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Simulation and experiment on supercooled sessile water droplet freezing with special attention to supercooling and volume expansion effects

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ABSTRACT

The freezing process of supercooled water droplets on cold plates is studied experimentally and numerically. A numerical model that considers both the supercooling effect on the physical properties and the volume expansion effect on the droplet freezing profile is established to simulate the droplet freezing behaviors using the Solidification/Melting model. Experiments are conducted on both hydrophilic and hydrophobic surfaces for 5, 10, 20, 30 and 40 μL supercooled water droplets. The droplet freezing behaviors including the freezing front movement and freezing time are observed using the image recognition technology. The evolution of the freezing front calculated by the numerical model agrees better with the experimental observation than the traditional model that ignores the supercooling effect or uses the initial droplet profile. The model reduces the deviation of freezing time from about 30% to about 10% for both hydrophilic and hydrophobic surfaces. With use of the average value of the freezing times yielded by the numerical and theoretical models, a correlation is developed for predicting the freezing time. It can correlate more than 90% of the simulation data and all of the experimental points within ±25%. As the cold plate temperature, droplet volume and contact angle increase, the freezing time increases, with the plate temperature and contact angle possessing a more significant influence than the droplet volume on the freezing process.

1. Introduction

Freezing of supercooled water droplet is often observed in many engineering and environmental processes. In aerospace, aircraft icing caused by supercooled droplet impinging greatly reduces the lift and increases the drag, constituting a huge threat to the aircraft flight safety [1–3]. In the power sector, ice accretion on wind turbines or transmission lines may lead to a variety of problems [4]. In meteorology, hailstorms may cause damage to buildings, crops, and automobiles [5]. In refrigeration, frost formation on an evaporator increases the thermal resistance and blocks the airflow passage [6–8], resulting in a deteriorated thermal performance. In cryopreservation, water crystallization occurs during the food freezing process [9]. Studies on freezing process of a supercooled water droplet can help to better understand the ice/frost formation and accumulation and the anti-ice/-frost mechanisms of hydrophobic surfaces [10,11], they can even provide insights into material solidification [12] and 3D printing [13].

Many experiments have been conducted on supercooled water droplet freezing [14]. Hindmarsh et al. [15,16], Strub et al. [17], Chaudhary & Li [18] and Alizadeh et al. [19] all experimentally observed the temperature transition characteristics during droplet freezing. The freezing process can be divided into five distinct stages as illustrated by Fig. 1: (1) liquid cooling (supercooling), (2) nucleation, (3) recalescence, (4) freezing, and (5) solid cooling. The nucleation is the starting point of the recalescence and may occur spontaneously. The recalescence takes place instantaneously and usually lasts tens of milliseconds, during which the supercooling drives rapid kinetic crystal growths from crystal nuclei. At the end of the nucleation/recalescence stage, the droplet changes into a uniform mixed-phase state consisting of water-ice mixture, with its temperature reverting to the equilibrium freezing point of 0°C due to the release of latent heat and its volume expanding because of the sudden change in density. The freezing stage is a longer

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Nomenclature

$a_1 \sim a_5$, A, B	coefficient
b	radius of the curvature at the apex, m
Bo	Bond number
c	specific heat, J kg^{-1} K^{-1}
H	freezing front height, m
h	enthalpy, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	latent heat of solidification, J kg^{-1}
q	heat flux, W m^{-2}
R	freezing front radius, m
S	energy source term, J m^{-3} s^{-1}
St	Stefan number
T	temperature, °C
T_A	ambient air temperature, °C
T_C	cold plate temperature, °C
T_F	freezing temperature (point), °C
T_N	nucleation temperature, °C
$T_{Liquidus}$	liquidus temperature, °C
$T_{Solidus}$	solidus temperature, °C
ΔT	difference between freezing temperature and cold plate temperature, $T_F - T_C$, °C
ΔT_F	phase change temperature range, $T_{Liquidus} - T_{Solidus}$, °C
t	time, s
V	volume of water-ice mixture, m^3
v	freezing rate (velocity), m s^{-1}
v_S	slipping velocity, m s^{-1}
x	x axis, m
X	physical properties
z	z axis, m

