THE APPLICATION OF INSTABILITIES IN MICROFLUIDIC JETS TO DIGITAL OFFSET-CLASS PRINTING

*Gilbert Hawkins, James Chwalek, Christopher Delametter, Edward Furlani, David Jeanmaire,
John Lebens, David Trauernicht, and Qing Yang*
Eastman Kodak Company, Rochester, New York, USA

ABSTRACT

The tendency of fluid jets to break up into droplets of multiple sizes has been well known since the times of Lord Rayleigh.¹ However the ability to make and control individual droplets from arrays of such jets has come only recently, due in part to the availability of microstructure manufacturing technologies and to the recognition of the potential importance of such arrays to variable data printing. We describe a new inkjet printing technology based on thermally stimulated drop breakup of jets of complex fluids that allows variable data printing to move into "high-speed," "offset class" markets, which include publication and short-run commercial printing markets, often served today by offset lithography, and transactional printing markets, often served by imposition print technologies. The physics of microjet instabilities and the ability to make low-cost microfluidic devices enable such high-speed digital applications.

INTRODUCTION

Inkjet printing for consumer applications has revolutionized desktop printing of documents, including high-quality color images. The two currently commercialized printhead technologies, thermal and piezo drop-on-demand (DOD) technologies, contribute substantially to the revenues attributed to MEMS devices. These technologies have been slow to penetrate commercial applications because the printing speed of consumer devices is far less than that typically associated with technologies such as offset lithography. Of course, the speed of offset printing derives from the fact that identical images are produced without variable data content. The desirability to print variable data at the speed and cost of offset printing has long been recognized but not yet achieved. We believe that the continuous inkjet (CIJ) technology described here offers a practical path for such offset class digital printing, due to the convergence of new principles of device operation, the availability of integrated electronic/fluidic device manufacturing, as well as new developments in ink and media formulations.

Figure 1a: A new principle of inkjet printing, based on thermal pinch-off of continuously jetted fluid streams.

Figure 1a illustrates schematically a new type of silicon-based CIJ printhead based on thermally stimulated drop formation. Ink in

the reservoir is pressurized and jets through the nozzles in the form of fluid columns that propagate (vertically in Fig. 1a) and eventually break up into drops. Figure 1b shows a cross-section of a CIJ device of the thermal stimulation type, which is made by integrated CMOS-MEMS processing using deep reactive ion etching to form the ink reservoirs as channels through the silicon wafer. The nozzle bores are etched through all of the various dielectric layers of the CMOS process and are typically 10 μm in diameter and located on 20–40 μm centers. The choice of silicon as a material technology is an important one, both because silicon-based materials have historical precedence for their compatibility with liquid inks, and because the ability to integrate electronic logic for nozzle addressing greatly simplifies the already complex fluidic packaging of devices with thousands of nozzles.

As opposed to the case of DOD printheads, the energy supplied to eject fluids in CIJ technology is not local to the nozzles. For example, the reservoir in Fig. 1a contains fluid pressurized by a pump external to the printhead. Due to the strength of the silicon materials and to the fact that the energy does not have to be supplied by micro devices located at each nozzle, it is possible to eject a very wide variety of fluids by continuously maintaining many atmospheres of pressure in the reservoir. Because the pressure is constant in CIJ technology, rather than being pulsed as in DOD technology, the duty cycle for fluid ejection is 100% and the velocity of the jets can be varied over a wide range, for example 10–40 m/s.

Figure 1b: Cross-section of CMOS-MEMS integrated printhead.

PHYSICS OF DROP FORMATION

The ability to rapidly eject fluids from closely spaced arrays of nozzles allows CIJ devices to print at very high speeds. In general, a fixed amount of colorant (dye or pigment) is required per unit area of printed media to achieve the required maximum optical density, and thus ink flux scales with speed. Also, because of the ability of CIJ devices to jet very viscous fluids, the concentration of colorants in the ink can be quite high, further enabling high print speeds; CIJ print speeds can exceed a thousand feet per minute. With such potential come problems to be solved, the first of which is the need to form drops of known and controlled volumes and the second of which is to select the drops to be printed. The solution to these two problems forms the basis of the technology discussions below.

