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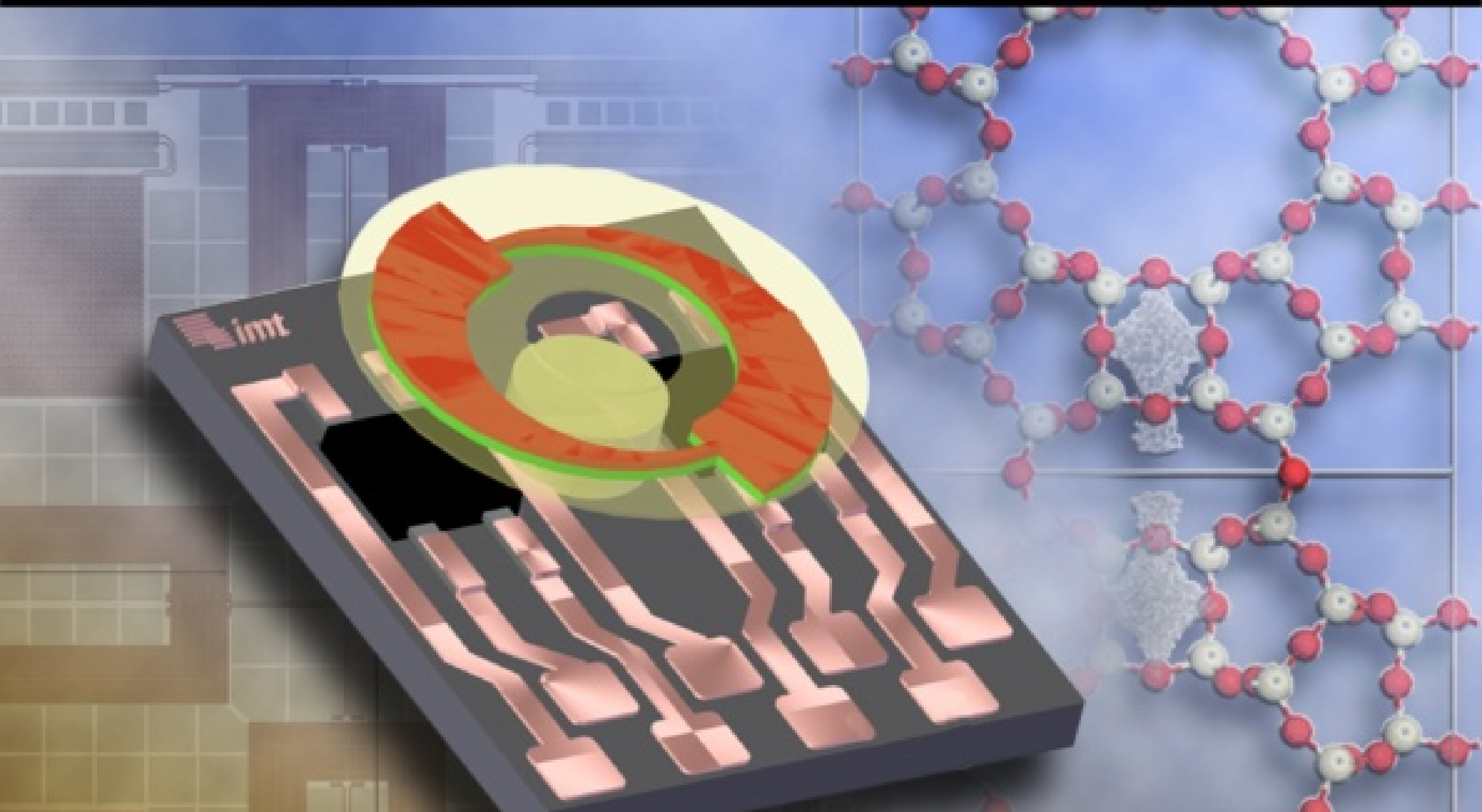

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Analysis of an Electrostatic MEMS Squeeze-film Drop Ejector

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Abstract: We present an analysis of an electrostatic drop-on-demand MEMS fluid ejector. The ejector consists of a microfluidic chamber with a piston that is suspended a few microns beneath a nozzle plate. A drop is ejected when a voltage is applied between the orifice plate and the piston. This produces an electrostatic force that moves the piston towards the nozzle. The moving piston generates a squeeze-film pressure distribution that causes drop ejection. We discuss the operating physics of the ejector and present a lumped-element model for predicting its performance. We calibrate the model using coupled structural-fluidic CFD analysis. *Copyright © 2009 IFSA.*

