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Freezing of sessile water droplet for various contact angles

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ABSTRACT

We present both modeling and experimental study of the freezing of a sessile water droplet on a cold surface with different contact angles. The numerical model consists of two parts. One is to determine the geometric profile of sessile droplets by the Young-Laplace equation, and the other is to solve the two-dimensional Stefan problem via the equivalent heat capacity method. An experimental setup is built to observe the freezing process, and the moving water–ice interface is recorded by a CCD camera. A good agreement is found between the experimental observations and the numerical simulations of the moving water–ice interface in a sessile droplet deposited on both hydrophilic and hydrophobic cold surfaces, suggesting that the present model can well describe the freezing process of sessile droplets. Based on the modeling and simulations, it is shown that for a given droplet the freezing time exponentially increases with increasing contact angle. Results of our study are helpful to better understand the anti-ice/-frost mechanism of the superhydrophobic surfaces.

1. Introduction

Freezing of water droplets on cold solid surfaces is of importance to many engineering and environmental processes [1–4]. Due to its adverse effects [5,6], many efforts have been made to retard the ice/frost formation and accumulation on surfaces of turbine blades, aircrafts, heat exchangers, etc.

In recent decades, various studies reported the delay of the ice/frost formation on the superhydrophobic surfaces (with contact angle $\theta \geq 150^\circ$) [7–10]. During the frosting process [11], the water vapor in the moist air first condenses on the cold solid surface. Then, the condensed water droplet is frozen to form a frost layer. Finally, the frost layer continuously grows. Therefore, freezing of droplets is an important portion in the entire icing/frosting process, and understanding of the freezing process is necessary for anti-ice/-frost studies [12].

Tourkine et al. [13] experimentally studied the freezing time of depositing water on a cold copper plate and a superhydrophobic surface, and they showed a significant delay of the freezing on the superhydrophobic surface. They also obtained an experimental correlation of freezing time versus the volume and height of the droplets. Using a CCD camera, Lin et al. [14] recorded the moving water–ice interface inside droplet, and illustrated the phenomenon of heterogeneous nucleation of the droplet on a cold surface. Huang et al. [15] reported the effect of contact angle on water droplet freezing for a series of hydrophobic surfaces. Their experimental results indicated that a larger contact angle gives rise to a longer freezing time.

Tabakova and Feuillebois [16] numerically modeled the freezing process of supercooled droplets on a cold surface as a two-dimensional Stefan problem. Based on one-dimensional quasi-steady heat transfer analysis, Anderson et al. [17] studied the effects of dynamic contact angle on the freezing of droplets experimentally and analytically. Using the boundary-integral method, Ajaev and Davis [18,19] studied a two-dimensional containerless solidification problem and discussed the solidification rate and shapes of solid particles. Chaudhary and Li [20] recently reported an experimental and numerical study of the freezing of droplets on both hydrophilic and hydrophobic surfaces. In their experiments, the temperature evolution of selected points was recorded by an infrared camera and thermocouples. Compared to the experimental data, their enthalpy-based numerical simulations showed a close agreement in the freezing time.

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Nomenclature

a	capillary length (m)
b	radius of curvature at the apex (m)
c_p	specific heat capacity (J kg^{-1} K^{-1})
D	equivalent diameter (m)
g	gravity acceleration (m s^{-2})
h	height of droplet (m)
h_c	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
p	pressure (Pa)
r	radius of droplet-substrate interface (m)
T	temperature (°C)
T_m	melting temperature (°C)
t	time (s)
v	volume (m^3)
x	radial coordinate (m)
z	height coordinate (m)
Greek symbols	
γ	surface tension (N m^{-1})
ϕ	angle (°)
ρ	density (kg m^{-3})
θ	contact angle (°)
Subscripts	
a	air
init	initial
l	liquid phase
s	solid phase
Superscripts	
*	nondimensional

In this work, we present both numerical modeling and experimental studies of the freezing of sessile droplets on cold surfaces with various contact angles. In the modeling part, we first use the Young-Laplace equation to determine the geometry of sessile water droplets so as to improve the accuracy of the model. Then, we adopt the equivalent heat capacity method to solve the two-dimensional Stefan problem. An experimental setup is built to study the freezing process, and the moving water–ice interface is recorded by a CCD camera. Through a comparison of the experimental observations and the numerical predictions, the model is validated for both hydrophilic and hydrophobic surfaces.

