ARTICLE IN PRESS

Journal of Crystal Growth (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/jcrysgro

Ice growth and interface oscillation of water droplets impinged on a cooling surface

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ARTICLE INFO

Communicated by Simon Brandon

Keywords:
A1. Solidification
A1. Interfaces
A1. Heat transfer
A1. Water droplets
A1. Ice shells
A1. Interface oscillation

ABSTRACT

We focused on the attenuation of air-water interface oscillation for impinged water droplets freezing on a cooling surface. We carried out not only experiments but also two-dimensional numerical simulation on the droplets using a Phase-field method and an immersed boundary method. The Reynolds number and Weber number were in the range of 35–129 and 1.6–22, respectively. The experimental and computational results showed that the height of the impinged droplets on the symmetrical axis started to oscillate as a result of the impact of the collision of droplets with the surfaces in all the cases that we investigated. The measured frequency of the oscillations in the case of the adiabatic droplets was equal to the frequency estimated from the equation for the capillary-gravity waves on sessile droplets (Temperton, 2013) [30]. The oscillations converged rapidly in all impinged water droplets that froze on the cooling surface. This is due partly to the growth of ice shells along the air-water interface and partly to decreases in water volume as a result of the ice growth mainly on the cooling surface. In addition, the thermal field was disturbed not only by the latent heat transfer but also by the upward component of recirculating flow induced by the droplet impingement.

1. Introduction

In ice accretion, an ice layer is formed on a cooling surface by the freezing of supercooled water droplets, which have collided with the surface. The surfaces of the droplets oscillate as a result of the collision. Thus, the air-water interface fluctuates. Furthermore, the ice-water interfaces move inside the droplets as the ice regions increase because of the freezing. Consequently, the air-ice interfaces also move. Thus, the investigation of these three kinds of unsteady interfaces is necessary for elucidating the ice accretion.

Ice accretion causes serious troubles, such as (1) poor visibility through the windshields of aircraft, trains and automobiles; (2) the breaking of power transmission lines; (3) a deterioration of the aerodynamic performance of aircraft wings; and (4) damage to the casing of jet engines and air-conditioning equipment [1]. As a result, many studies have been carried out concerning the elucidation of ice accretion and the development or improvement of anti-icing technologies.

Some experimental studies have been carried out for the solidification of liquid droplets on horizontal cooling surfaces [2–13]. Ten of them dealt with the freezing of water droplets [3,4,6–13]. In Ref. [3,7–13], time changes in the shape or the location of ice-water interfaces were measured for the droplets 4–25 μl in volume. The effects of the wettability of cooling surfaces on the freezing were discussed in Ref. [4,7,9,11–13]. Time changes in the location and shape of the ice-water interface (freezing front) were measured in Ref. [9,10]. These time changes were predicted by solving the equation for the Stefan problem with assumptions of neglecting convection, supercooling and volume expansion in Ref. [10,11]. Time change in the droplet temperature was measured only in Ref. [4]. The oscillation amplitude and oscillation damping time scale of the air-water interface after the spread of droplets on ice surfaces were measured only in Ref [3].

However, despite these experimental efforts, the effects of droplet impingement on the ice growth of deposited droplets, and thus the ice accretion, have not yet been clarified. In addition, the assumptions of neglecting convection, supercooling and volume expansion mentioned above are not valid for the impinging droplets. Consequently, numerical simulation has recently been expected. Several attempts have already been made at this numerical simulation [14–18]. Galerkin finite element methods were used for the prediction of the solidification of impinged molten droplets and sessile droplets in Ref. [15,16]. The volume of fluid (VOF) methods were used for the prediction of impinging droplets in Ref. [17,18]. As far as the present authors know, though, there are no other reports on numerical simulation.

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http://dx.doi.org/10.1016/j.jcrysgro.2016.12.095

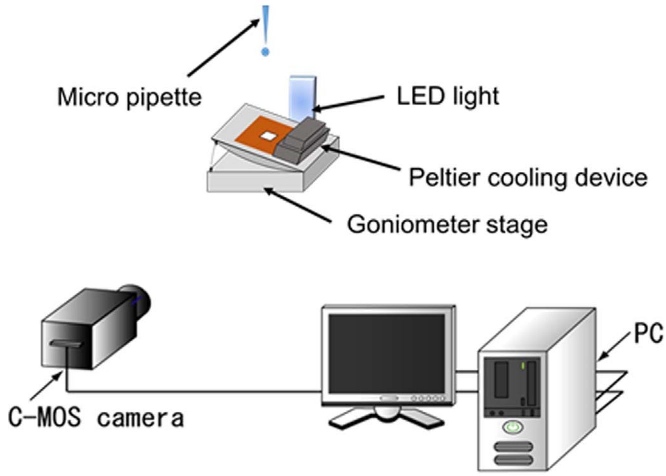

Fig. 1. Apparatus.

