Visualization of the Freezing and Melting Process of a Small Water Droplet on a Cold Surface

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Abstract. An experimental investigation was conducted to visualize the freezing and melting process of a small water droplet on a cold surface by using Laser Induced Fluorescence (LIF) technique. It was found that, during the freezing process, the interface between the liquid phase water and solid phase ice moved upward continuously and finally an ice crystal with a cusp-like top was formed. After the shutdown of the bath circulator, frosts appeared on the top of the ice crystal and continued to grow for a short period of time. Then the frosts started to melt, followed by the protrusion part of the ice crystal. After that, a solid-liquid interface was formed inside the ice crystal and kept moving upward until the ice crystal was melted completely. The present work provides some tentative insights into the microphysical process related to the icing and melting process of water droplets.

Keywords: Freezing, Melting, Frost, Interface, Water droplet, Visualization.

1. Introduction

When humid air comes in contact with a cold surface whose temperature is below both the dew point of the air and the freezing point of water, frost may form on the surface. The occurrence of frosting is undesirable for most industrial applications such as air conditioners and refrigerators. A frost layer formed on an evaporator not only increases the air side thermal resistance, but also reduces the airflow area, both of which reduce the evaporator performance.

Hayashi et al divided the frost formation process into three different periods, that is, the crystal growth, the frost layer growth, and the frost layer full growth period [1]. The frost crystal growth period, i.e. the freezing process of water droplets, is of significant importance even though the process is very fast. This period is the starting point of the frost deposition process and has attracted many researchers over the years. Carte experimentally investigated the freezing process of water droplets on various surfaces by using a microscope method. The relationship between the lowest freezing temperatures with surfaces, the volume of the water droplets, and the rate of cooling was obtained [2]. Visagie employed a small quartz Bourdon tube to measure the pressures that developed inside freezing water droplets and found the cracking pressure tended to increase with the shell thickness and was dependent on the freezing rate [3]. Feuillebois et al numerically studied the two-step freezing process of a subcooled liquid droplet, without considering the combined effect of a variation in mass density during freezing with the Stefan problem [4]. Hoke observed the frost deposition on a variety of substrates and found that the water distribution on the substrate at the end of the condensation period was strongly dependent on substrate temperature, humidity ratio, and substrate contact angle [5]. Tabakova and Feuillebois modeled the solidification and subsequent cooling of a supercooled liquid droplet that was lying on a cold solid substrate after impact, with an assumption that solidification occurred for a given fixed droplet shape [6]. Hindmarsh et al used magnetic resonance imaging (MRI) to provide spatially resolved structural and chemical composition characterization of freezing droplets [7].

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Recently, Wang et al experimentally investigated the freezing process of water and peanut oil droplets on a cold surface and the protrusion phenomenon observed during the tests was explained in details [8]. Wu et al illustrated the condensation and freezing process of water droplets on a cold surface [9]. Suzuki et al studied the effects of smooth and rough coatings of FAS-17 on contact angles, sliding angles, and freezing temperatures of the water droplets [10]. Nitsch experimentally studied water freezing and supercooling by methods of thermal analysis in a water droplet of 5mm in diameter and found the degree of water supercooling was influenced by previous thermal treatment but only to a certain extent [11]. More recently, a lifetime-based Molecular Tagging Thermometry (MTT) technique has been developed and implemented to reveal the time evolution of the unsteady heat transfer and dynamic phase changing process within small icing water droplets [12, 13].

Even though extensive researches have been conducted in previous studies [2-13], to the authors’ best knowledge, the complete freezing and melting process of a water droplet on a cold surface has not been experimentally investigated yet. In this study, we report an experimental visualization of the freezing and melting process of a small water droplet on a cold surface by using Laser Induced Fluorescence (LIF) technique. The present study is aimed to elucidate underlying fundamental physics to improve our understanding about the important microphysical processes pertinent to icing phenomena.