A "chaotic" sequence of drop formation is shown in Fig. 2. This formation was generated from a linear array of 70 jets of fluid

that are propagating vertically downward; each jet flows from a separate nozzle bore opening. Pressurized jets emerge from the nozzle bores as fluid columns each about the diameter of the bore and travel rapidly, typically 20 m/s, for a distance of a few mm before breaking up “randomly” to form discrete drops moving along the same vertical paths. Figure 2 shows only the discrete drops; the printhead and the fluid columns are about 1 mm above the image. Although the fluid flux from each jet is constant, the volumes of the drops vary widely, and the largest drops may even touch drops from neighboring jets.

Figure 2: Chaotic breakup of jetted fluid streams.

Chaotic drop formation is not of use for image printing, which requires control over drop volumes, velocities, and trajectories, preferably using very low energies for reasons of thermal management. We achieve drop control at very low energies by introducing small thermal perturbations using heaters surrounding the nozzle bores.² The perturbations are spaced along the jet in the form of heat “bands,” each a fraction of the jet radius in length along the jet, and having a surface temperature rise of a few degrees C. These perturbations locally reduce the surface tension around the jet and initiate a hydrodynamic process of collapse or pinch-off of the jet at the point of the heat band. The energy required for pinch-off is low because surface tension perturbations capitalize on the natural propensity of the jet to break up into drops in order to minimize the surface free energy. This technique is applicable to a wide variety of fluids because most free fluid surfaces exhibit reduced surface tension upon heating. The surface tension gradients, and hence surface forces, associated with thermal stimulation are the underlying perturbations responsible for initiating pinch-off of the column; a drop is formed between adjacent pinch-off points. As is well known,¹ drops spaced at about nine times the radius of the jet are formed most rapidly, and a very low energy stimulation at this spatial frequency is sufficient to lock droplet formation into a repetitive pattern of nearly equal drop volumes, as shown in Fig. 3, in which the jets are shown propagating left to right. In past CIJ inkjet devices, such stimulation has been achieved by acoustic resonance of the printhead, at frequencies as high as 1 MHz. However, acoustic stimulation cannot be applied to a single jet independent of other jets in an array, due to acoustic cross talk; and uniform acoustic stimulation in an array of jets is difficult to achieve.

The jets in Fig. 3 were thermally modulated to form drops of regular volumes at frequencies near 1 MHz using independent heaters at each nozzle. At the left of Fig. 3, the fluid columns shown are just starting to pinch off at the locations where heat was originally applied. The heat pulses, typically of 1 μ s duration, need produce a rise of only about 2 °C at the surface of the jet to cause the column to pinch off or “collapse” after a delay time of typically 20 μ s. Each heat pulse, by reducing the surface tension in a “band” around its associated fluid column, sets in place a time-delayed collapse of the jet at the location of the centroid of temperature gradient. Satellite drops in Fig. 3 that form during jet collapse

rapidly recombine with the main drops due to the pull of surface tension during their separation.

Figure 3: Thermally stimulated formation of drops.

Figures 4a and 4b are SEM micrographs of a nozzle bore formed in a CMOS interlayer dielectric stack and of the associated embedded heater formed in first gate polysilicon in accordance with the schematic illustration of Fig. 1b. The heater ring closely surrounding the bore in Fig. 4a cannot be seen on the surface of the membrane through which the bore is formed due to the planarity of the fabrication process. The rectangular structures in Fig. 4a are metal traces connecting the CMOS driver to the heater. The use of VLSI processing results in very precise geometries for the jet exit orifice and for the heater. This precision is important to ensure accurate jet directionality. The membrane surrounding the 10 μ m diameter nozzle bore is less than 2 μ m in thickness.

Figure 4a: Silicon nozzle; the bore diameter is about 8 μ m. The 1 μ m width thin-film heater is buried in the adjacent dielectric.

