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Numerical simulation of liquid film formation and evaporation in dip coating☆

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ABSTRACT

Numerical simulation is performed for liquid film formation and evaporation on a moving vertical plate, which occurs in dip coating. The liquid–gas interface is tracked by a sharp-interface level-set (LS) method, which is modified to include the effect of phase change at the interface. Numerical techniques for the liquid–gas–solid contact line on a moving plate and the conservation of particle concentration are incorporated into the LS method. The flow and thermal characteristics associated with the dip coating are investigated by solving the conservation equations of mass, momentum, energy, vapor mass fraction, and particle concentration. The effects of plate velocity and temperature on the dip coating process are investigated.

1. Introduction

Dip coating is a simple and efficient process for manufacturing thin film structures. In the dip coating process, a solid substrate is dipped into a liquid pool including functional materials and withdrawn up with an entrained liquid film. Thereafter, it stops moving and the liquid is drained and dried (or evaporated) to recover the functional materials on the substrate.

Landau and Levich [1] first presented a theoretical model for the liquid film formation on a vertical plate pulled up from a liquid pool. Neglecting the effect of evaporation and assuming that the capillary number $Ca = \mu_l V_w/\sigma$ is small, they derived the relation between the liquid film thickness W_l and the plate withdrawal velocity V_w as

$$W_l \propto {V_w}^{2/3} \tag{1}$$

Their relation was supported from several theoretical and experimental works [2–4].

Qu et al. [5] investigated experimentally the effect of evaporation on the liquid film formation in dip coating. Their data showed that the evaporation rate has little influence on the film thickness, which follows Eq. (1), but it significantly affects the film length, which is determined by the balance between the plate withdrawal velocity and the evaporation rate. The steady-state film length was observed to vary as $V_w^{5/3}$. The apparent contact angle at the liquid film tip or the liquid–gas–solid contact line also depends on the plate velocity and the evaporation rate.

Ghosh et al. [6] studied dip coating of colloidal particles in low velocity regimes of plate withdrawal. Their experimental images demonstrated that periodic stripe patterns form spontaneously at the liquid–gas–solid contact line as long as the plate velocity is very low. The stripe width and spacing were observed to decrease as the plate velocity increases. Subsequently, Watanabe et al. [7] conducted more comprehensive experiments for the stripe pattern formation including the effects of particle concentration, evaporation rate, surface tension of solvents as well as plate velocity. Their data showed that the stripe width varies as $V_w^{-0.8}$ or V_w^{-1} but the stripe spacing is almost independent of the plate velocity. The evaporation rate has little influence on the strip width and spacing. Berteloot et al. [8] further investigated dip coating of colloidal particles and demonstrated experimentally that the particle deposition quantity varies as $V_w^{2/3}$ in a low velocity regime of V_w, which is referred to as the Landau-Levich regime, while it varies as V_w^{-1} in a lower velocity regime, which is referred to as an evaporative regime, where the particle deposition occurs directly at the liquid–gas–solid contact line.

Numerical studies of dip coating were performed by several researchers using a finite element method (FEM) [9], a marker-and-cell (MAC) method [10] and a volume-of-fluid (VOF) method [11]. However, their analysis was not extended to include the effects of evaporation and particle concentration. Numerical simulations of liquid evaporation and particle distribution were reported elsewhere in the literature. Most of the computations were carried out using body-fitted moving-grid methods [12,13] and FEMs [14–18], but the Lagrangian methods are generally not easy to handle breaking and merging of the interface. Briones et al. [19] computed droplet evaporation using the VOF method, which was modified to include the effect of evaporation. However, the interface conditions for the coupled vapor concentration, temperature

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Nomenclature

c	specific heat
Ca	capillary number
d_p	particle diameter
D_p	diffusion coefficient of particles in liquid
D_v	diffusion coefficient of vapor in air
F	fraction function
g	gravity
h	grid spacing
h_{lg}	latent heat of vaporization
H	height
L	length
M	molecular mass
$\dot{m}$	mass flux across the interface
n	unit normal vector
p	pressure
t	time
T	temperature
u	flow velocity vector, (u, v)
V_w	plate withdrawal velocity
W_l	liquid film thickness
x, y	cartesian coordinates
Y_p	particle volume fraction
Y_v	vapor mass fraction

Greek symbols

α	step function
β	$\rho_g^{-1} - \rho_l^{-1}$
κ	interface curvature
λ	thermal conductivity
μ	dynamic viscosity
ρ	density
σ	surface tension coefficient
τ	artificial time
ϕ	distance function from the liquid–gas interface

