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Deformation and breakup of a pendant drop with solidification

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ABSTRACT

This paper presents a numerical simulation of deformation and breakup of a solidifying liquid drop pendant from a cold solid surface by an axisymmetric front-tracking method combined with an interpolation technique for enforcing the no-slip velocity boundary at the solid–fluid interface. Many dimensionless parameters such as the Prandtl number *Pr*, the Stefan number *St*, the Rayleigh number *Ra*, the Ohnesorge number *Oh* and the Bond number *Bo* are varied to reveal their effects on the process. Numerical results show that depending on the flow conditions, the liquid drop can break up while solidifying. Starting from non-breakup, increasing *Bo* (from 1.0 to 3.5) or *Pr* (from 0.01 to 3.16) causes the solidifying drop to break up into liquid drops that fall away from the solid surface. The transition from non-breakup to breakup also appears when decreasing *St* from 1.0 to 0.01, *Ra* from 1000 to 50, or *Oh* from 0.316 to 0.01. In addition, the effects of these parameters on the solidification time and the height of the solidified products are investigated. Moreover, the effects of volume change (in terms of the solid-to-liquid density ratio) upon solidification and the tri-junction (in terms of the growth angle) are introduced. We also present a phase diagram of *Bo* versus *St* that shows the region of the non-breakup-to-breakup transition.

1. Introduction

Liquid drops with change in phase appear in many industrial and natural situations such as atomization [1], crystal growth [2,3], metallurgy and others [4,5]. Accordingly, there have been many works related to liquid drops with phase change.

Concerning isothermal drops, Kagawa and Iguchi [6] directed a liquid through a nozzle at very low flow rates to form drops in a dripping mode in which the drop diameter depended strongly on the wettability. Kim [7] experimentally investigated a water drop pendant from a smooth solid surface. The drop was excited with vertical vibrations, and broken up under adequate frequencies. Numerically, Wilkes and Basaran [8] used a Galerkin/finite element method to investigate oscillations of a liquid drop pendant from or sessile on a rod that moved in the vertical direction sinusoidally in time. No breakup occurred in this work. In a latter work [9], a similar problem but with large-amplitude, time-periodic oscillations causing the drop to break up was numerically investigated with the same numerical method reported in [8]. Some other numerical works concerning oscillation and breakup of liquid drops pendant from a solid surface can be found in [10–12].

Vibrating the solid surface where the liquid drop adheres is one method to enhance the liquid drop breakup. This method is applied when the Bond number is small. However, in many natural and engineered problems, gravity, i.e. high Bond numbers, can induce breakup. Numerically, for instance, Zhao et al. [13] developed a variational level set method to capture the motion of multiple junctions, and applied the method to simulate drop detachment from a ceiling under the gravitational field. This simulation was also mentioned by Osher and Fedkiw [14]. Xing et al. [15] performed simulations of drop deformation and breakup due to gravity using a lattice Boltzmann method-based single-phase free surface model. The ceiling where the drop adhered was treated as wettable or unwettable. Another lattice Boltzmann method was used to simulate drop detachment from a ceiling in Tilehboni and co-workers' work [16]. The authors varied the Eotvos number in the range of 3–48 at a small Ohnesorge of 0.07, and found that the drop detaches from the wall at the Eotvos number greater than 6 for the wettable wall, and at all investigated Eotvos numbers for the unwettable wall. However, in all above-mentioned works, heat transfer with phase change during drop deformation and breakup has not been included.

Concerning liquid drops with phase change heat transfer, Anderson et al. [17], Hu and Jin [18], Enríquez et al. [19], Snoeijer and Brunet [20] and Jin et al. [21] experimentally investigated water drops freezing on a cold plate. The solidified drops with a cone near the axis of symmetry were found due to the volume expansion and tri-junction effects. Some other materials, e.g.

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silicon and germanium, produced similar patterns, i.e. conical top surface at the center, after the drops completing solidification [22,23]. Theoretically, Sanz [24] used a simplified model assuming a flat phase change front with neglecting gravity to find the front location for drop solidification supported at the end of a rod. Recently, Zhang et al. [25] developed a theoretical model with the effect of gravity to reproduce the frozen water drop shape after complete solidification. Numerically, Schultz et al. [26] investigated water drops freezing on a cold plate under zero gravity, using a boundary integral method. The solidifying interface was not assumed flat any more. The problem was extended with the presence of gravity and surface tension effects in the numerical work of Virozub et al. [27], where the authors solved the Young-Laplace equation in conjunction with a constant growth angle to find the position of the liquid–gas front. Chaudhary and Li [28] carried out both numerical and experimental investigations on freezing of water drops on surfaces with different wettablility. The numerical results were yielded from solving the enthalpy-based heat conduction equation. A more complete investigation of drop solidification on a cold plate was carried out by Vu and co-workers [29,30] using a direct numerical simulation method, i.e. the front-tracking method. However, in these works, the investigated drops were sessile on the plate, i.e. gravity pointing to the plate, and thus slightly deformed. No breakup occurred.