Keywords: MEMS inkjet, Microdispensing, Drop-on-demand, Squeeze film drop ejector

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1. Introduction

Research towards the development of devices that enable the controlled generation and delivery of picoliter-sized droplets has increased dramatically over the last several years, due in part to rapid advances in microfluidic, biomedical, and nanoscale technologies. Novel applications for such devices are proliferating, especially in fields that benefit from high-speed and low-cost patterned deposition of discrete samples (droplets) of micro- or nanoscale materials. A wide range of materials can be jetted for deposition including liquid metals, dispersions of nanoparticles, electrical, and optical polymers, myriad biomaterials, sealants and adhesives. Emerging applications in this field include printing functional materials for flexible electronics, microdispensing of biochemicals, printing biomaterials (e.g. cells, genetic material), and 3D rapid prototyping [1-7]. Currently, the most notable and commercially successful application is inkjet printing wherein streams of picoliter-sized drops are ejected at high repetition rates onto a media to render an image.

Inkjet printing can be broadly divided into two distinct printing methods; continuous inkjet printing (CIJ), and the more common drop-on-demand (DOD) printing. In CIJ printing, droplets are produced continuously but only a fraction of these are used to form the image. The unused droplets are deflected and guttered prior to reaching the image, and this unused ink is recycled to the printhead. Conventional CIJ systems rely on piezoelectric transducers for drop generation and electrostatics for drop deflection. Recently, Eastman Kodak has introduced a novel CMOS/MEMS-based CIJ technology that utilizes the thermo-capillary Marangoni effect for drop generation and air flow for drop deflection [8-11].

In DOD printing, droplets are produced as needed to form an image. The droplets are typically generated using a high-intensity short-lived pressure pulse within a microfluidic chamber beneath an orifice plate. The temporal amplitude of the pressure pulse can be tuned to control the characteristics of the ejected droplet, i.e. volume and velocity. The most common methods for producing the DOD drop ejection pressure involve piezoelectric actuation or the generation of a thermally induced vapor bubble (bubble-jet) [12].

In this paper we study an electrostatic DOD device in which drop ejection is based on a fluidic squeeze-film effect. Specifically, we study a MEMS drop ejector that consists of a microfluidic chamber with a piston that is suspended a few microns beneath and orifice plate (Fig. 1).

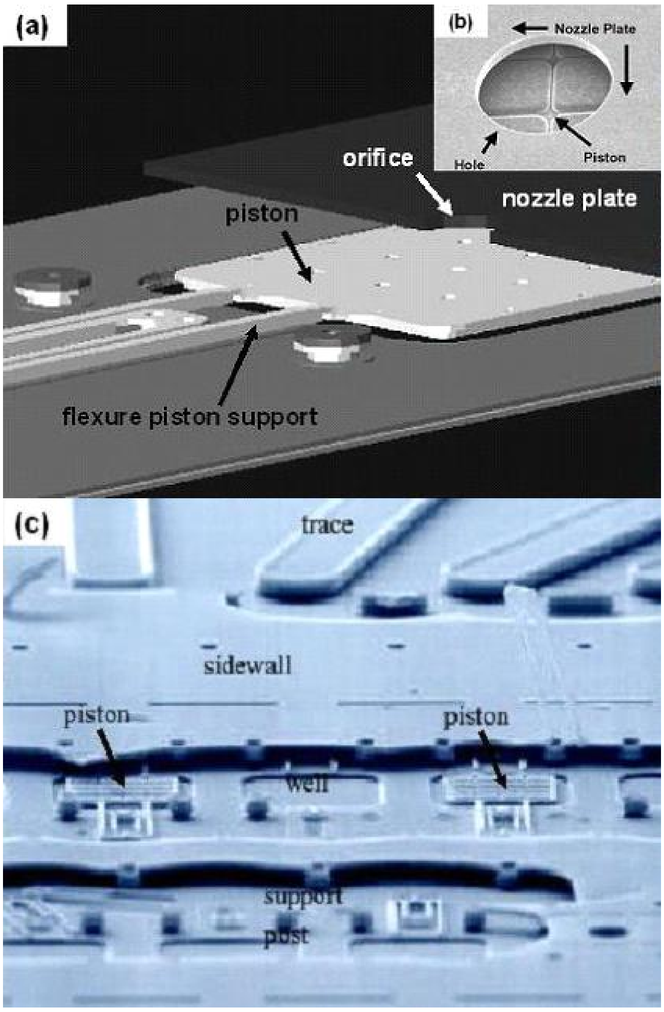

Fig. 1. MEMS drop ejector (adapted from reference [14]): (a) schematic showing cantilevered piston and cut away view of nozzle plate, (b) close up view of orifice and piston, and (c) SEM of ejectors (cover removed).

