cold concave surfaces, it is of particular interest to know the detailed information on these processes.

In this study, a deionized water droplet was deposited onto the cold concave surface by a droplet generator and its impact and freezing processes were recorded by two cameras. A parameter study of the temperature and the radius of the concave surface was carried out. The present study is aimed to elucidate the underlying fundamental physics to improve our understanding about the important microphysical processes pertinent to the icing phenomena.

2. Experimental

2.1. Concave surfaces

Since the radius of curvature of the fan blades of aero-engine is usually in the order of mm and higher, three concave surface models and one flat surface model were tested in the present study, the materials of which were stainless steel (306). A channel was produced in each model in order to form the concave surface. The schematic of the cross section of these surface models is shown in Fig. 1. All these models had a longitudinal length (L) of 50.0 mm. Besides, the width of the model (W), the height of the lowest point of the channel (h_1), and the height of the base plate (h_2) were 50.0 mm, 35.0 mm, and 5.0 mm, respectively. The radius (R) of the concave surface was varying in the range from −25.0 mm to −10.0 mm, while the azimuthal angle (θ) was changing from 0° to 180°. In addition, all these models went through careful polishing process and their surface roughness (Ra) was measured to be 0.05 μm. Before the experiment, these models were ultrasonically cleaned in ethanol and distilled water for 20 min and 30 min, respectively. After that, the substrates were dried in an oven at 50 °C for 1 h.

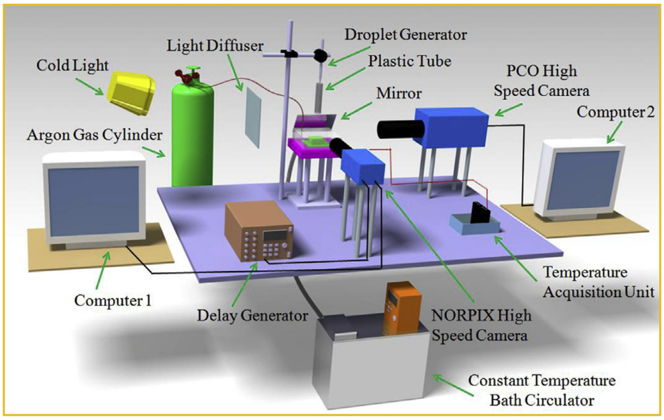
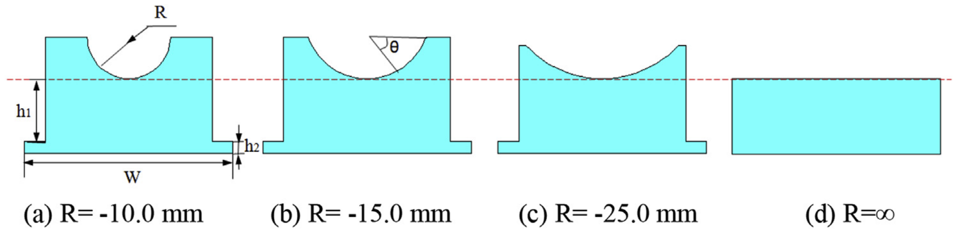


Fig. 2. Experimental setup.

2.2. Experimental setup

The schematic of the current experimental setup is shown in Fig. 2, which is similar to that in our previous studies [5–8,23]. During the experiment, the test surface was cooled down to a subfreezing temperature by a constant temperature bath circulator (AC150-A25, Thermo Scientific). The temperature of the concave surface was monitored by a temperature acquisition unit (9211, National Instrument). The uncertainty of the temperature measurement was estimated to be within 0.05 °C. A home-made droplet generator was used to produce deionized water droplets. Once the water droplet was released, it fell onto the test surface due to gravity. A plastic tube was placed in between the test surface and the droplet generator, which was used to reduce the disturbances of surrounding air on the movement of the water droplet. In order to minimize the desublimation of the vapor on the test surface, a plexi-glass cover (75.0 mm L × 75.0 mm W × 50.0 mm H) with a small orifice (Φ = 8.0 mm) on its top surface was used to cover the test surface during the experiments. Besides, since the molecular weight of the Argon gas is higher than that of the air, pressurized Argon gas was injected into the cover before the measurement to further reduce the desublimation of the vapor on the test surface. Once the test surface reached a desirable temperature, the orifice was open and a deionized water droplet was released to impact the test surface. The impact process along azimuthal direction and the freezing process of the water droplet on the test surface were obtained by a high speed camera (Dimax HD, PCO) and then stored in computer 2 for later analysis. The PCO camera was operated at a frequency f = 2000 Hz for the droplet impact process and f = 10 Hz for the droplet



(a) R= -10.0 mm (b) R= -15.0 mm (c) R= -25.0 mm (d) R=∞

Fig. 1. Schematic of the cross section of the surface models.