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Droplet formation under the effect of a flexible nozzle plate

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ABSTRACT

Droplet formation from a flexible nozzle plate driven by a prescribed-waveform excitation of a piezoelectric is numerically investigated using a computational fluid dynamics (CFD) model with the volume of fluid (VOF) method. The droplet generator with a flexible nozzle plate, which is free to vibrate due to the pressure acting on the plate, is modeled in a CFD computational domain. The CFD analysis includes the fluid–structure interaction between fluid and a flexible plate using large deflection theory. The problem is characterized by the nondimensional variables based on the capillary parameters of time, velocity, and pressure. The CFD model is validated with the experiment results. This study examines the characteristics of the applied waveforms and nozzle plate material properties to change the vibrational characteristics of the nozzle plate. The effect of fluid properties on the droplet formation process is also investigated focusing on surface tension and viscous forces. Increasing the impulse of the piezoelectric can be used to cause a higher droplet velocity and it is shown that the vibration of the nozzle plate has a strong effect on the droplet velocity, shape, and volume. Surface tension has a strong influence on the droplet formation characteristics in contrast to viscous forces. For the combination of a fluid with high surface tension and the most flexible nozzle plate, this system cannot cause the droplet ejected out of the nozzle.

1. Introduction

Droplet formation is a microfluidics application in areas such as printer heads, medical dispensers, thin film coating, etc. The effort to control either the size or velocity of the droplet after break-off is of great importance. Drop-on-demand (DOD) systems were introduced to improve the quality of droplets while providing delivery control. One method of DOD systems is based on piezoelectric driven impulse. This study investigates the dynamic mechanisms of piezoelectric DOD droplet formation along with the possibility of improving the characteristics of droplets after break-off. The concept is to include a flexible nozzle plate on top of the fluid chamber. The basic design is the use of flextensional technology, which relates to the deflection of a thin flexible membrane and the fluid boundary. In contrast to this, Yang and Liburdy [1] studied the effect of including a passively moving boundary (a flexible nozzle plate) and compared results with a lumped element model. In this latter case, the fluid–structure interaction needs to be taken into account. The current study aims to find the characteristics of DOD droplet formation produced by an actuated diaphragm coupled with flexible nozzle plate using detailed computational simulations.

The formulations of the Navier–Stokes equations for incompressible flow with a free surface have been used in a number of studies in an effort to understand the physical mechanisms governing droplet formation. In 1980s, Fromm [2] obtained the numerical solutions for DOD jets based on a two dimensional mathematical model. Shield et al. [3] compared one dimensional numerical simulation with the experiment result. An approach used to track free surfaces between two fluids is the volume of fluid (VOF) method introduced by Hirt and Nichols [4]. Here a grid is used with a fraction function to define the relative volume of one fluid relative to the total volume within the grid element. The VOF model has become a popular method in free surface models used in computational simulations. An improved method based on VOF for modeling surface tension effects on fluid motion has been developed by Brackbill et al. [5]. The droplet pinch-off process is a complex physical phenomenon where traditional use of surface tension forces is not well understood. Egger [6] investigated the break-off process by focusing on the singularity of a set of universal exponential forms of the solution of the Navier–Stokes equations. Moreover, the thread break-up was also studied by Henderson et al. [7] and Brenner et al. [8], with results agreeing with those of Egger [6]. In recent simulations using VOF, Fawehinmi et al. [9] defined the break-off process by the scale of volume fraction corresponding to the mesh size in a computational domain. Recently, Yang and Tsai [10] validated their simulations with the experiment results from Shield et al. [3], and investigated further the effects of fluid