Figure 4b: Imbedded heater, first gate polysilicon, provides thermal stimulation.

The rather small aspect ratio of the bore membrane thickness to the bore diameter is not found to limit directional accuracy of the

jet, which is instead governed by the membrane flatness and the flow pattern of fluid in the underlying channel in the silicon substrate. In fact, such a small aspect ratio is a requirement for thermal steering of the jets, as will be discussed, and is a requirement that would be difficult to achieve without MEMS processing technology.

Figure 5 illustrates the geometrical model input used for 3D computational simulation of jet breakup. The model applies voltage pulses of about 1 μ s duration to a heater ring surrounding the nozzle and solves for both the thermal and hydrodynamic system responses using known silicon materials parameters.

Figure 5: Device geometry for coupled thermal and hydrodynamic modeling. Material covering the heater and planarizing the top surface is not shown. The axisymmetric distribution of heat is shown only on one side of the fluid column to illustrate the radial temperature distribution.

Computational modeling results are shown in Fig. 6, left side, for the temperature profile at pinch-off of the jet in Fig. 5 subjected to a single 1- μ s heat pulse having amplitude sufficient to increase the surface temperature of the jet by about 2 $^{\circ}$ C. The model heat pulse was applied at the exit orifice, shown at the bottom of Fig. 6, about 20 μ s before the Fig. 6 snapshot. The delay time between application of the heat pulse and pinch-off depends strongly on the radius and surface tension of the jet and weakly on pulse amplitude.² The band of heat applied to the jet has lengthened more than twofold along the jet during this time, principally due to convection induced by the surface tension gradient; the pinch-off point nearly coincides with the temperature centroid in the case of a spatially symmetrical heat pulse.

Just as a single heat pulse later creates a pinch-off point on the jet, two temperature pulses, spaced apart in time (and hence spaced apart in space on the moving fluid jet), will create two pinch-off points along the jet and thereby form a drop, whose volume scales with the time delay between the pulses and the velocity of the jet. By applying heat pulses at various positions along the fluid column, as illustrated by the arrows on the right side of Fig. 6, drops of arbitrary volume can be formed. It should be understood that although these concepts are useful guides, the actual experimental situation can be complicated by the fact that each pinch-off point can trigger the formation of secondary pinch-off points spaced about the primary by multiples of the Rayleigh length (about 9 times the jet radius). These secondary drops usually coalesce with the primary drops or are swept into fluid catchers. Pulses spaced closer than about 7 radii interfere with one another and may not produce a simple drop; pulses spaced more than about 40 radii may result in multiple drops that do not coalesce.

Figure 7 illustrates drops formed by the device of Fig. 3 using

heat pulses applied at various positions along the fluid column. The larger drops shown in Fig. 7 are not constrained to volumes that are integer multiples of the smallest drop volume, a property that can be used advantageously in contone printing applications.

Figure 6: Model of thermal stimulation and pinch-off of a fluid jet. Left: pinch-off due to a single heat pulse (orange). Right: multiple heat pulses (arrows) spaced variably in time form multiple drop volumes.

Figure 7: Variable sized drops, not constrained to integer volume ratios.

The experimental results of Figs. 3 and 7 correspond to simple, low-viscosity fluids such as dye-based inks. However, most practical inks are complex fluids containing polymers and pigments and/or exhibiting non-Newtonian behavior such as shear thinning. Such fluids behave qualitatively similarly to the case of simple fluids, because their instabilities are also driven by surface tension, but they yield more complex modes of breakup, as shown in the comparison of model and experiments in Fig. 8 for a practical ink with substantial polymer content. Under the assumption that shear-induced changes in rheology relax slowly on the time scale of drop formation, model predictions are seen to reproduce the experiments surprisingly well. The breakup modes depend sensitively on the spacing of the heat pulses compared to the jet radius, consistent with the models.