The piston is supported by cantilevered polysilicon flexure members that act as restoring springs when piston is displaced from its equilibrium position (Fig. 1a). To eject a drop, a potential difference is applied between the orifice plate and the piston, and this produces an electrostatic force that moves the piston towards the orifice. The moving piston generates a squeeze-film pressure distribution in the fluid sandwiched between it and the nozzle, which acts to eject the drop (Fig. 2). Specifically, a peak pressure (stagnation pressure) occurs at a specific radius (stagnation radius), which is greater than the orifice radius. Thus, the fluid within the stagnation radius is confined, and forced through the nozzle as the piston moves towards it. A portion of this fluid ultimately detaches from the ejector and forms into a droplet; the remainder retracts back into the ejector as the piston returns to its equilibrium position. A drop ejector based on this principle has been fabricated and characterized at Sandia National Laboratories using the SUMMiT process (Fig. 1) [13, 14].

In this paper, we discuss the basic operating physics of the ejector and we present an analytical lumped-element model for predicting its performance. We use the model to study device performance. We compare the analytical predictions with CFD analysis that takes into account the coupled piston-fluid interactions.

2. Mathematical Model

The development of MEMS DOD devices requires substantial modeling in advance of device fabrication. Modeling is needed to obtain sufficient understanding of drop generation to enable device optimization taking into account critical device parameters as well as the fluid rheology. A rigorous DOD analysis requires coupled structural-CFD (and/or thermal-CFD) analysis. Moreover multiphase CFD analysis is needed to model the evolution of the free-surface of the ejected column of fluid as it passes through the orifice and develops into a droplet. Methods for modeling such coupled phenomena represent an active and growing area of research. Indeed, the multiphase aspect of the computation is itself under intense investigation. While various numerical techniques have been developed for simulating free-surface flows, each has advantages and drawbacks, and all such methods tend to be computationally intensive. The computational methods can be broadly classified as Lagrangian or Eulerian, or hybrid combinations of the two [15-17]. In Lagrangian methods, the fluid interface is tracked with computational nodes that move with the fluid velocity. While this provides an accurate description of the free-surface, its main disadvantage is that the mesh can become severely distorted over time, and the careful monitoring of mesh quality is required with frequent remeshing that significantly adds to computational overhead. Arbitrary Lagrangian–Eulerian methods (ALE) can remedy this problem by allowing the nodes to move independent of the fluid velocity thereby maintaining mesh quality and minimizing remeshing, but implementation can be nontrivial for complex flows. In the Eulerian approach, the computational mesh is fixed, and an unknown function is introduced and solved for whose values define the volume fraction of fluid in each computational cell. The most common implementation of this approach is the volume of fluid (VOF) method [17]. We use a fully-coupled structural-VOF analysis for our study of the DOD ejector.

2.1. Lumped-Element Analysis

As a supplement to computationally intensive fully-coupled CFD analysis, one can often simplify a problem and study device performance using an electromechanical-fluidic lumped-element approach. We develop such a model for the DOD drop ejector using an axisymmetric analysis (Fig. 2). The motion of the piston is obtained from the equation for the force balance on the piston

$$\left(m_p + m_{eff}(t)\right)\frac{dv_p}{dt} = F_a(t) - kx_p(t) - 2\pi\int_0^{r_p} p(r, v_p, t)\, r\, dr + \sum F_f\ , \tag{1}$$

where m_p, $x_p(t)$, and $v_p(t)$ are the mass, position, and velocity of the piston, $m_{eff}(t)$ is the effective mass of the fluid that it accelerates, $F_a(t)$ is the applied electrostatic force, k is a spring constant for the polysilicon support members, and $p(r, v_p, t)$ is the squeeze-film pressure distribution that develops between the piston and the nozzle, which acts to resist the piston motion. The term $\sum F_f$ represents other forces due to the fluid motion.