Greek symbols

α	liquid fraction
β	mass fraction
η	characteristic slipping velocity, m s^{-1}
θ	contact angle, rad
θ_D	dynamic growth angle, rad
θ_R	receding angle, rad
ρ	density, kg m^{-3}

Subscripts

m	mixture
N	nucleation
i	ice
Ref	reference
w	water
0	initial

process and may last tens of seconds, during which the remaining water-ice mixture is completely solidified [15,19]. Zhang et al. [20] experimentally investigated the freezing front and droplet profile of a sessile water droplet on a horizontal cold plate and proposed a theoretical model to calculate the final droplet profile at the end of the freezing process with consideration of the supercooling effect [21]. Marín et al. [22] observed the geometry of the droplet freezing front and found that the conical tip angle was independent of the substrate temperature and wetting angle, and had a value of about 140°. Ismail & Waghmare [23] claimed that the universal conical tip reported by Marín et al. [22] could also be achieved when the freezing droplet was asymmetric. Tropea & Schremb [24] compared the freezing features of sessile water drops with those obtained using the Hele-Shaw cell.

As for the simulation on the droplet freezing process, all studies focused on the freezing stage based on the heat balance. Vu et al. [25,26] numerically investigated the drop solidification on a cold plate with the presence of volume change by combining the front-tracking method with an interpolation technique to deal with the non-slip boundary condition at the solid surface, and this resulting combinatorial method was effective in simulating the variation of drop profile with time during solidification. Zhang et al. [27] simulated the freezing process of a sessile droplet based on its initial profile using the equivalent heat capacity method and temperature-dependent thermal properties. The numerical results showed that the contact angle between the droplet and solid surface had a strong influence on the freezing time which exponentially increased with the contact angle for a given droplet volume. However, they took no account of the supercooling effect which might result in a large error in the final freezing time. Chaudhary & Li [18] carried out their simulations by numerically solving the enthalpy-based heat conduction equation with consideration of the supercooling effect. They found that the time taken for a droplet to freeze depended on the droplet temperature at the pre-recalescence instant as well as the surface wettability. However, they compared only the topmost temperatures between the simulation and experiment but failed to compare the variations of the freezing front because they used the initial droplet profile. Blake et al. [28] simulated the freezing of supercooled water droplets impacting a cooled substrate using the VOF and Solidification/Melting model in Fluent.

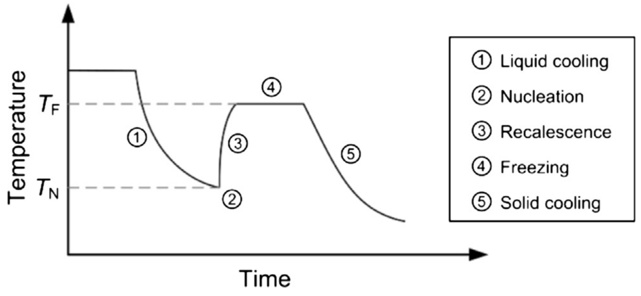

Fig. 1. Temperature transition at five stages during droplet freezing [15,16,18].

Although many studies have been done on the numerical simulation of droplet freezing process [15,16,28,29], they simply mentioned the nucleation/recalescence phenomenon and few of them paid attentions to the supercooling effect at the nucleation/recalescence stage and its impact on the subsequent freezing stage during the whole freezing process. In fact, the sudden changes of droplet volume and physical properties, especially the latent heat, may significantly alter the freezing rate and consequently the freezing time. The water-ice mixture has a smaller latent heat than the water, which works to accelerate the freezing process. Further, the previous studies neglected the volume expansion in the simulation [18,27], which acts to slow down the freezing process due to the increase of droplet height. For these reasons, the predictions of the variations of the freezing front and final freezing time in the previous simulations were not so successful, although the freezing rate and time are extremely important for the ice accretion prediction.

In this work, the freezing process of water droplet on cold plates is studied numerically and experimentally. A numerical model involving the VOF multiphase model and the Solidification/Melting model in CFD Fluent software is built to simulate the droplet