DROP SELECTION

The ability to form drops of various sizes at very high frequencies, using low excitation energies for a wide variety of fluids, is not sufficient to print images. As opposed to DOD inkjet

technology, the CIJ drop ejectors are always “on” and the printed page would be saturated with ink unless a subset of drops is selected for printing. (Those drops not printed are typically gathered in a catcher and reused, similar to the working principle of a CRT display.) A large variety of methods have been proposed to select printing drops; some are simpler to implement than others. To capitalize on the very high frequencies of operation of CIJ technology, the means of selecting drops must be equally fast, i.e., it must be responsive in about 1 μ s. One method, electrostatic deflection of charged drops, is in commercial use today. However, the images produced are limited in resolution for many reasons, including restrictions on inks and repulsion of like-charged drops. Also, the electric fields required to deflect drops are quite high. Another method of drop selection, mechanical steering by MEMS devices in contact with the jets or drops, has been proposed, but the technical hurdles are formidable. Dense arrays of mechanisms would be required, each capable of a large range of motion (>100 μ m) on a microsecond time scale. Also, problematic for a mechanical technology is the fact that liquids generally adhere to and build up on solid surfaces, even initially hydrophobic surfaces.

Figure 8: Experimental and CFD model results for drop break-off of a complex fluid.

Two other methods of drop selection, which suffer fewer practical limitations, have been developed at Kodak for thermally stimulated CIJ. The first is asymmetric heating of jets as they exit the nozzles, and the second relies on airflow to separate large from small drops. These methods are illustrated schematically in Figs. 9 and 10, respectively. Steering by asymmetric heating relies on the fact that the formation of drops requires only a perturbation of the fluid jet, not a symmetrical perturbation. By splitting the heating ring into two or more segments, drop formation may be accomplished in a manner virtually identical to that described above by applying heat pulses to one or more segments. However, when heat is asymmetrically applied, in addition to drop formation, the drop trajectories are steered, typically in a direction away from the side of the nozzle heated. Steering is a complex phenomenon³ based on temperature-induced changes in viscosity, density, and surface tension. Understanding the effects of surface tension requires 3D modeling, since the forces on the jet viewed from above the nozzle derive from surface tension gradients that torque the fluid stream. For many practical types of ink, the dominant steering mechanism is modulation of the velocity of horizontal

flow of fluid under the activated heater due to a reduced fluid viscosity near the heated surface. Horizontal momentum flow is transmitted through the nozzle bore, provided the membrane surrounding the bore is very thin, so that the velocity profile in the bore cannot equilibrate to a parabolic distribution. Such a case is modeled on the left of Fig. 9, which shows the fluid column deviating from the vertical axis by a few degrees. Because this angle is principally determined by momentum conservation, fluid flowing vertically up through the bore represents a disadvantageous weight component that reduces steering of the jet. Hence, the patented structure shown on the right of Fig. 9, with a mechanical membrane blocking the path of fluid flow vertically from the reservoir to the bore, exhibits several-fold greater steering, as is confirmed experimentally. In the model in Fig. 9, an additional heater has been included in the blocking membrane, as that inclusion is without cost in the fabrication process steering and can be reversed.

Figure 9: Thermal steering by asymmetric heating of fluid jets. Left: Open chamber geometry. Right: Central flow blocked.

The mechanism of drop selection by airflow makes use of the ability of thermal stimulation to control drop size on a drop-by-drop basis, as illustrated in Fig. 10. A force that depends on drop size is applied perpendicular to the drop trajectories. One such mechanism is laminar gas flow, simply depicted in Fig. 10 as applied by a vacuum channel adjacent the streams of drops. Small drops in this case are pulled into the tube while larger drops (typically 2x–4x larger) travel onto the media and are printed. The difference in trajectory deflection is due to the scaling of inertia vs. drag, the deflection margin scaling approximately as the inverse drop radius. This drop selection technique favors small drops, which is advantageously an industry trend for reasons of image quality. Alternatively, the large drops may be intercepted by a fluidic catcher and the small drops printed. Other methods of drop selection capitalizing on the attributes of thermal stimulation as well as combinations of methods have also been proposed and deserve further study.

