Thermally Induced Marangoni Instability of Liquid Microjets with Application to Continuous Inkjet Printing

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ABSTRACT

We present an integrated microfluidic device for producing multiple steady steams of picoliter-sized droplets at kilohertz frequency rates. The device has a pressurized reservoir that feeds hundreds of active nozzles, each of which produces a continuous jet of fluid. The jets are inherently unstable and can be individually thermally modulated at the orifice to produce droplets with a well-defined volume, at a consistent distance downstream from the nozzle. The thermal modulation at the orifice causes a variation in surface tension that propagates downstream inducing Marangoni instability, which is the underlying cause of drop formation. Controlled thermal modulation of each jet is achieved using CMOS/MEMS technology wherein a resistive heater element is integrated into the nozzle surrounding each orifice as depicted in Figs. 1-3. In this presentation we discuss the operating physics of this device, methods for modeling its performance, and its application to high-speed continuous inkjet printing.

Keywords: continous ink jet, Marangoni instability, modulation, thermo-capillary instability, microfluidic drop generator, slender jet analysis.

1 INTRODUCTION

The analysis of jet instability has a long history with initial investigations dating back to Lord Rayleigh [1]. However, despite the duration of this research, and the substantial interest in this topic, relatively few results exist on the instability of thermally-modulated orifice-driven microjets, and very few applications exist that leverage this phenomenon [2-4]. The basic mechanism of jet instability and drop formation in thermally modulated jets is Marangoni instability. This is induced by heating the jet in a time-dependent fashion as it flows through the orifice. This pulsed heating modulates the surface tension σ at a wavelength $\lambda = v_0\tau$, where v_0 is the jet velocity and τ is the period of the heat pulse as shown in Fig. 1.

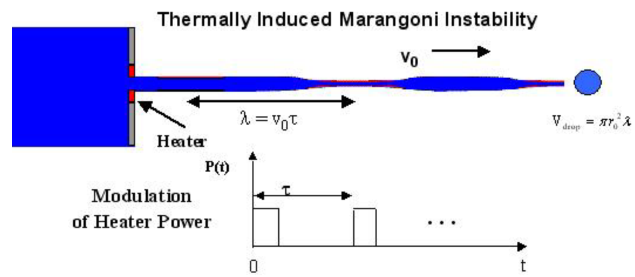

Figure 1: Illustration showing a single nozzle with an integrated heater at the orifice, and a thermal modulation pulse used to induce Marangoni instability and drop formation.

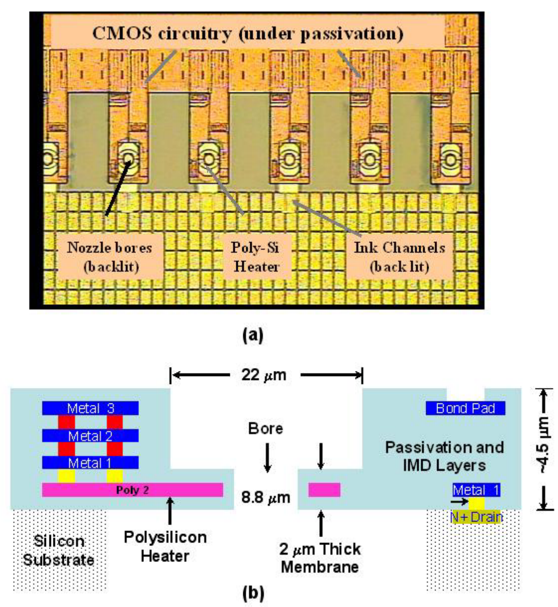

Figure 2: Inkjet printhead: (a) top surface of liner array of nozzles, (b) cross-section of nozzle/heater structure showing CMOS circuitry.

To first order, the temperature dependence of σ is given by

$$\sigma(T) = \sigma_0 - \beta(T - T_0)$$

where $\sigma(T)$ and σ_0 are the values at temperatures T and T_0, respectively. Since σ is temperature dependent, the down-stream advection of thermal energy gives rise to a spatial variation (gradient) of surface tension along the jet. This produces a shear stress at the free-surface, which is balanced by inertial forces in the fluid, thereby inducing a Marangoni flow towards regions higher surface tension (from warmer regions towards cooler regions). The Marangoni flow causes a deformation of the free-surface (slight necking in the warmer regions and ballooning in the cooler regions) that ultimately leads to instability and drop formation. Each jet can be individually thermally modulated using CMOS/MEMS technology wherein a resistive heater element is integrated into the nozzle around each orifice as depicted Figs. 1 - 3. The drop volume can be adjusted on demand by varying τ, i.e., $V_{drop} = \pi r_0^2 \mathrm{v}_o \tau$. Thus, longer pulses produce larger drops, shorter pulses produce smaller drops, and different sized drops can be produced from each orifice as desired.