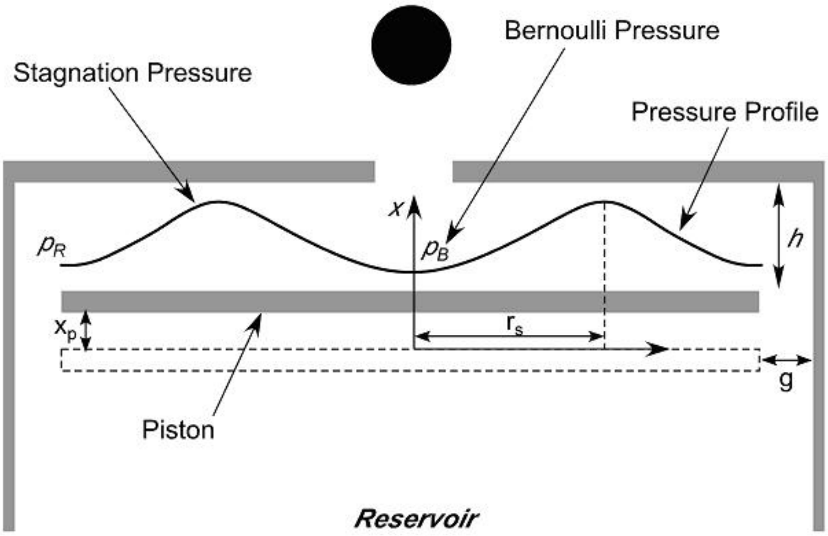

Fig. 2. Axisymmetric model of MEMS drop ejector.

2.2. Stagnation Pressure

The pressure distribution $p(r, v_p, t)$ developed by the moving piston is obtained by applying Reynolds lubrication theory to the axisymmetric geometry shown in Fig. 2. The pressure above the piston satisfies the following equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p(r,t)}{\partial r}\right) = -\frac{12\mu}{h^3(t)}v_p(t) \qquad (r_0 \le r \le r_p), \tag{2}$$

where μ is the fluid viscosity, v_p is the piston velocity, r_o and r_p are the radius of the orifice and the piston respectively, and $h(t)$ is the distance from the piston to the nozzle plate. The general solution to this equation is of the form

$$p(r,t) = -\frac{3\mu v_p(t)}{h^3}r^2 + c_1\ln(r) + c_2, \tag{3}$$

where c_1 and c_2 are constants determined from boundary conditions [18]. The pressure peaks at a value p_s at the stagnation radius $r_s(t)$,

$$r_s(t) = \sqrt{\frac{h^3 c_1}{6\mu v_p(t)}}\,, \tag{4}$$

as shown in Fig. 2. We assume that fluid above the piston and within the stagnation radius ($r \le r_s(t)$) flows towards the orifice, while fluid beyond this point ($r > r_s(t)$) flows into the reservoir. The boundary conditions for this problem are

$$\begin{aligned} p(r,t) &= p_B(t) \qquad (r = r_o) \\ p(r,t) &= p_R(t) \qquad (r = r_p)\text{,} \end{aligned} \tag{5}$$

where $p_B(t)$ and $p_R(t)$ are the pressures beneath the orifice $(r \le r_o)$, and at the edge of the piston, respectively, which are related to the flow rates at those points. Analytical expression for $p(r,t)$, $r_s(t)$, $p_B(t)$ and $p_R(t)$ can be found in the literature [18].

2.3. Effective Mass

We take into account inertial effects by estimating the mass of fluid accelerated by the piston as it moves. We assume that the fluid within the stagnation radius flows towards the orifice, while the fluid beyond this point flows through the gap into the reservoir. From our analysis we find that the total effective mass of the fluid is [18]

$$m_{eff}(t) = \rho\pi\left[\frac{r_p^{\,3} + r_0^{\,3} + 4r_s^{\,3}}{3} - r_s^{\,2}\left(r_p + r_0\right)\right] + \rho\pi l_0 r_s^{\,2}(t) + \rho\pi l_0 r_s^{\,2}(t) + \rho\pi l_p\left(r_p^{\,2} - r_s^{\,2}(t)\right). \tag{6}$$

2.4. Equation of Motion

The equation of motion Eq. (1) contains an expression $\sum F_f$ that accounts for additional forces due to fluid flow. We collect all the relevant terms and obtain the following equation for the motion of the piston

$$\begin{aligned} \left(m_p + m_{eff}(t)\right)\frac{dv_p}{dt} &= F_a(t) - kx_p(t) - \pi r_o^{\,2} p_B(v_p,t) \\ &\quad - 2\pi\int_{r_o}^{r_p} p(r,v_p,t)\,r\,dr - \rho\frac{\pi^2\left(r_p^{\,2} - r_s^{\,2}\right)^2}{\left(2\pi r_p g\right)} v_p^{\,2}(t) \; - \rho\pi\frac{r_s^{\,4}}{r_o^{\,2}} v_p^{\,2}(t) \\ &\quad - \rho\pi\left[\frac{r_p^{\,3} + r_0^{\,3} + 4r_s^{\,3}}{3} - r_s^{\,2}\left(r_p + r_0\right)\right]\frac{v_p^{\,2}(t)}{\left(h_0 - x_p(t)\right)}. \end{aligned} \tag{7}$$

To perform device simulation, we integrate this nonlinear ODE using a fourth-order Runge-Kutta method.

