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The impact and freezing processes of a water droplet on different cold spherical surfaces

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ABSTRACT

In the present study, we experimentally investigated the impact and freezing processes of a water droplet on different cold spherical surfaces. During the experiment, the spherical surface was put into a cover in which pressurized Argon gas was injected 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 spherical surface and its impact and freezing processes were recorded. The results showed that, during the recoiling process of the water droplet, the spreading factors at low surface temperature cases were larger than that of the room temperature case, regardless of the radius of the spherical surface. In addition, the radius of the spherical surface had an apparent effect on the spreading factor when the surface temperature was relatively low (eg. $T_w = -9.5$ and -14.0 °C). During the freezing process of the water droplet, the change of the temperature as well as the radius of the spherical 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 but also poses hazards to the safety of the aero-engine [1,2]. Generally speaking, the icing on the fairing of aero-engine involves the impact and freezing processes of water droplets on cold spherical surfaces. Thus, a better understanding of these processes would be very desirable for researchers to predict the ice accretion on the fairing of aero-engine more accurately.

Over the years, the impact process of a water droplet on different spherical surfaces has been attracting researchers around the world. For example, Hardalupas et al. [3] observed the sub-millimeter droplet impingement onto spherical surfaces. Their results showed that the re-atomisation was repeatable and influenced by surface morphology. Chow and Attinger [4] investigated the microdroplet impact dynamics on a curved substrate and found that the substrate curvature had no significant influence on the maximum spread factor for a substrate-droplet curvature ratio below 0.3, but had an effect on the splashing. Bakshi et al. [5] studied the impact of droplets with spherical targets. The film thickness variation on the spherical surface showed that the dynamics comprised three distinct phases, namely the initial drop deformation phase, the inertia dominated phase, and the viscosity dominated phase. The first two phases collapsed onto each other for different values of Reynolds number, while the transition to the third phase occurred earlier at low Reynolds numbers. When the target size was increased, the film thinning process was slower with a larger value of residual thickness. Li et al. [6] developed a numerical model for three-dimensional direct simulation of droplet impinging onto a spherical surface on a fixed Eulerian mesh. The simulation results showed that the impacted sphere size had a significant effect on the impact dynamics of the droplet. Mitra et al. [7] studied the impact of water, isopropyl alcohol and acetone micro-liter droplets on a heated spherical brass particle in the temperature range of 20–250 °C both experimentally and numerically. They found a saturation temperature of the surface which determined the transition from wetting contact to non-wetting contact. In the non-wetting contact regime, the drop temperature was found to be significantly lower which led to significant reduction in heat transfer coefficient. Liang et al. [8] observed a single liquid drop impinging onto a static drop located on steel spheres. By increasing the Weber number, experimental observations present outcomes of rebound, coalescence, and the circular liquid sheet. The effect of Weber number and curvature ratio on the liquid sheet diameter was discussed. Gumulya et al. [9] developed a three-dimensional, CLSVOF-

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based numerical model to study the hydrodynamics of water droplets of various diameters impacting a heated solid particle. The spread of the droplets upon impact was found to be dependent on the Weber number, with surface tension and viscous forces then acting to recoil the droplet. Recently, Khaled [10] investigated the impact and freezing processes of a water droplet on a super cold spherical surface. He observed the cracking of the ice layer when a deionized water droplet impacted a −50 °C cooled sphere 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. Mitra et al. [11] studied droplet-particle interaction of size ration less than unity in the film boiling regime on a highly thermally conductive spherical particle surface. They found a critical Weber number range, noted from rebound to disintegration regime transitions. The results showed that maximum contact area increased with Weber number, but contact time decreased.

Even though some researches have been performed on the impact process of a water droplet on spherical surfaces in previous studies [3–11], to the authors' best knowledge, only limited study of a water droplet impact and freezing processes on super cold spherical surfaces (−50 °C) has been experimentally performed [10]. According to the Ref. [12], aircraft icing phenomenon occurs most often when the temperature is in the range from 0.0 °C to −10.0 °C. Thus, it is of particular interest to know the detailed impact and freezing processes of a water droplet on cold spherical surfaces under relatively higher subfreezing temperatures.

In this study, a deionized water droplet was deposited onto the cold spherical surface by a droplet generator and its impact and freezing processes were recorded. A parameter study of the temperature and the radius of the spherical 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. Spherical surfaces

Since the radius of the fairing of aero-engine is usually in the order of mm and higher, four spherical surface models were tested in the present study, the materials of which were stainless steel (306). The schematic of the cross section of these surface models is shown in Fig. 1. All these models had a length (L) of 50.0 mm and a width (W) of 50.0 mm. Besides, the height of the apex (h_1), the height of the base plate (h_2), and the height of the stage (h_3) were 15.0 mm, 5.0 mm, and 8.0 mm, respectively. The radius (R) of the spherical surface was varying in the range from 15.0 mm to 30.0 mm. 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.

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 [13–17]. 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 spherical 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. 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 impinge the test surface. The impact and freezing processes 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 freezing process, respectively. The exposure time of the PCO camera was 120 μs. Besides, the impact process of the water droplet was also recorded by another high speed camera (FR180, NORPIX) from a different perspective and then stored in computer 1. The objective of using two high speed cameras was to make sure that the water droplet impinged right onto the apex of the spherical surface. A delay generator (575, BNC) was adopted to trigger this NORPIX camera operating at a frequency f = 500 Hz for the droplet impact process. The exposure time of the NORPIX camera was 129 μs. In addition, a light diffuser was utilized to enhance the uniformity of the incoming cold light. The above-mentioned equipment, except the computers, cold light, Argon gas cylinder, and circulator, was put on an anti-vibration table to reduce the effect of outside disturbances.

2.3. Experimental conditions

During the experiment, the relative humidity and temperature of the air in the laboratory were kept at 66.0 ± 5.0% and 25.5 ± 1.0 °C, respectively. The initial height of the water droplet (H) investigated in the present study was 15.0 cm. In addition, through adjusting the constant temperature bath circulator, four test surface temperatures (T_w) were tested, which were 25.5 °C, −5.0 °C, −9.5 °C, and −14.0 °C, respectively. In order to testify the uniformity of the temperature distribution along the azimuthal direction of the cold spherical surface, the surface temperatures at three different azimuthal angles (0°, 45°, and 90°) were monitored and the maximum temperature difference among them was found to be within 0.05 °C. In the present study, ten repeated tests were carried out for each case.

2.4. Droplet diameter

Before the water droplet arrives at the test surface, its shape can be approximately considered as an ellipse. Based on the obtained images [18,19], the according equivalent diameter of the water droplet can be calculated by Eq. (1):

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

where D_0 is the equivalent diameter of the droplet, D_v the vertical

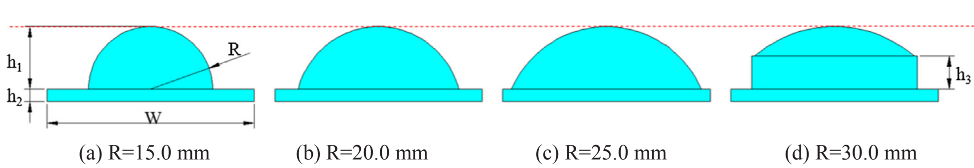

Fig. 1. Schematic of the cross section of the surface models.