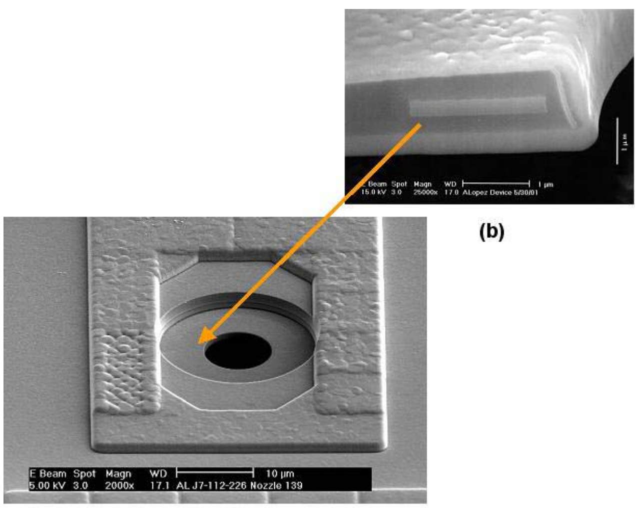

Figure 3: Nozzle with embedded integrated heater element: (a) top of nozzle, (b) cross-section of nozzle showing embedded heater.

2 THEORY AND MODELING

A rigorous analysis of drop formation for this application requires the solution of a fully coupled thermal/fluid/free-surface initial/boundary value problem that takes into account (i) the temperature dependence of all fluid properties (viscosity, density, and surface tension), (ii) the related temperature dependent changes in velocity and pressure at the orifice, (iii) thermal diffusion within the orifice manifold and reservoir, (iv) thermal diffusion and advection within the microjet, (v) the variation of surface tension and induced Marangoni flow along the jet, and (vi) the complex free-surface dynamics.

In this section we discuss three methods for analyzing drop formation: (i) an analytical formula for estimating the time-to-breakup $\mathrm{T_b}$ as a function of the modulation wavelength, jet radius, and fluid properties; (ii) a 1-D numerically-based slender-jet model for predicting the free-surface at pinch-off (drops and filaments); and (iii) a fully-coupled thermal-CFD approach for studying drop formation and satellites during and after the formation of multiple droplets.

The equations governing the behavior of a non-isothermal viscous microjet of an incompressible Newtonian fluid with surface tension σ, viscosity μ, density ρ, specific heat c_p, and thermal conductivity k, are as follows:

Navier-Stokes:

$$\rho \frac{Dv}{Dt} = -\nabla p + \mu \nabla^2 v, \tag{1}$$

where $\dfrac{D}{Dt} = \dfrac{\partial}{\partial t} + v \bullet \nabla$.

Thermal:

$$\rho c_p \frac{DT}{Dt} = k \nabla^2 T. \tag{2}$$

Continuity:

$$\nabla \bullet v = 0. \tag{3}$$

In these equations, v, p, and T are the velocity, pressure and temperature distributions along the microjet. In addition to these equations, there is a complete set of boundary conditions that need to be satisfied to have a self-consistent theory [3], [4].

2.1 Analytical Analysis

Equations (1)-(3) as applied to orifice-driven thermal modulations are too complicated to solve in closed-form. However, an analytical solution exists for a related problem, which can be used to estimate the time-to-breakup $\mathrm{T_b}$ for the process of interest here [4]. This analysis is based on a linearization of equations (1)-(3), and an uncoupling of the thermal diffusion. The linearized infinite jet analysis provides reasonable estimates of $\mathrm{T_b}$ for orifice-driven modulation as long as the jet velocity v_0 is much greater than the capillary velocity $\mathrm{v_c} = \sqrt{\sigma/(\rho r_0)}$. When thermal diffusion is taken into account, the solution is of the form

$$\delta_h(\eta,t) = \frac{\Delta\sigma}{2\sigma_0}\frac{\left[\frac{r_0^2-r_h^2}{r_0^2}+\frac{2}{r_0^2}\sum_{m=1}^{\infty}c_m e^{-\alpha\gamma_m^2 t}J_0(\gamma_m r_0)\right]}{\left[1-r_0^{\,2}\left(\frac{2\pi}{\lambda}\right)^2\right]} \tag{4}$$

$$\times\left[1+\frac{\alpha_-}{\alpha_+-\alpha_-}e^{\alpha_+ t}-\frac{\alpha_+}{\alpha_+-\alpha_-}e^{\alpha_- t}\right]\cos\left(\frac{2\pi\eta}{\lambda}\right).$$

