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# Freezing and melting of a sessile water droplet on a horizontal cold plate

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ABSTRACT

Water droplet freezing phenomena widely exist in the fields of aerospace, power, meteorology and refrigeration. In this research, the freezing and melting processes of a sessile water droplet on a horizontal cold plate are studied experimentally. The nucleation temperature of a supercooled droplet is determined and analyzed statistically. The freezing behaviors of a water droplet, which are characterized by the freezing front and the droplet profile, volume and height, are obtained through the photographic approach. Experiments are done on water droplets having four different volumes including 1, 5, 10 and 20 μL. The experimental results show that the ice nucleation is stochastic, and its occurrence needs a large degree of supercooling. The nucleation temperature approximately satisfies the normal distribution, it scatters over a wide range, with the average nucleation temperature decreasing with reducing droplet volume. The droplet volume and height increase suddenly at the nucleation and recalescence stages, as time passes the volume expansion rate diminishes while the height increment rate increases. A colder plate yields a higher freezing rate and consequently a shorter freezing time. In contrast, a frozen droplet begins to melt at an almost fixed temperature of about 0.5 °C, and the larger the droplet, the longer the melting time.

## 1. Introduction

Freezing of a supercooled water droplet is a complex process accompanying phase change heat transfer and moving boundary of water/ice interface. Freezing phenomena widely exist in the fields of aerospace, power, meteorology and refrigeration. In aerospace, aircraft icing presents a serious hazard for flight, which occurs when supercooled droplets in clouds impinge and stick on aircraft under natural icing conditions. It increases drag and reduces lift and controllability, even leads to serious flight accidents [1,2]. Theoretical models exist for aircraft icing simulation [3–5], they are based on the energy balance during equilibrium phase transition but ignore the non-equilibrium effect of supercooling. In power sector, ice accretion on wind turbines or transmission lines is a threat to the safe operation of equipment [6,7]. In meteorology, hailstorms cause damage to buildings, crops and automobiles, which may result in large economic and insured losses [8]. In refrigeration, frost formation on evaporator increases the thermal resistance and blocks the airflow passage [9–13], causing a deteriorated thermal performance. Studies on freezing process of a sessile supercooled water droplet may contribute to not only the fundamental understanding of the freezing phenomena but also the improvement of the ice accretion prediction.

Many experiments on freezing of a supercooled water droplet have been conducted [14]. Hindmarsh et al. [15,16], Strub et al. [17], Chaudhary et al. [18] and Alizadeh et al. [19] all described the temperature transition characteristics of a supercooled water droplet during its freezing process based on their experimental observations, they divided such a process into five distinct stages, as shown by Fig. 1: (1) liquid cooling (supercooling), (2) nucleation, (3) recalescence, (4) freezing, and (5) solid cooling, of which the nucleation, recalescence, and freezing stages are directly related to the freezing of a droplet. The nucleation is the starting point of the recalescence and may occur spontaneously. The recalescence takes place quickly and usually lasts tens of milliseconds, during which the supercooling drives rapid kinetic crystal growths from crystal nuclei. The droplet changes into a uniform mixed-phase state, which is comprised of a mixture of ice and water, with its temperature rising to the equilibrium freezing point of 0 °C due to the latent heat release. The freezing stage is a longer process and may last tens of seconds, during which the remaining water-ice mixture becomes completely solidified [15,19]. The freezing front advances from the liquid-solid interface to the droplet topmost point.

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**Nomenclature**

| | |
|---|---|
| $c$ | heat capacity, J kg$^{-1}$ K$^{-1}$ |
| $Gr$ | Grashof number |
| $H$ | droplet height, m |
| $h$ | enthalpy, J kg$^{-1}$ |
| $L$ | latent heat of solidification, J kg$^{-1}$ |
| $Nu$ | average Nusselt number |
| $Pr$ | Prandtl number of air, 0.707 |
| $St$ | Stefan number |
| $T$ | temperature, °C |
| $\Delta T$ | supercooling degree, °C |
| $t$ | time, s |
| $V$ | droplet volume, L |

*Greek symbols*

| | |
|---|---|
| $\beta$ | mass fraction |

*Subscripts*

| | |
|---|---|
| F | freezing |
| i | ice |
| Ref | reference |
| w | water |
| 0 | nucleation |