2. Modeling and simulation

2.1. Geometry of a sessile droplet

Referred to the coordinate system in Fig. 1, the geometric profile of an axisymmetric sessile droplet on a solid surface can be described by the Young-Laplace equation which was expressed by Bashforth and Adams as below [21].

$$\frac{z''}{(1+z'^2)^{3/2}}+\frac{z'}{x(1+z'^2)^{1/2}}=\frac{2}{b}+\frac{\rho g z}{\gamma} \quad (1)$$

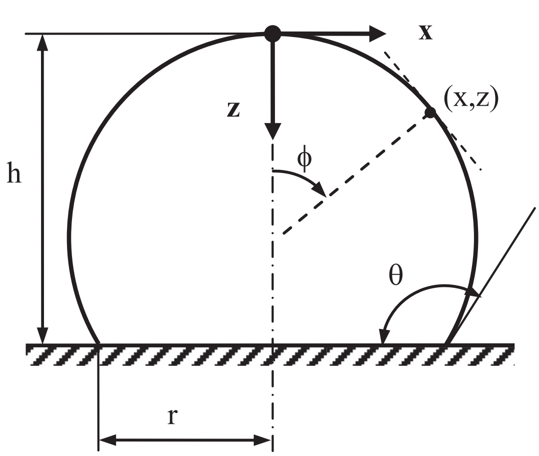

Fig. 1. Coordinate system of an axisymmetric sessile droplet on a solid surface.

where x and z are respectively horizontal and vertical distance from the origin located at the apex point of the droplet, $z' = dz/dx$ and $z'' = d^2z/dx^2$, ρ the density of the liquid, g the gravity acceleration, γ the surface tension of the liquid, $b = 1/z''(0)$ the radius of the curvature at the apex.

Using the capillary length of liquid $a = (\gamma/\rho g)^{1/2}$ as the characteristic scale, we can rewrite Eq. (1) as two coupled first-order differential equations

$$\begin{cases} \dfrac{dx^*}{d\phi}=\dfrac{x^*\cos\phi}{x^*z^*+x^*p^*-\sin\phi} \\ \dfrac{dz^*}{d\phi}=\dfrac{x^*\sin\phi}{x^*z^*+x^*p^*-\sin\phi} \end{cases} \quad (2)$$

where φ is a angular parameter, $x^* = x/a$ and $z^* = z/a$ nondimensional coordinates, and $p^* = 2a/b$ nondimensional pressure at the apex. Then the nondimensional volume of the droplet is given by

$$v^* = v\big/a^3 = \pi r^*(r^*h^* + r^*p^* - 2\sin\theta) \quad (3)$$

where v is the volume of the droplet, θ the contact angle, $r^* = r/a = x^*(\theta)$ the nondimensional radius of the droplet at the three-phase contact line and $h^* = h/a = z^*(\theta)$ the nondimensional height of the droplet.

To solve the ordinary differential Eq. (2), the fourth-order Runge-Kutta algorithm [22] is adopted in this work, and the details of the numerical processes are given in Appendix.

2.2. The phase change heat transfer

The solidification of liquid belongs to the Stefan problem involving a moving solid–liquid interface together with release of the latent heat. For simplification, we make the following assumptions: (1) the convection in the liquid region is negligible, since the scale of the droplet is small. In addition, for a water droplet on a cold surface, the presence of temperature gradient is helpful to suppress the natural convection; (2) the effect of volume expansion of freezing is not considered. The density of ice is about 8% lower than that of water, so the volume expansion is not significant during the solidification; and (3) the supercool of the liquid phase is not considered, since the nucleation agent is used to eliminate the supercool degree in our experiments.