The analytical solution (4) describes the behavior of the free-surface $h(\eta,t)=r_0[1+\delta(\eta,t)]$. The function $\delta(\eta,t)$ obtains a maximum when $\eta\equiv\eta_{\max}=\pm\frac{\lambda}{2},\pm\frac{3\lambda}{2},\pm\frac{5\lambda}{2},\ldots$, and a minimum when $\eta\equiv\eta_{\min}=0,\pm\lambda,\pm2\lambda,\pm3\lambda,\ldots$,. Jet breakup (pinch-off) occurs when $\delta(\eta_{\max},t)=1$ or $\delta(\eta_{\min},t)=-1$ (when $h(\eta,t)=2r_0$ or 0, respectively). Thus, the time to breakup can be computed by solving for the value of t = T_b that gives $\delta(\eta=0,t)=-1$. Parametric calculations of T_b vs. reduced wavenumber k = $2\pi r_0/\lambda$ and jet radius are shown in Fig. 4. This analysis was performed for a microjet of water with a 10 μm diameter [4].

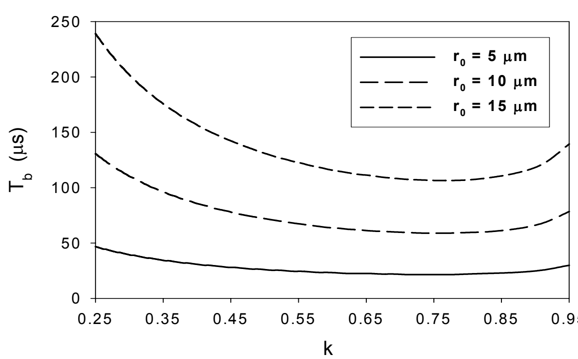

Figure 4: T_b vs. wavenumber k and jet radius.

2.2 Slender Jet Analysis

For slender microjets, which are of interest here, equations (1)-(3) can be simplified using a perturbation expansion in r for the unknown variables h, T and v, and retaining the lowest order terms. This leads to the following 1-D slender jet equations:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial(2\sigma H)}{\partial z}+\frac{3\mu}{\rho h^2}\frac{\partial}{\partial z}\left(h^2\frac{\partial v}{\partial z}\right)+\frac{2}{\rho h}\frac{\partial\sigma}{\partial z}, \tag{5}$$

$$\frac{\partial h^2}{\partial t}=-\frac{\partial\left(h^2 v\right)}{\partial z}, \tag{6}$$

$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial z}=\alpha\frac{1}{h^2}\frac{\partial}{\partial z}\left(h^2\frac{\partial T}{\partial z}\right)-\frac{2\alpha h_c}{hk}\left(T-T_\infty\right). \tag{7}$$

In this approximation there is thermal diffusion along the axis of the microjet and convection off its surface, but no radial diffusion (1-D approximation).

We have implemented Eqs. (5)-(7) in MATLAB using a finite difference approach, and can accurately predict jet instability up to pinch-off as function of modulation wavelength and fluid properties as shown in Fig. 5. Parametric analysis of this phenomenon can be completed in a several minutes.

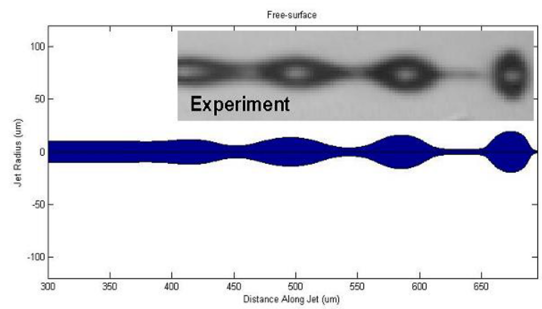

Figure 5. Slender jet analysis vs. experimental data.