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Nomenclature

c_i	mass fraction
C, C_i	volume fraction, volume fraction of *i*th specie
E	Young modulus (GPa)
E^*	nondimensional stiffness, E/P_c
E_c	capillary stiffness
F_i, F_{c_i}	source term in momentum equation, source term of *i*th specie
h	nozzle plate thickness
I^*	nondimensional impulse, Eq. (10)
l	position of the leading edge
l_c	capillary length
L^*	nondimensional leading edge position, l/l_c
m_i	mass of *i*th specie
P	pressure
P_c	capillary pressure
P^*	nondimensional pressure, P/P_c
r	radius
t	time
t_c	capillary time
u, v, w	velocity components
u_c	capillary velocity
U^*	nondimensional droplet velocity, u/u_c
V	volume
V_c	capillary volume
V^*	nondimensional volume, V/V_c
w	plate displacement in Eq. (3)
x, y, z	Cartesian coordinates
Greek symbol	
δ_{plate}	nozzle plate displacement
δ^*_{plate}	nondimensional plate displacement, δ_{plate}/h
δ^*_{piezo}	nondimensional piezoelectric displacement δ_{piezo}/h
$\delta^*_{\max}$	nondimensional maximum piezoelectric displacement $\delta_{\max}/h$
κ	radii of curvature
μ	viscosity
μ^*	ratio of fluid viscosity to water's viscosity
ρ	density
ρ_i	density of *i*th specie
σ	surface tension
σ^*	ratio of fluid surface tension to water's surface tension
τ	nondimensional time, t/t_c
τ_{rampup}	nondimensional rampup time, t_{rampup}/t_c
ϕ	airy stress function

properties on droplet formation from the squeezed-type piezoelectric droplet generator.

In this study, fluid–structure interactions are important in determining the interplay of fluid internal pressure and nozzle plate deflection which then affects droplet formation. Considerable efforts have been made to develop models for the simulation of microfluidic devices by Yarin [11], Bourounia and Grandchamp [12], and Krevet and Kaboth [13]. These methods are very complex and time consuming especially if coupled analyses are performed. Only a few studies model microfluidic devices with actuation mechanisms while considering the full fluid–structure interaction, such as by Percin et al. [14], Wijshof [15], and Hermann and Joachim [16].

2. Mathematical model

The droplet formation process is modeled based on a piezoelectric actuated pressure pulse within a specific fluid reservoir. Consequently, the piezoelectric actuation motion, the reservoir, the flexible nozzle plate and the region outside of the nozzle into which the fluid is ejected are all included in the solution domain. The droplet generator being modeled is shown in cross-sectional view in Fig. 1.

The mathematical model used in this simulation is the three-dimensional continuity equation and Navier–Stokes equations as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{D(\rho u_i)}{Dt} = -\partial_i p + \rho g_i + \mu \partial_j \partial_j u_i + F_i \tag{2}$$

where u_i is the velocity vector with components of u, υ and w. In Eq. (2), the surface tension force can be considered as a source term F_i applied to the momentum equations.

During droplet formation, the flexible nozzle plate is considered to be one of the boundary conditions. The governing equation used to determine the boundary deflection is based on the dynamics of nonlinear large deflection plate theory from Rao [17] as:

$$\nabla^4 \phi = -\frac{Eh}{r} w_r w_{rr} - \frac{D}{\rho h} \nabla^4 w - \frac{c_{\text{damping}}}{\rho h} \dot{w} + \frac{1}{\rho h \cdot r} (\phi_r w_r)_r + \frac{P}{\rho h} = \ddot{w} \tag{3}$$

where w is plate displacement, with subscript r and t representing partial derivatives with respect to these variables, respectively, P is the pressure acting on the nozzle plate, D is the flexural rigidity, and c_{damping} is a damping ratio. Here the excitation that causes the nozzle plate to deflect is from the pressure of the fluid in the reservoir at the interface between fluid and plate itself. The nozzle plate deflection changes the shape of the wall boundary and consequently, the pressure distribution in the fluid.

3. Numerical simulation

3.1. Computational method

The commercially available COMET computational fluid dynamics (CFD) numerical code was used in this study. The finite volume method with VOF-based Front Capturing and Continuum Surface Force (CSF) model methods were implemented. The incorporation of fluid–structure interaction effects of the deformable nozzle is through the applied boundary conditions. The incompressible property of fluid is required for the conservation of VOF fraction along with mass and momentum. The CSF model is used to determine the surface tension acting at the interface between liquid and gas phases, as developed by Brackbill et al. [5]. Considering the CSF model, the surface tension causes a pressure discontinuity, ΔP, at the interface between the two fluid phases which can be expressed as follows:

$$\Delta P = \sigma \kappa \tag{4}$$

where σ is the surface tension coefficient and κ the mean surface curvature, where κ is determined by

$$\kappa = -\nabla \cdot \left(\frac{\nabla C}{|\nabla C|} \right) \tag{5}$$

and C is the volume fraction in the VOF model.