A LEVEL-SET METHOD FOR COMPUTATION OF DROPLET MOTION IN AN INKJET PRINTING PROCESS

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ABSTRACT

A numerical method is presented for computing the droplet motions in an inkjet printing process. The liquid-gas or droplet shape is determined by a level-set method which is modified to treat the immersed solid surface and the contact angle at the liquid-gas-solid interline. The no-slip condition at the fluid-solid interface as well as the matching conditions at the liquid-gas interface is accurately imposed by incorporating the ghost fluid approach based on a sharp-interface representation. The numerical method is applied to simulation of droplet ejection and deposition in an inkjet process.

INTRODUCTION

An inkjet printing process, in which droplets are ejected through a micro nozzle by a pressure pulse that results from the movement of a piezoelectric element and deposited on the substrate to form a desired film pattern, has received increasing attention in various applications such as LCD, DNA micro array, light-emitting diodes and micro-lens. Generally, the ejected liquid breaks up into not only a lead droplet but also multiple satellite droplets. The formation of satellite droplets is undesirable in high quality printing or micro devices requiring elaborate flow control. Also, for high-resolution patterning, it is very important to accurately place a droplet to the target position. However, the inkjet process possibly has some undesired patterning errors caused by the inaccuracy in nozzle position and ejecting angle.

Significant efforts have been made to develop a numerical method for analysis of the inkjet process which can be used to find the optimal design parameters in various inkjet applications. The volume-of-fluid (VOF) method, where the interface is tracked by the liquid volume fraction, has been widely used for computing the retraction and ejection of liquid jet through a nozzle[1,2] and droplet impact and deposition on the pre-patterned micro-structure[3]. However, the implementation of the method for two-fluid flows with immersed solid boundaries is not straightforward because the the interface reconstruction has to be made in an irregular fluid region rather than a Cartesian cell, which requires much more complicated geometric calculations. Very recently, as another Eulerian method, a level-set (LS) method was also applied to the droplet motion in inkjet printing by Yu et al.[4]. In the LS method, the interface is tracked by the LS function defined as a signed distance from the interface. Since the LS function is smooth and continuous, the interface determination is much simpler than in the VOF method requiring geometric calculations. Yu et al. included a dynamic contact angle model in the LS formulation. In their computation, however, the nozzle shape was relatively simple so that the contact angle condition could be applied without systematic implementation procedures. Also, their method was based on diffuse-interface modeling, in which the interface is treated as a transition region smoothed over several grid spacings.

In this study, the LS method is improved for computation of inkjet process by incorporating the ghost fluid approach based on a sharp-interface representation, which is effective for accurately enforcing the no-slip condition at the fluid-solid interface as well as the matching conditions at the liquid-gas interface. The numerical method is applied to the computation of droplet ejection and droplet deposition on the pre-patterned micro-structure in an inkjet printing process.

NUMERICAL FORMATION

The liquid-gas interface is tracked by the LS function ϕ, which is defined as a signed distance from the interface. The negative sign is chosen for the gas phase and the positive sign for the liquid phase. The LS formulation is extended to treat the immersed (or irregularly shaped) solid surface not coinciding with the computational mesh. We introduce another LS function, ψ, which is defined as a signed distance from the fluid-solid interface. The negative sign is chosen for the solid region and the positive sign for the fluid region. The equations governing the conservation of mass and momentum extended for two-phase flows with an immersed solid surface can be written as