Subscripts

a, v	air, vapor
f	fluid
g, l	gas, liquid
I	interface
o	initial
p	particle
sat	saturation
w	wall
∞	ambient

and evaporation flux are not easy to implement in the VOF method. Tanguy et al. [20] applied a level-set (LS) method to droplet evaporation combining with the ghost fluid approach to accurately implement the interface conditions. Son [21,22] and Ahn and Son [23] extended the LS method for computation of droplet or liquid film evaporation on a solid surface by including a dynamic contact angle model. Recently, Lee and Son [24] and Son [25] developed the LS method for computation of particle concentration in microdroplet evaporation. However, the above numerical methods were not applied to the dip coating process including the effects of evaporation and plate movement.

In this work, we extend the LS method for computation of the liquid film formation and evaporation in dip coating. Numerical techniques for the liquid–gas–solid contact line on a moving plate and the conservation of particle concentration are incorporated into the LS method. The effects of plate withdrawal velocity and temperature on the liquid film formation and particle distribution in dip coating are quantified.

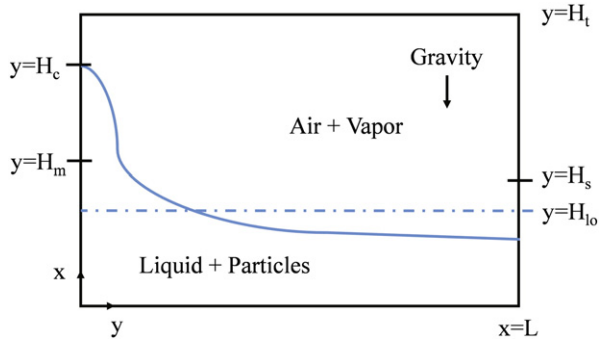

Fig. 1. Computational domain.

2. Numerical analysis

The present numerical approach is based on the sharp-interface LS formulation developed in our previous studies [21–25] for liquid evaporation and particle motion in a droplet or liquid film. The LS method is extended for analysis of the liquid film formation and evaporation on a moving plate and the associated particle distribution. Fig. 1 shows the configuration used for simulation of dip coating. The flow, temperature and concentration fields are assumed to be two-dimensional. The liquid–gas interface is tracked by the LS function ϕ, which is defined as a signed distance from the interface. The positive sign is chosen for the liquid phase and the negative sign for the gas phase. In this work, the following assumptions are made: (1) the gas

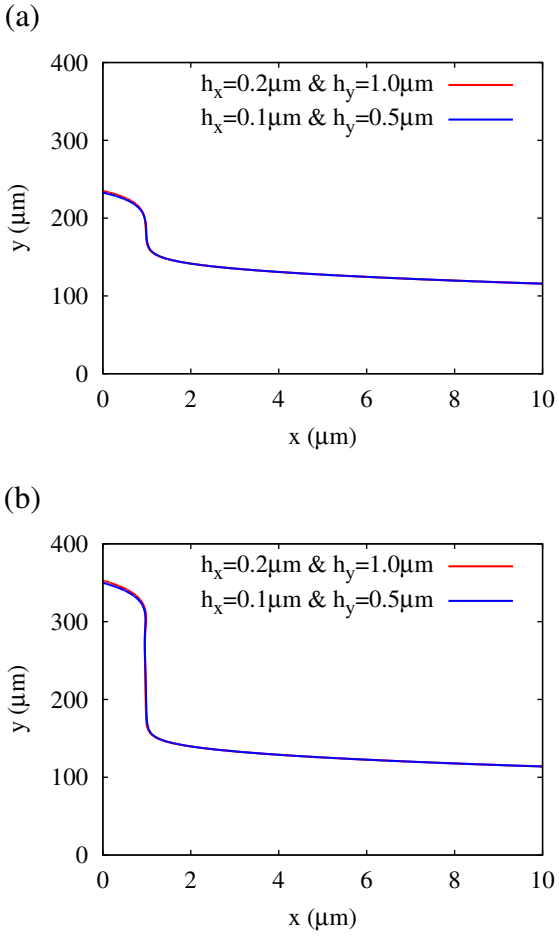

Fig. 2. Effect of mesh size on the evolution of liquid–gas interface for $T_w = 50^oC$ and $V_w = 100mm/s$ at different times: (a) t = 1.3 ms and (b) t = 2.6 ms.