We have carried out experiments and numerical simulation of impinging water droplets on a cooling surface to elucidate key factors for the freezing of the impinged water droplets. In the present study, we focus on the oscillation of the air-water interface of the droplets, and the attenuation of the oscillation due to the freezing. We compare our experimental results with computational results.

2. Experiments

2.1. Apparatus

The apparatus used in the present study is shown in Fig. 1. It consists of a Gonio-stage, a light-emitting-diode (LED) lamp, an electronic cooling (Peltier) device, a monochrome C-MOS camera (Photron: FASTCAM-1024PCI 100K) and a PC. The apparatus was set up in a temperature-controlled room.

A coolant flowed inside the cooling device. The temperature of the cooling device was measured with a thermocouple embedded in the device. The temperature or its decreasing rate was controlled at a predetermined value with a controller (Sensor Control Inc. Japan, FC3510).

2.2. Procedures

A polystyrene plate of 20×20×0.30 mm^3 was used as a specimen. We separately measured the contact angle by using the images of stationary water droplets on this plate. The average contact angle, θ_w, was 95°. The plate was in contact with a copper plate. This copper plate was cooled by the cooling device.

Pure water was dropped on the plate with a micropipette. The images of the impinging droplets on the plate were captured with the video camera. The image-capturing conditions are shown in Table 1. The captured images were processed with the PC. Three or four droplets were observed in each case. The margins of errors for the interface location and interface velocity were approximately 0.021 mm and 11 mm/s, respectively.

Table 1
Image-capturing conditions.

Area size [mm^2]	10.8×10.8
Pixel numbers	512×512
Pixel resolution [μm^2]	21×21
Aperture	F8
Frame rate [frame/s]	500
Shutter speed [s]	0.002
Total frames for one run	13,000

Table 2
Experimental conditions.

Case	1	2	3	4
Droplet volume [mm^3]	3.0	3.0	3.0	3.0
Dropping height [mm]	2–5	2–5	2–5	50–70
Air temperature [°C]	17	17	5	5
Cooling device temperature [°C]	17	−20	−20	−20

2.3. Experimental condition

Table 2 shows the experimental conditions. The distances between the plate surface and the lower surface of a droplet being released were in the range of 2–5 mm or 50–70 mm. These distances are too short for the droplet velocity to reach the terminal velocity. The temperature of the room was maintained at 5 or 17 °C. The predetermined temperature of the cooling device was −20 °C. The actual surface temperature of the plate was approximately −10 °C. In all the cases shown in Table 2, the volume of droplets was 3.0 mm^3. This volume corresponds to the volume of typical rain drops. The equivalent diameter, 2 R, was 1.78 mm.

3. Numerical simulation

To identify the phase interfaces, we adopted a phase-field method. This method is a kind of diffuse interface model. We also used an immersed boundary method to avoid water flow inside the ice region.

3.1. Phase-field method

A phase-field variable, ϕ, was defined in the whole computational domain. ϕ =0 was assigned for one phase, ϕ =1 was assigned for another phase, and $\lambda < \phi < 1 - \lambda$ ($\lambda \ll 1$) denotes the interface. Phase-field methods have the following advantages; (i) boundary conditions are unnecessary at the interfaces, and (ii) additional calculation of curvature is unnecessary. We applied two independent phase-field variables for the identification of the ice-water interface and the ice-air interface.

3.2. Governing equations

We solved the following Allen-Cahn equation of ϕ for the ice-water interface inside the droplets:

$$\frac{\partial \phi}{\partial t} = M_\phi \left[a^2 \nabla^2 \phi - \left(f_{sol} - f_{liq} \right) \frac{dp}{d\phi} - W \frac{dq}{d\phi} \right] \tag{1}$$

where t is the time; M_ϕ is the mobility of the phase-field variable; a is the gradient coefficient; f is the energy density function of chemical potential; p is the gradient function; q is the double-well type energy barrier and W is the coefficient of q. Eq. (1) can be written as follows, using the weight function to obtain a smooth change in the energy density of chemical potentials $p(\phi) = \phi^3(10-15\phi + 6\phi^2)$ [19]:

$$\frac{\partial \phi}{\partial t} = M_\phi [a^2 \nabla^2 \phi + 4W\phi(1-\phi)(\phi - 0.5 + \beta)] \tag{2}$$

$$\beta = \frac{3}{2W}\Delta f = -\frac{15}{2W}\frac{L(T-T_m)}{T_m}\phi(1-\phi) \tag{3}$$

where T is the temperature; T_m is the melting point and L is the latent heat of solidification. The mobility of the phase-field variable, M_ϕ, was defined by the following equation [20]:

$$M_\phi = \frac{bT_m k}{3\delta L}, \quad k = \frac{V}{T_m - T} \tag{4}$$

where δ (=$|x(\phi = \lambda) - x(\phi = 1 - \lambda)|$) is the thickness of the interface; b