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} = -H_\psi \nabla p + \nabla \cdot (\mu / F_\psi) \nabla \mathbf{u} + H_\psi \mathbf{f} \qquad \text{if} \quad H_\psi > 0 \tag{2}$$

$$\mathbf{u} = 0 \qquad \text{if} \quad H_\psi = 0 \tag{3}$$

where

$$\mathbf{f} = -\rho \mathbf{u} \cdot \nabla \mathbf{u} + \rho \mathbf{g} - \sigma (\nabla \cdot (\nabla \phi / |\nabla \phi|)) \nabla H_\phi + \nabla \cdot \mu (\nabla \mathbf{u})^T$$
$$H_\phi = 0.5[sign(\phi) + 1], \quad H_\psi = 0.5[sign(\psi) + 1]$$
$$\rho = \rho_g (1 - F_\phi) + \rho_l F_\phi, \quad \mu^{-1} = \mu_g^{-1} (1 - F_\phi) + \mu_l^{-1} F_\phi$$

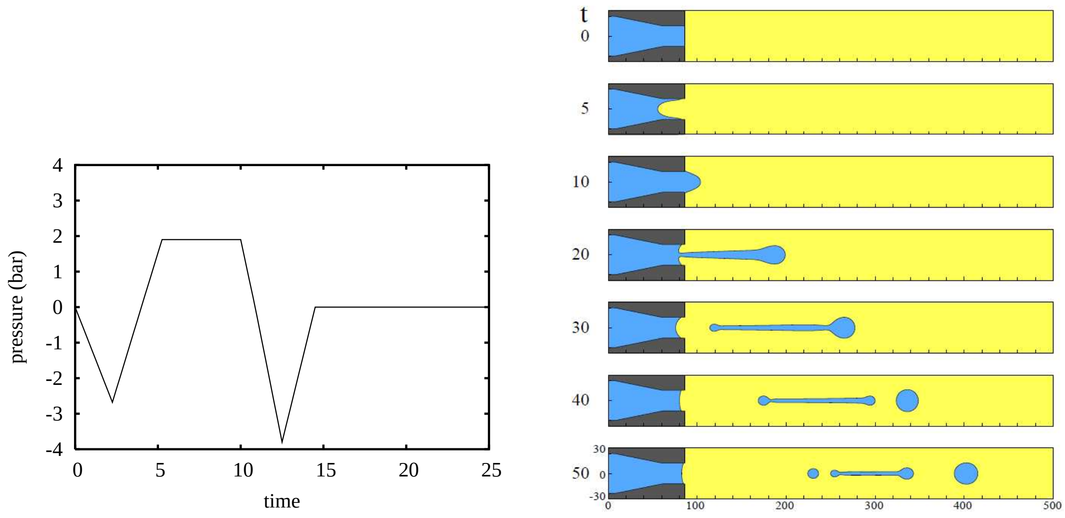
Here, H_ϕ is the discontinuous step function rather than the smoothed step function varying over several grid spacings and the interface curvature is evaluated by the smooth LS function. The effective viscosity formulation μ / F_ψ helps to get a correct viscous stress near the immersed solid boundary. The fluid properties (ρ, μ) are interpolated by the fractional function F_ϕ, which is evaluated from the LS function.

In the LS formulation, the interface is described as $\phi = 0$. To implement the contact angle condition at the liquid-gas-solid contact line, the LS advection equation can be written as

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = 0 \qquad \text{if } \psi > 0 \tag{4}$$

$$\frac{\partial \phi}{\partial \tau} = \cos \varphi - \mathbf{n}_s \cdot \nabla \phi \qquad \text{if } \psi \leq 0 \tag{5}$$

where τ is an artificial time. The unit normal vector $\mathbf{n}_s$ pointing into the solid region is determined as $-\nabla \psi / |\nabla \psi|$.