2.3 Coulped Thermal-CFD Analysis

A rigorous solution of equations (1)-(3) requires a fully coupled thermal-CFD analysis. A commercial software package FLOW-3D is used for this in our laboratory [5]. The thermal-CFD simulations take into

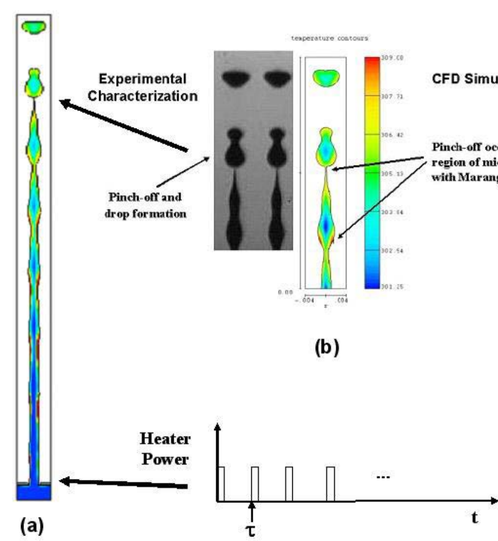

Figure 6. CFD simulation and comparison with experiment.

account detailed models of the orifice (material properties, layering, and dimensions), as well as the applied power level and pulsing scheme. These simulations track the formation of multiple droplets during, and long after, pinch-off, as shown in Fig. 6. Each simulation typically requires a few days to complete, and a detailed post-processing is conducted to examine key physical processes such as thermal diffusion along the jet and its impact on surface tension, and induced pressure and velocity variations near the orifice.

3 APPLICATION TO INKJET PRINTING

An integrated microfluidic device (printhead) for continuous inkjet applications has been fabricated based on the physics described above. The basic operation of the device is shown in Fig. 7. In one mode of operation, each orifice is individually thermally modulated to produce large or small drops on demand, on a continual basis. The large drops are used for printing, while the small drops are deflected away from the print media using air flow, and recycled (Fig. 7). When a printing drop is required (i.e. one that will be deposited onto the print media to form the image), a large drop is produced by increasing the period τ of the thermal pulse (Fig.1). When there is no printing, a small drop is produced by reducing τ.

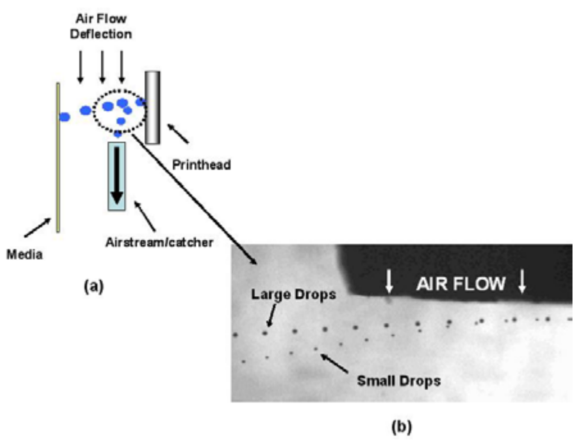

Figure 7: Continuous inkjet printing: (a) schematic showing drop size selective printing, (b) experimental picture showing airflow induced separation of large and small drops.

A fabricated 10 cm long printhead is shown in Fig. 8. This device consists of a linear array of hundreds of active nozzles, and can produce variable sized drops from each orifice at kilohertz frequency rates. Fig. 9 shows a color picture printed with this technology. The picture was printed in a single pass using different nozzle manifolds to deposit the different colors. The media was moving at 1m/s relative to the printhead. Thus, this technology enables high-speed color printing and holds great potential for a broad range of continuous inkjet applications.

4 CONCLUSIONS

CMOS/MEMS technology has been used to produce a novel microfluidic droplet generator for inkjet printing that can generate steady streams of picoliter-sized droplets with unprecedented speed and versatility. These devices operate on the principle of Marangoni instability and hold great potential for low-cost, high-speed, inkjet printing as well as many other applications.

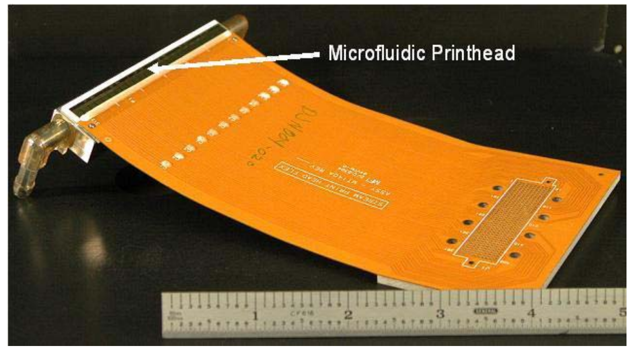

Figure 8: Fabricated microfluidic printhead.

Figure 9: Printed color picture.

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