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Experimental investigation of the impact and freezing processes of a water droplet on an ice surface

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ABSTRACT

In the present study, we report for the first time the detailed dynamic motions of a water droplet impacting on an ice surface. Besides, the effects of the initial height of the water droplet and the ice surface temperature on the impact and freezing processes of the water droplet were experimentally investigated. During the experiment, an ice surface was generated first and then kept at a desired temperature by a constant temperature bath circulator. After that, a deionized water droplet was deposited onto the ice surface and its impact and freezing processes were recorded. 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. Besides, at the same initial height of the water droplet, the decrease of the ice surface temperature resulted in the reduction of the maximum spreading factor and an apparent increase of the height of the ice bead. Moreover, once the droplet initial height was increased, the maximum spreading factor increased while the height of the ice bead reduced significantly.

1. Introduction

In nature, water freezing on cold surfaces is ubiquitous and poses hazards to many applications, such as wind turbines [1], aircraft [2], and power transmission lines [3], etc. Generally speaking, ice accretion on these applications can be divided into two steps. Firstly, an ice surface presented on some kind of cold solid surfaces. Secondly, water droplets kept depositing and freezing on the newly formed ice surface. Thus, understanding the impact and freezing processes of water droplets on the ice surface would be very desirable for researchers to develop more efficient anti-icing or de-icing methods.

Over the years, the impact and freezing processes of a water droplet on different smooth cold solid surfaces have been attracting researchers around the world. The commonly studied materials of the solid surfaces include metal [4–10], glass [8,11], composite [8], and silicon [12]. During the impact process, when the water droplet gets in touch with the cold surface, the interface temperature is strongly dominated by the surface temperature, and not the initial droplet temperature [12]. It is well known that the viscosity of water depends heavily on temperature. Thus, the viscosity of the water at the interface increases with the reduction of the surface temperature, which causes the water droplet to move less intensely [7,8]. Besides, the surface characteristics are found to have a minor influence on the spreading time and gliding time but an apparent effect on the equilibrium time [8]. In addition, once the equilibrium state is reached, the contact diameter of the water droplets depends on the wettability of the surfaces [8]. During the freezing process, the water droplet on a cold surface undergoes a typical heterogeneous nucleation process [13–22]. It is well known that the water droplet stays at supercooled state for some time before the freezing process begins. The sessile droplet looks like a truncated sphere at this time. The freezing process starts at the bottom of the water droplet and a liquid-solid interface forms. As time goes by, more and more liquid water turns into ice and the liquid-solid interface moves upward. After the entire droplet is frozen, one small protrusion appears on the top of the ice bead which looks like a cone [19,22]. As for the freezing process, the cold surface characteristics are found to affect not only the freezing time of water droplets, but the shape of the ice beads as well [8].

Due to the extraordinary water repellency capability of the superhydrophobic surfaces (SHSs), the investigations on the impact and freezing processes of water droplets on cold superhydrophobic surfaces have also been performed recently. As for the impact process of the water droplet, when the superhydrophobic surfaces are placed in a dry environment, the water droplets fully

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retract and bounce off the surface leaving no residue on the cold superhydrophobic surfaces [12]. Thus, SHSs can dynamically prevent ice formation, even if the surface is maintained at temperatures well below freezing. However, when the superhydrophobic 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 [23]. Besides, lower temperatures increase the viscosity of supercooled droplets, thus increasing contact time and reducing the probability of bouncing [24]. As for the freezing process of the water droplet, 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 [25–30].

More recently, Jin et al. [31] reported the observations of the successive freezing processes of three water droplets on an ice surface, which lasted in the range from 50.0 s to 150.0 s. However, the impact process of the water droplet on the ice surface was not measured due to the low frame rate of the Intensified CCD camera. Their results showed that both ice surface temperature and the initial height of the water droplet had significant effects on not only the droplet freezing time, but the contact diameter, angle, and height of the final ice bead as well. When the initial height of the water droplet was relatively small, the subsequent water droplet could only cover a portion of the ice bead formed by the previous droplet.

Even though extensive researches have been performed on the impact and freezing processes of a water droplet on various cold solid surfaces in previous studies [4–31], to the authors' best knowledge, the detailed dynamic motions of a water droplet impacting on an ice surface has not yet been experimentally investigated. Since the actual applications mentioned above usually involve the impact process of a water droplet on an ice surface [1–3], it is of particular interest to know the details of the water droplet kinematics during this process.