Related to drops pendant from a solid surface, and with change in phase, Sanz et al. [31] used a technique similar to that described in [24] to investigate the effect of gravity on the shape of the solidified drop. However, large deformation and breakup has not been considered.

It is evident that detailed fully resolved simulations on deformation and breakup with solidification of a drop pendant from a cold solid surface are still lacking in the literature. Finishing this missing gap is the major goal of the present study on this problem, which is crucially important in nature and in its industrial applications [5,32–34]. In this study, the front-tracking/finite difference method combined with interpolation techniques [29,30,35,36] is used to simulate the deformation and breakup during solidification of a liquid drop pendant from a cold solid surface (plate). The liquid is a pure phase change material. We focus on the Prandtl number, the Stefan number, the Bond number, the Rayleigh number, the interfacial tension (in terms of the Ohnesorge number) to reveal their effects on the process. We also investigate the effects of volume change and tri-junction on the process.

2. Mathematical formulation and numerical method

Fig. 1 shows the investigated problem. An axisymmetric liquid drop pendant from a cold solid surface or plate (kept at temperature T_c) deforms due to gravity during solidification. The fusion temperature of the liquid is T_m, and $T_m > T_c$. Initially, the temperature is set to T_0 in the entire domain, and the liquid drop has a hemispherical cap. Since the temperature of the cold plate T_c is less than the fusion value, a solid layer forms near the cold wall, and then the solidification front moves away from the wall, i.e. in the direction of gravity (Fig. 1a). The fluids are assumed incompressible, immiscible and Newtonian. In addition, we neglect the effect of evaporation during the solidification process. In term of a single field representation [35–37], the governing equations are given as:

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

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

$$\nabla\cdot\mathbf{u}=0 \quad (3)$$

Here, $\mathbf{u}$, p and $\mathbf{g}$ are the velocity vector, the pressure, and the gravitational acceleration, respectively. T and the superscript T

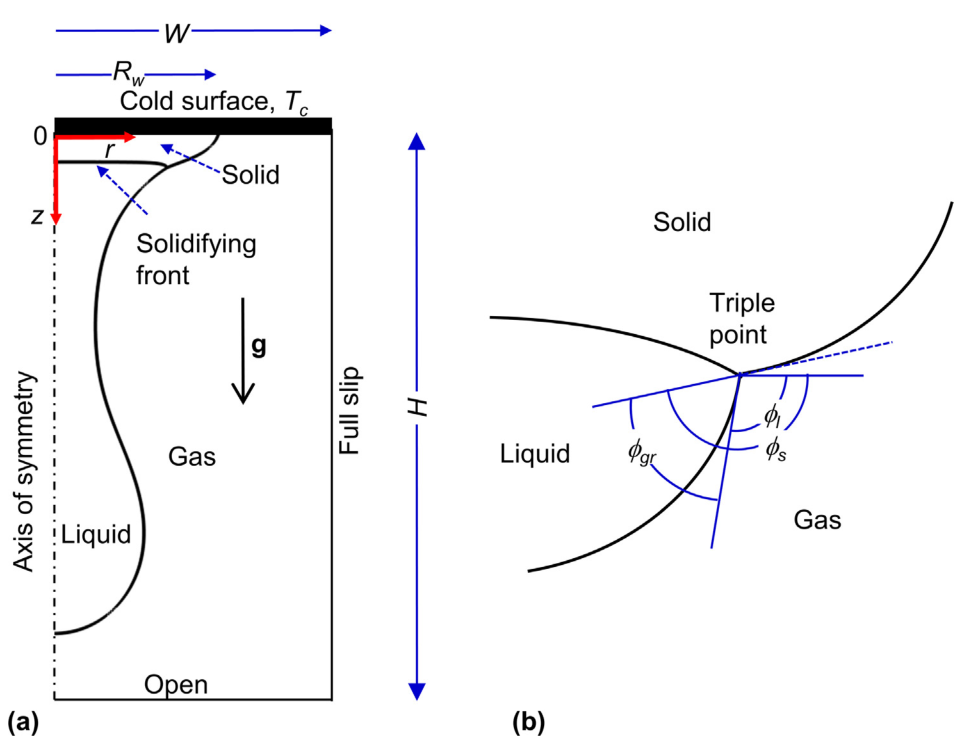

Fig. 1. Evolution of an axisymmetric liquid drop pendant from a cold solid surface during solidification: (a) computational domain and (b) growth angle at the triple point (i.e. tri-junction).