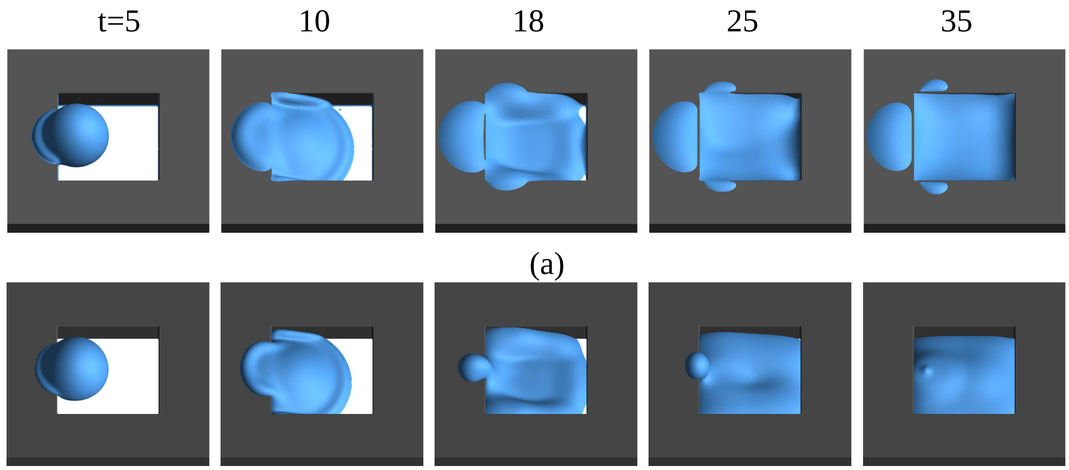
(a) (b)

Figure 1. Numerical simulation of a inkjet process: (a) the imposed inflow pressure and (b) the computed droplet motion.

RESULTS AND DISCUSION

Figure 1 shows the typical results of droplet ejection motion in inkjet process. In presenting the numerical results including figures, lengths are scaled by $1\mu m$, velocities by $1m/s$, and time by $1\mu s$. In this computation, we use a nozzle diameter of 25, the advancing contact angle (φ_a) of 70^o, the receding contact angle (φ_r) of 20^o and the ink properties reported in the work of Yu et al.[4]. The forcing pressure at the nozzle bottom, which results from the movement of a piezoelectric element, is simplified from the data provided by Yu et al., as depicted in Figure 1(a). During the early period, the liquid is retracted into the nozzle by a negative pressure pulse. Thereafter, while the pressure forcing is positive, the liquid is ejected through a nozzle and forms an elongated column. It is seen at $t = 20$ of Figure 1(b) that the liquid inside the nozzle is pulled back by the second negative pressure pulse while the ejected liquid column is moving forward. As the liquid column becomes thinner at the nozzle exit, it pinches off near $t = 23$. Thereafter the liquid column breaks into one primary droplet and then multiple satellite droplets. The droplet ejection pattern plotted in Figure 1(b) shows good agreement with the experimental images given in Figure 10 of [4].

We also performed a numerical simulation of micro droplet deposition on the pre-patterned micro-structure. Figure 2 shows the numerical results of droplet deposition pattern with droplet placement error. In the computation, the droplet has a diameter of 35, the hole has a width of 50 and a depth of 10. The impact velocity of droplet is 8 and the substrate has a contact angle of 30^o. When the contact angle of micro-structure is 30^o, the droplet spreads on both of the micro-structure and substrate and some portion of ink is left on microstructure. In contrast, when the contact angle of micro-structure is increased to 120^o, most of droplet is observed to fill the hole. The numerical simulation of a patterning process using microdroplet ejection demonstrates that the multiphase characteristics between the liquid-gas solid phases can be used to overcome the patterning error.



(a)

(b)

Figure 2. Effect of contact angle on droplet deposition pattern: (a) $\varphi = 30^o$ and (b) $\varphi = 120^o$.

CONCLUSION

A new level-set method was developed for simulation of a droplet ejection and deposition motion in an inkjet printing process. The method was based on a sharp-interface representation for accurately enforcing the no-slip condition at the immersed solid surface of an ink nozzle as well as the matching conditions at the liquid-gas interface. From the numerical results, the method was proven to be applicable to investigate the effects of dynamic contact angle and pressure pulse type on the performance of an inkjet process and the multiphase characteristics between the liquid-gas solid phases can be used to overcome the patterning error.

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