In this study, a small reservoir was designed and fabricated. During the experiment, the deionized water in the reservoir was first cooled down to form a frozen surface. Then, a deionized water droplet was deposited onto the ice surface by a droplet generator and the impact and freezing processes were recorded by two cameras. A parameter study of the ice surface temperature and the initial height of the water droplet 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. Experimental setup

The schematic of the current experimental setup is shown in Fig. 1, which is similar to our previous studies [7,8,11,31]. A small reservoir (50.0 mm L × 50.0 mm W × 3.5 mm H) was designed and fabricated, the bottom surface of which was a red copper plate (50.0 mm L × 50.0 mm W × 1.5 mm H). The side walls of the reservoir were made of plexi-glass. At the beginning of the experiments, the reservoir was filled with deionized water. Then, its bottom surface was cooled down to a subfreezing temperature by a constant temperature circulator (AC150-A25, Thermo Scientific). During this process, the deionized water in the reservoir froze and formed an ice surface. The temperature of the ice 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 droplet was released, it fell onto the ice surface due to gravity. A plastic tube was placed in between the reservoir and the droplet generator, which was used to reduce the disturbances of surrounding air on the movement of the water droplet. Besides, in order to minimize the desublimation of the vapor on the ice surface, a plexi-glass cover (75.0 mm L × 75.0 mm W × 25.0 mm H) with a small orifice (Φ = 8.0 mm) on its top surface was used to cover the reservoir during the experiments. Once the ice surface reached a desirable temperature, the orifice was open and a deionized water droplet was placed on the ice surface. The impact process of the water droplet on the ice surface was obtained by a high speed camera (Dimax HD, PCO) operating at a fixed frequency (f = 2000 Hz) and then stored in computer 2 for later analysis. Besides, the freezing process of the water droplet was recorded by another CCD camera (SensiCam, PCO) and then stored in computer 1. A delay generator (575, BNC) was adopted to trigger this SensiCam CCD camera operating at a fixed frequency (f = 2 Hz). In addition, a light diffuser was utilized to enhance the uniformity of the incoming cold light.

2.2. Experimental conditions

During the experiment, the relative humidity and temperature of the air in the laboratory were kept at 64.0 ± 4.0% and 27.0 ± 0.5 °C, respectively. The initial height of the water droplet (H) investigated in the present study was changed from 10.0 cm to 40.0 cm. In addition, through adjusting the bath circulator, three ice surface temperatures (T_w) were tested, which were −5.0 °C, −10.0 °C, and −15.0 °C, respectively. In the present study, ten repeated tests were carried out for each case.

2.3. Droplet diameter

Before the water droplet arrives at the ice surface, its shape can be approximately considered as an ellipse. Based on the obtained images [32,33], the according equivalent diameter of the water droplet can be calculated by Eq. (1):

$$D_0 = (D_v D_h^2)^{1/3} \tag{1}$$

where D_0 is the equivalent diameter of the droplet, D_v the vertical length of the droplet, D_h the horizontal length of the droplet. In the present study, we used a droplet generator to produce water droplets with a fixed equivalent diameter (D_0 = 2.92 mm). In order to verify the repeatability of the droplets, 100 droplets were tested and the uncertainty was found to be less than 0.02 mm.

2.4. Dimensionless numbers

Since air resistance exerts an influence on the droplet during its falling process, the velocity of the droplet right before it impinges the ice surface can be calculated by Eq. (2) [34,35]:

$$U_0 = \sqrt{\frac{g}{\alpha}(1 - \exp(-2\alpha H))} \tag{2}$$

where H is the water droplet falling height, $\alpha = 3\rho_{air}C_f/(4\rho_{water}D_0)$. Since the droplet Reynolds number is larger than 1000 in the present study, C_f can be simply treated as a constant, 0.44, by following the previous studies [36,37]. Thus, the velocity of the water droplet right before it impinged the ice surface, U_0, could be calculated. The uncertainty of this terminal velocity could be determined experimentally. Based on the last two successive images of the water droplet right before its arrival at the ice surface, the uncertainty of the terminal velocity was estimated to be within 0.025 m/s.