A NEW LOOK AT AN OLD THEORY

In the linear theory of slender jets,¹ the time required for the collapse of a fluid column into a series of drops subject to a sinusoidal perturbation of the column depends on the wavelength of the perturbation approximately in accordance with Fig. 11, the classic “growth rate” of the perturbation vs. the perturbation wave vector k , defined as twice π divided by the spatial wavelength. The perturbation can be one in radial profile, temperature profile, velocity profile, pressure profile, or some combination thereof;

there are generally three independent boundary conditions. The column collapses at an extremum of the perturbation, and while the solutions differ slightly depending on what is perturbed, the wavelength dependence is always similar to that shown in Fig. 11, because collapse is driven by geometrical reduction of the surface free energy, which is a maximum at a spatial wavelength of about 9 times the column radius.

Figure 10: Separation of drops by air deflection.

Figure 11: Classic growth rate of sinusoidal perturbations on a fluid jet.

In Fig. 11, at spatial frequencies higher than those on the extreme right of the graph, $k = 1/\text{radius}$, the jet fails to collapse, limiting the size of droplets that can be produced for a given jet radius. For this case, the time dependence of the radius is shown in Fig. 12; the jet radius oscillates in time, behaving as a viscously damped simple harmonic oscillator (SHO). In fact, it can be shown that the equations governing the evolution of thin jets are isomorphic to those of a SHO with effective mass, spring constant, and damping parameters shown in Table 1. The terms in Table 1 are the conventional SHO mass m , spring constant K , resonant frequency ω , damping coefficient α , damping time τ , and resonant Q -factor Q for a column of fluid of density ρ , surface tension σ , and viscosity μ , perturbed at reciprocal wavelength k . These terms have straightforward physical interpretations: the effective oscillating mass m scales as the moving mass of a capillary wave, the effective spring constant is related to the surface tension and the geometrical distortion of the surface, and the damping is governed by viscosity. Note that the spring constant is negative for wavelengths associated with jet collapse, which for all of the wavelengths is shown in Fig. 11. For these wavelengths, just as for a mass-and-spring harmonic oscillator with a negative spring

constant, the position of the mass or, analogously, the radius of the jet, diverges, so that the system is releasing, not storing, potential energy. In this regime, Q could be said to be formally negative. For shorter wavelengths for which the jet radius oscillates rather than collapses, Q is only on the order of unity for an aqueous jet, as shown in Table 2. Note that it is important to distinguish between periodicity in time for a given spatial wavelength along a fluid column vs. the time response of a spatial periodic perturbation along the jet. These very different concepts become entangled because the spatial perturbation along a jet is frequently the result of a temporal perturbation applied at the nozzle on a moving jet, a very natural concept experimentally.

Figure 12: Time dependence of jet radius for stimulation at various spatial wavelengths of an imposed perturbation in surface tension. The perturbation is imposed at time equal zero and thereafter remains constant.

Table 1: Effective harmonic oscillator parameters for a fluid jet excited at wave vector k .

Parameter	SHO	JET
mass	m	$\frac{\rho r_0 \lambda^2}{2\pi^2} \text{ cap. depth} \sim \lambda$
spring const.	K	$\sigma_0 [r_0^2 k^2 - 1]$
res. freq.	$\omega_0^2 = K / m$	$\omega_0^2 = \frac{\sigma_0 k^2}{2\rho r_0} [r_0^2 k^2 - 1] \Theta_H$
coef. friction	α	$6r_0\mu$
damping	$\tau^{-1} = \alpha / m$	$\frac{3\mu}{\rho} k^2$
Q	$Q = \frac{\omega_0 \tau}{2\pi}$	$Q = \frac{\omega_0 \tau}{2\pi}$

