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Fully resolved simulations of drop solidification under forced convection

Truong V. Vu

School of Transportation Engineering, Hanoi University of Science and Technology, 1 Dai Co Viet, Hai Ba Trung, Hanoi, Viet Nam

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ABSTRACT

We present the fully resolved simulation results of a liquid drop solidifying on a cold plate in laminar forced convection by a front-tracking method that is combined with an interpolation technique to deal with the non-slip boundary condition at the solid surface. The drop is assumed to not slide or roll on the plate during solidification. The numerical results show that unlike free convection, forced convection results in asymmetric solidified drops whose centroid is moved to the direction of forced convection. Various parameters such as the Reynolds number *Re*, the Prandtl number *Pr*, the Stefan number *St*, the Capillary number *Ca*, the dimensionless temperature of the crossing gas flow θ_{in}, and the density ratio of the solid to liquid phases ρ_{sl} are varied to reveal their effects on the process. The effect of the growth angle ϕ_{gr} is also investigated. Increasing *Re* (in the range of 50–600) or *Ca* (in the range of 0.001–0.1), or decreasing any one of *Pr* (from 0.32 to 0.01), ρ_{sl} (from 1.2 to 0.8), ϕ_{gr} (from 20° to 0°) causes the solidified drop centroid to move more in the forced convection direction. However, the variation of θ_{in} (in the range of 0–4) or the drop position has a very minor effect on the solidified drop shape. The effects of these parameters on time for complete solidification are also studied.

1. Introduction

Solidification of liquid drops is a complicated problem in heat and mass transfer due to the presence of the solidifying and liquid–gas interfaces and their non-linear movement. The phenomenon widely exists in many natural and engineered situations such as atomization [1], crystal growth [2,3], wind turbines [4], refrigeration [5], metallurgy and others [6]. In aviation, ice formation on aircraft from supercooled droplets has been known as a serious hazard for flight [7–9]. Accordingly, there have been many works related to liquid drops with change in phase.

Concerning liquid drops in a cross flow, Seevaratnam et al. [10] performed both experimental and numerical investigations of the deformation of oil drops adhering to a wall in a channel induced by a laminar water flow. The authors constructed flow maps for different modes: sliding, crawling and detachment. Basu et al. [11] proposed a theoretical model for the detachment of a partially wetting drop. Some other works related to drops in a cross flow can be found elsewhere (e.g. [12–14]). However, in these works, there was neither heat transfer nor phase change.

Concerning liquid drops with heat transfer, Mandal et al. [15] performed an experimental investigation on a sessile water drop on a plate at various temperatures (from subfreezing to normal room temperatures) with an airflow introduced parallel to the plate. The authors found that the temperature of the plate has a major influence on the incipient motion of drop shedding. A similar experimental work was done by Roisman et al. [16]. The drop was exposed to a high-Reynolds-number shear flow to dislodge. A theoretical model was also proposed to estimate the aerodynamic forces acting on the drop. However, in these works [15,16] the authors have not considered in details solidification as well as how the gas flow affects the solidification process.

Related to solidification of drops, many experimental works have been done to investigate the solidified drop shape or solidification time. For instance, Anderson et al. [17], Hu and Jin [18], Enríquez et al. [19], Snoeijer and Brunet [20] and recently Jin et al. [21] placed water drops on a plate whose temperature was below the freezing temperature of water, and thus an ice layer formed at the plate and moved upwards during solidification. After solidification, the shape of the solidified product with an apex at the top was different from the initial liquid drop because of the effects of volume expansion and the tri-junction. Satunkin [22] and Itoh et al. [23] performed experiments using molten semiconductor materials, e.g. silicon [22,23], germanium and antimonide [22], and found similar solidified drop patterns, i.e. conical top surface at the center. The numerical simulations of this problem can be found in Schultz et al. [24], Virozub et al. [25], Chaudhary and Li [26], and our previous works [27,28]. However, the above-mentioned studies considered only the liquid drop solidifying under free convection.

E-mail address: vuvantruong.pfae@gmail.com

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Concerning drop solidification under forced convection, Jin et al. [29] experimentally investigated the icing process of a sessile water drop on a cold plate with a cross airflow. The authors found that the flow induced an asymmetric solidified drop, and delayed the freezing process. Jung et al. [30] introduced a nitrogen flow to a freezing water drop, and found a similar pattern for the frozen drop. In Hariharan and Ravi's invention [2], they used laser beam to melt piles of silicon (Si) powder to form molten Si drops on a plate, and then the plate was cooled while moving to crystallize the Si drops, i.e. the molten Si drops crystallizing under forced convection. Numerically, Zhang et al. [31] used a two-dimensional volume of fluid method to simulate the freezing process of a water drop under forced convection. However, the authors have not produced a conical shape after complete solidification as observed in experiments, and the results were applied only for water. As mentioned above, this problem is not limited to water, but applies to some other materials such as metals or semiconductors [2,22,23].

It is evident that detailed fully resolved simulations of the solidification process of a liquid drop in a cross flow are still lacking in the literature. This gap motivates our present study on this problem, which is extremely important not only in academy but also in nature and engineered applications [2,4,7]. In this study, we use a two-dimensional front-tracking method combined with interpolation techniques [28,32–34] to simulate the deformation and solidification of a liquid drop on a cold plate under forced convection. We focus on the effects of the Reynolds number, the Prandtl number, the Stefan number and the Capillary number on the process. We also consider the effects of volume change (in terms of the solid-to-liquid density ratio) and tri-junction (in terms of the growth angle).