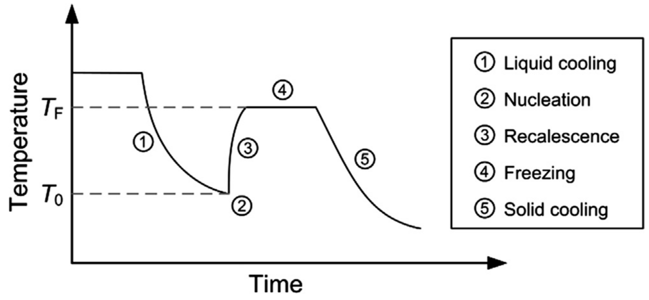

**Fig. 1.** Temperature transition of five stages during freezing process of a droplet [15,16,18].

The nucleation and recalescence are so short that the studies on them resorted mainly to experiments. Chaudhary et al. [18] and Alizadeh et al. [19] found that the recalescence started from one point and then extended rapidly to the entire water droplet. Using a high-speed camera in experiments, Jung et al. [20] noticed that evaporative cooling of supercooled liquid by airflow engendered ice crystallization by homogeneous nucleation at the droplet-air interface as opposed to the expected heterogeneous nucleation at the substrate surface. Rahimi et al. [21] found that a slightly hydrophilic substrate modified by (3-aminopropyl) triethoxy-silane showed longer freezing delays than both more hydrophilic and more hydrophobic substrates. They suggested that not only the surface wettability and topography but also the surface chemistry played a significant role in the kinetics of ice formation when a water droplet was placed on a precooled substrate. Wu et al. [22] observed that when the cold wall had a temperature above −12 °C, the smaller the droplet and its contact angle and the smoother the wall surface, the later the occurrence of the nucleation stage. Jin et al. [23] reported that the freezing process of a water droplet on a cold surface started earlier at a lower ambient pressure.

The longer lasting freezing stage was explored from different aspects. Hindmarsh et al. [15,16] and Chaudhary et al. [18] experimentally and numerically investigated the temperature transition of a freezing water droplet. Li et al. [24] developed an experimental approach to directly visualize the global freezing phase changes of micro liquid droplets using infrared (IR) thermograph and acquired the droplet temperature variations throughout the transient process. Marín et al. [25,26] captured the geometry of the freezing front in freezing process and performed systematic measurements of the angles of the conical tip. They found that cone angle was independent of substrate temperature and wetting angle, and it took a value of 139° ± 8°. Tropea et al. [27] compared the freezing features of sessile water drops and those observed using the Hele-Shaw cell. Zhang et al. [28] and Huang et al. [29] both found that a larger contact angle led to a longer freezing time. Hu and Jin [30,31] developed a molecular tagging thermometry (MTT) technique to realize temporally-and-spatially resolved temperature distribution measurements within micro-sized water droplets.

Although many experiments have been done, they mainly focused on the temperature transmission during freezing process, the whole freezing time, and the effects of environment on the nucleation delay. Limited attentions were paid to the droplet profiles and freezing front traits. There exist great uncertainties with the nucleation temperature for a supercooled droplet on a cold plate, which needs to be further studied. The volume expansion characteristics of a water droplet during freezing is also an interesting topic, knowledge on it can help better model the freezing of a droplet. Meanwhile, our literature survey reveals little work on melting of a frozen droplet, despite that studies on that may contribute to the anti/de-ice and defrost. Jin et al. [32] observed the melting of a frozen droplet and gave a brief description of it.

In this research, the freezing and melting processes of a water droplet on a horizontal cold plate are experimentally studied. The freezing behaviors are characterized by the freezing front and the droplet profile, volume, and height. The nucleation temperature of a water droplet is determined and analyzed statistically. The freezing and melting processes are compared and discussed.

## 2. Experimental setup and method

Fig. 2 shows the experimental setup used in this research, which consists of a test section, a semiconductor thermoelectric cooler system, a data acquisition system and a photograph acquisition system.

The test section includes an aluminum plate and a micro-injector. The aluminum plate serves as the cold surface for water droplet freezing, it has a dimension of 40 mm length × 40 mm width × 1 mm thickness and a wetting angle of 85 ± 5°, which is measured by a contact angle goniometer (JC2000C1, China, ±1° accuracy). In the experiment, water droplets are generated by the micro-injector and are placed on the cold aluminum plate to make them cool down and freeze.

The semiconductor thermoelectric cooler system consists mainly of a programmable DC power supply (Agilent N5766A, America, 0.02 V regulation accuracy), a semiconductor cooler (TEC1-12706), a channel and a constant temperature bath. Cold water from the constant temperature bath flows through the channel to carry away the heat generated by the semiconductor cooler. The temperature of the cold aluminum plate is controlled to decrease linearly by adjusting the output voltage of the DC power supply, which is connected with the semiconductor cooler and is