The analogy of a jet to a harmonic oscillator is useful in understanding drop formation in printing. This analogy is illustrated by the potential energy surface of Fig. 13, in which the z -axis represents a generalized potential energy, the x -axis a spatial variable (position of a mass on a spring, a puck sliding in a bowl, or the radius of a fluid jet), and the y -axis an effective restoring constant (spring constant). The straight white line on the surface corresponds to a change in sign of the spring constant. Toward the back of the surface, the spring constant is positive and the spatial coordinate oscillates, for example, following the white trajectory of positive curvature, the usual behavior of a SHO. Toward the front

of the surface, the spring constant is negative; the trajectory generally diverges, following, for example, the white trajectory with negative curvature. This is the behavior expected of a SHO having a negative spring constant as well as that of a collapsing jet. Mathematically, the solution sets are related by transforming the frequency-dependent solutions of an oscillator to the time domain by integration in the complex plane.

Table 2: Numerical values for the effective oscillator parameters of an aqueous jet perturbed at a spatial wavelength of about 4 times the radius.

Parameter	Numerical values for perturbations half the Rayleigh wavelength	Jet parameters
mass	e^{-13} kg (0.1 pL)	$\frac{\rho r_0 \lambda^2}{2\pi^2}$ cap. depth $\sim \lambda$
spring const.	0.1 N/m	$\sigma_0 [r_0^2 k^2 - 1]$
res. freq.	800,000 Hz	$\omega_0^2 = \frac{\sigma_0 k^2}{2\rho r_0} [r_0^2 k^2 - 1] \Theta_H$
coef. friction	$3e^{-8}$ kg/s	$6r_0\mu$
damping	Inverse $3.5e^{-6}$ s	$\frac{3\mu}{\rho} k^2$
Q	~ 1	$Q = \frac{\omega_0 \tau}{2\pi}$

The energy required for jet pinch-off is understandably small, since the system itself is providing the energy and the applied perturbation serves to synchronize pinch-off events. On the other hand, in the region of Fig. 13 for short wavelength perturbations, the radius of the fluid column exhibits damped oscillation, not pinch-off. Of course, it is possible to perturb the system so strongly in the short wavelength regime that very small droplets of some type are produced. The very large energies required would characterize a DOD ejector, in which the system-free energy is overwhelmed by the applied perturbation.

The graph of Fig. 11 suggests that the ability to rapidly change drop size would energetically be costly, as it is tempting to view the system as a resonant oscillator preferring a periodic perturbation of wavelength about 9 times the jet radius. Fortunately for applications in printing, where variable drop size is generally advantageous, this conclusion is incorrect. As shown in Fig. 14, a “delta-function” train of heat pulses, arbitrarily spaced, is more effective in forming drops than are sinusoidal perturbations of equal heat content. A single “delta-function” heat pulse collapses a jet nearly as effectively as a sinusoidal perturbation at the peak of the growth rate curve in Fig. 11. This frequently overlooked fact stems from the role of the surface tension gradient as the driving force for drop breakup. It is consistent with the oscillator analogy of a system of low Q and is essential to enable the applications to printing described here.

In conclusion, although continuous inkjet was an historically early printing technology, its use has not become widespread due to perceived limits in resolution and image quality. Now, changes in the physical principles of CIJ operation that allow control over drop breakup independently at each nozzle and changes in the ability to fabricate arrays of devices have given new life to a growing segment of variable data printing that allow it to compete in offset class image quality, cost, speed, and substrate flexibility (ink latitude). Our learnings along the way include appreciation for simplicity of device fabrication, avoidance of “creeping elegance of design,” a need to capture at least one aspect of device

performance that on fundamental grounds appears superior to any competition, the ability to scale devices physically to cover multiple applications, a technical vision of extensible functionality, and the ability to enable at least one very large market in which one can afford the luxury, often a necessity, of realistic development times.

Figure 13: Solution plane for trajectories of a linear fluid jet: Potential energy (vertical axis) vs. jet radius and wave vector k of an applied surface tension perturbation.

Figure 14: The delay time between application of a periodic temperature perturbation and jet collapse as a function of the wavelength of the perturbation for sinusoids and for pulses of equal average heat.

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