2. Experimental Setup

Fig. 1 shows the schematic of the experimental setup used in the present study. A droplet generator (CFT-8401A, Medrich) was used to generate small water droplets (6.21µL in volume and initial temperature of 20.1°C) to impinge onto a red copper test plate. The water droplets contained a mixture of Rhodamine B (5×10⁻⁶ mol/L) and DI water. The temperature of the test plates, which was monitored by using a thermocouple, was kept constant at a pre-selected low temperature level by using a constant temperature bath circulator (AC 150-A25, Thermo Scientific). A laser sheet (~600µm in thickness) from a pulsed Nd:Yag laser at a wavelength of 532nm was used to illuminate the Rhodamine B molecules along the middle plane of the small water droplets. A filter (570FG05-50, Max levy) was placed in the front of a CCD camera (Sensicam Qe, Cooke Corp.) so that only fluorescence emissions could be captured by the camera. The camera and the pulsed Nd:Yag laser were connected to a workstation via a digital delay generator (BNC 575-8C), which controlled the timing of the laser illumination and the image acquisition. It is noted that, due to the low concentration of the tracer molecules used for the measurements, the effects of the molecular tracers on the physical properties of water and icing process are believed to be very small. Since the low energy level and repetition rate of the pulse laser excitations are used for the fluorescence measurements, the effects of the energy deposition due to the pulsed laser excitation on the icing process is expected to be negligible.

3. Results and Discussions

During the experiment, the relative humidity, temperature, and pressure of the surrounding air were kept constant.
at 62.3%, 20.1°C, and 102658 Pa, respectively. Fig. 2 shows the time sequence of the acquired fluorescence images of the freezing process of a water droplet on a cold red copper test plate ($T_w = -6.4^\circ C$). In the fluorescence images, the brighter region in the upper portion of the droplet represents the liquid phase (water), while the darker region at the bottom indicates the solid phase (ice). It can clearly be seen that the liquid water at the bottom of the droplet was frozen and turned to solid ice rapidly, while the upper portion of the droplet was still in liquid state. As time went by, the interface between the liquid water and the solid ice gradually moved upward. At about 14s later, the droplet was found to completely turn into a solid ice crystal. One small protrusion appeared on the top of the ice crystal at the end of the freezing process. The protrusion phenomenon has also been observed in previous studies [8, 12, 13].

Fig. 2 Fluorescence images of droplet icing process

Once the freezing process was completed, the constant temperature bath circulator was shut down. The temperature of the test plate increased as time went by, while the ice crystal underwent frost formation first and then underwent melting process. The whole process was recorded by fluorescence images as shown in Fig. 3. At the beginning, the vapor in the moist air de-sublimated (vapor-to-ice transformation) onto the surface of the ice crystal and frosts were formed. However, apparent frosts could only be found on the top of the ice crystal, while the rest of the ice crystal surface kept almost unchanged (Fig. 3b). The frosts grew with time in the direction normal to the surface of the test plate (Fig. 3c, d, and e). Then, the frosts started to melt (Fig. 3f), followed by the protrusion part of the ice crystal (Fig. 3g and h). It is of interest to mention that a solid-liquid interface, similar to that shown in Fig. 2, appeared at the bottom of the ice crystal (Fig. 3i). However, in this case, liquid water stayed below the interface due to its higher density than that of the ice. As time advanced, the interface between the liquid water and the solid ice was found to gradually move upward until the whole melting process was finished (Fig. 3j, k, and l).
4. Conclusions

In summary, we reported an icing physics study to visualize the freezing and melting process of a small water droplet on a cold surface by using Laser Induced Fluorescence (LIF) technique. It was found that, during the freezing process, the liquid water at the bottom of the droplet was frozen and turned to solid ice rapidly, while the upper portion of the droplet was still in liquid state. As time went by, the interface between the liquid water and the solid ice gradually moved upward and at last an ice crystal with a cusp-like top was formed. After the shutdown of the bath circulator, frosts appeared on the top of the ice crystal and continued to grow for a short period of time. Then the frosts started to melt, followed by the protrusion part of the ice crystal. After that, a solid-liquid interface was formed inside the ice crystal and kept moving upward until the ice crystal was melted completely.

The present work provides some tentative insights into the microphysical process related to the icing and melting process of water droplets. Effects of test plate temperatures, droplet sizes, and air humidity on the water droplet freezing and melting processes are recommended to be investigated in future studies.

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6. References


