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Droplet formation from a pulsed vibrating micro-nozzle

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Abstract

Micro-droplet formation from a passive vibrating micro-nozzle driven by a pulsed pressure wave is numerically simulated. The micro-nozzle is formed from an orifice in a thin walled plate that is allowed to freely vibrate due to the pressure loading on the plate. The analysis couples the fluid flow from the nozzle and the resultant droplet formation with the nozzle vibration calculated using large deflection theory. The problem is made nondimensional based on the capillary parameters of time, velocity and pressure. The applied pressure and nozzle material properties are varied to alter the vibration characteristics of the orifice plate used to form the nozzle. The initiation of drop formation is found to coincide with a threshold impulse input, defined as the product of the pressure magnitude and the pulse duration. Increasing the impulse can result in multiple satellite droplet formation, but the effect on the primary droplet size is minor. The vibration of the nozzle only weakly influences the droplet break-off time, but is shown to significantly affect the droplet volume, shape, and satellite droplet formation.

Keywords: Droplet formation; Vibration; Numerical simulation

1. Introduction

Micro-droplet formation for drop-on-demand applications based on rigid chamber designs has been studied for many years, for instance, see the early works Fromm (1982), Bogy and Talke (1984), and Shield et al. (1987). This general area has wide applications that include ink-jet printing, pharmaceutical dispensing, three-dimensional rapid prototype modeling, and others. Recently, there has developed growing needs to improve the control of parameters such as micro-droplet velocity and size, rate of droplet production and satellite formation. Some design options have been proposed in the recent past that involves active control of the driving forces required to form drops. For example, Kamisuki et al. (1998, 2000) described a micro-electro-mechanical diaphragm drop ejector, and experimentally characterized the droplet formation based on this design. Pan et al. (2002) numerically simulated the droplet formation process from this same design using commercially available software. This device is based on a rigid nozzle, driven by a piezoelectric actuated diaphragm. Percin and Khuri-Yakub (2003) proposed a design based on an open reservoir coupled with an actively vibrating nozzle plate driven by a piezoelectric stack.

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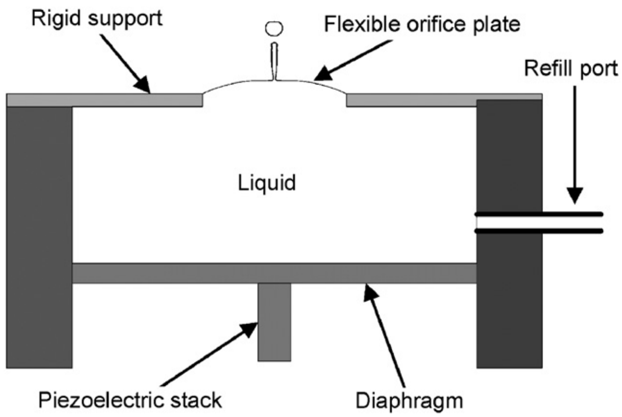

Fig. 1. Schematic of a concept drop ejector device with a flexible nozzle orifice plate bounding a liquid reservoir which is driven by a piezoelectric actuated diaphragm; figure is not to scale.

This study investigates the case of a naturally vibrating orifice micro-nozzle plate during micro-droplet formation. Rather than drive the plate actively, the pressure wave used to form the droplet is used to set the plate in a specific vibration mode. The modal response depends on the plate material, its geometry and the particular input pressure wave. The concept behind the use of a flexible nozzle is shown schematically in Fig. 1. The device consists of a rigid chamber that supplies fluid through a refill port, a piezoelectric crystal stack which can drive a diaphragm at a prescribed displacement pulse, and a flexible orifice plate which deflects based on the pressure within the fluid reservoir. The orifice plate is expected to be very thin, on the order of, or less than, the orifice diameter (which is taken here as 50 μm). The deflection of the plate will depend on the thickness, Young's modulus of the material used to form the plate and how the plate is attached, or the edge boundary condition. In this study it is assumed that the plate edge is rigidly attached to the stiff support forming the top boundary of the reservoir. In general, the plate deflection will be influenced by the fluid structure interaction between the driving diaphragm, fluid reservoir and orifice plate. In this simulation we apply a uniform pressure pulse at the bottom of the orifice plate and calculate the plate deflection, taking into account the circular hole in the plate. This deflection is assumed to be independent of the micro-droplet formation process since the volume of a droplet is insignificant compared to the volume of fluid in the reservoir.

A one-dimensional (1-D) model, restricted to axisymmetric and irrotational flow, for droplet formation has been used very successfully by a number of previous researchers Adams and Roy (1986), Shield and Bogy (1986), Yamamoto et al. (1991), and Eggers and Dupont (1994). Ambravaneswaran et al. (2002) compared one- and two-dimensional (2-D) models for axisymmetric gravity driven droplet formation. Their study shows that the difference between a 1-D model and a 2-D model is small, within a few percent, when the surface tension force dominates the flow. The primary limitation of the use of a 1-D model is the lack of its ability to account for the "overturn" or "backflow" phenomena. This condition may occur during micro-drop formation when the shape of the leading portion of the filament causes the fluid near the side edges of the drop to lag behind the leading edge in such a way as to cause the surface location to have multiple radial values at any given axial location along the filament. Eggers (1993) studied the break-off phenomenon showing that close to break-off the solution follows a universal exponential form. Day et al. (1998) studied the break-off shape of inviscid fluid finding that the break-off has unique shapes with two cones of angles of 18.1° and 112.8°. Chen et al. (2002) show for water that "overturn" occurs at a minimum radius of 1.3% of the nozzle radius.

The 1-D model in this study accounts for flow through a thin walled orifice nozzle with a time dependent deflection based on the orifice plate motion. The nozzle vibration is modeled using large deflection theory of thin plates. Large plate deflection theory, based on the energy method, has been used by Roman and Aubry (2003) to predict defections in micro-scale synthetic jets. In the synthetic jet, flow is not through the deflecting plate, as in the current study, but is used to drive flow through a cavity and then through a rigid tube, or fixed nozzle. The deflection analysis used by Roman and Aubry determines the total volume deflection and does not include local time dependent deflections. In the current study, time dependent nozzle deflection is used to predict droplet formation that is then compared to the droplet formation from the identical geometry using a perfectly rigid orifice plate. Table 1 lists the dimensional parameters of the problem studied. Note that the fluid properties are taken to be those of water, except in those cases where the viscosity is varied.