2. Mathematical formulation and numerical method

Fig. 1 shows the investigated problem: a liquid drop solidifying on a cold plate (kept at temperature T_c) in a laminar cross flow parallel to the plate. The liquid is a pure phase change material with the fusion temperature denoted by T_m ($T_m > T_c$). Initially, the temperature of the liquid phase is set to T_0, and the liquid drop has a hemispherical cap. To simplify the problem, we assume that $T_0 = T_m$. The gas phase is set at temperature T_g. The full slip and outflow conditions apply at the top and the right boundaries, respectively. At time $t > 0$, a gas flow at temperature $T_{in} = T_g$ is introduced at the left boundary with a uniform velocity U_{in}. A solid layer formed at the cold plate due to the plate temperature lower than the fusion value of the drop liquid evolves to the top of the drop. We assume that the fluids are incompressible, immiscible and Newtonian, and the cross flow is laminar. In addition, natural convection is neglected, and volume change is assumed to occur only at the solidification interface. Accordingly, in terms of one-fluid formulation [32,34,35], the governing equations are given as:

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} = -\nabla p + \nabla \cdot [\mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \int_f \sigma \kappa \delta(\mathbf{x} - \mathbf{x}_f)\mathbf{n}_f dS + \rho \mathbf{g} + \rho \mathbf{f} \quad (1)$$

$$\frac{\partial(\rho C_p T)}{\partial t} + \nabla \cdot (\rho C_p T \mathbf{u}) = \nabla \cdot (k \nabla T) + \int_f \dot{q}_f \delta(\mathbf{x} - \mathbf{x}_f) dS \quad (2)$$

$$\nabla \cdot \mathbf{u} = \frac{1}{L_h}\left(\frac{1}{\rho_s} - \frac{1}{\rho_l}\right)\int_f \delta(\mathbf{x} - \mathbf{x}_f)\dot{q} dS \quad (3)$$

Here, $\mathbf{u}$ is the velocity vector, p is the pressure, and $\mathbf{g}$ is the gravitational acceleration. T is the temperature except for the superscript T denoting the transpose. σ (assumed constant along the liquid–gas interface), and κ are the interfacial tension coefficient and twice mean curvature, respectively. L_h is the latent heat. The fluid and thermal properties including density ρ, viscosity μ, thermal conductivity k and heat capacity C_p are assumed constant in each phase. The Dirac delta function $\delta(\mathbf{x}-\mathbf{x}_f)$ is zero everywhere except for a unit impulse at the interface $\mathbf{x}_f$ with f denoting interface. $\mathbf{f}$ in the last term of Eq. (1) is the momentum forcing used to impose the no-slip condition on the solid–fluid interface [32,33]. The heat source $\dot{q}$ at the solidification interface is given as:

$$\dot{q} = k_s \frac{\partial T}{\partial n}\Big)_s - k_l \frac{\partial T}{\partial n}\Big)_l \quad (4)$$

where the subscripts s and l respectively represent solid and liquid. The growth angle at the triple point, i.e. tri-junction (see the inset in Fig. 1), is defined as [27,28,34]

$$\phi_{gr} = \phi_s - \phi_l \quad (5)$$

where ϕ_s and ϕ_l are the angles between the tangent to the solid–gas interface and the horizontal and between the tangent to the liquid–gas interface and the horizontal.

The above-mentioned governing equations are discretized by a second-order central-difference formulation for the spatial derivatives on a stationary staggered grid. We use an explicit second-order predictor-corrector scheme for time integration. The discretized equations are solved by a front-tracking/finite

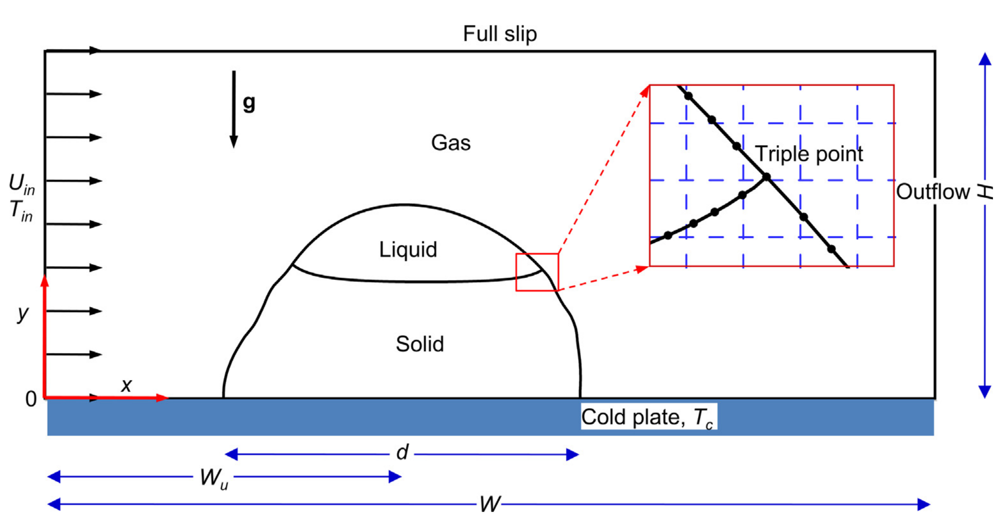

Fig. 1. A liquid drop solidifying on a cold plate under forced convection. The definitions of the parameters are shown in the text.