3. Results

We integrate the equation of motion to study the behavior of the drop ejector. We solve for the piston velocity, and use this to obtain the average velocity $v_o(t)$ and volume flow rate $Q_o(t)$ of the fluid ejected through the nozzle,

$$v_o(t) = \frac{r_s^2(t) v_p(t)}{r_o^2}, \tag{8}$$

and

$$Q_o(t) = \pi r_s^2(t) v_p(t). \tag{9}$$

It is important to note that this analysis does not take into account the complex free-surface dynamics that govern the fluid-nozzle interaction and the ultimate formation of the drop, i.e. pinch-off, satellites etc. To compensate for this, we estimate the actual observed flow rate $Q_{exp}(t) = \beta Q_o(t)$ using a fitting parameter β, which we determine using CFD analysis. Once determined, this parameter is fixed for all of the analysis. We also track the total volume of fluid V_{eject} ejected during actuation by integrating the flow rate through the orifice during the applied force,

$$V_{eject} = \int_0^{\tau} Q_{exp}(t)\, dt, \tag{10}$$

where τ is the duration of the applied voltage or E field.

We apply the model to a fabricated prototype ejector with an orifice radius r_o =10 µm [14]. The piston is polysilicon with a thickness of 2 µm. The reservoir gap is g = 10 µm, and the fluid is water. We study the ejection process using a constant electric field and no spring restoring force (k = 0). The applied field is E = 25 V/µm and the activation period is $\tau = 4.4 \mu s$. During this time, the applied electrostatic force on the piston is $F_a(t) = \varepsilon\pi\left(r_p^2 - r_o^2\right)E^2/2$ where $\varepsilon = 70\varepsilon_0$.

We track the flow rate through the orifice, piston velocity and ejected volume. We perform a parametric analysis where we vary the piston radius r_p = 50, 60 and 70 µm. For each radius, we evaluate ejection performance for three different initial piston-to-nozzle distances h_0 = 3.5, 4.0 and 4.5 µm. We calibrate our analytical model using CFD analysis that takes into account fluid-structure coupling, i.e. the moving piston creates a pressure distribution in the fluid, and its displacement depends on the applied electrostatic force and the resistance to motion due to the pressure.

We use the FLOW-3D software for the CFD, which is a volume-of-fluid (VOF)-based solver [19]. From our CFD analysis we determine a fitting parameter β = 0.75, i.e. the analytical model over predicts the ejected volume by 25 % compared to the CFD analysis. This is expected as the model does not take into account several effects that tend to lower the ejected volume including the back pressure at the orifice due to the developing meniscus etc. We use the same value of β for all our analysis. The calibrated analytical predictions are compared to the corresponding CFD predictions of ejected fluid volume in Table 1.

Table 1. Comparison of total volume ejected through the orifice during the ejection period 4.4 μs.

	$Q_{Analytical}/Q_{CFD}$ (pl)		
	R_p (μm)		
	50	60	70
h_0 (μm)			
3.5	4.13/4.4	4.93/5.2	5.67/5.6
4.0	4.79/5.0	5.7/5.7	6.64/6.35
4.5	5.27/5.54	6.4/6.35	7.48/7.05

It should be noted that a typical analytical calculation required only a few seconds to complete, while the fully-coupled CFD required 55 min to simulate 4.4 μs of the ejection process.

Once the lumped-element model is calibrated, it can be used for parametric analysis of ejector performance. We compare analytical and CFD predictions of the flow rate through the orifice, piston displacement, and ejected volume ($0 \le t \le \tau$) for a 140 μm piston with an initial position 3.5 μm beneath the nozzle. As shown in Fig. 3, the analytical model tends to over predict the orifice flow rate and the piston displacement during the initial stage of ejection, and under predict these variables during the latter stage. A CFD analysis of drop ejection for a 140 μm piston with h_0 = 3.5 μm is shown in Fig. 4. The final ejected drop volumes and velocities from the CFD analysis are given in Table 2. Only the primary drop volumes are recorded, i.e. satellite drops are not included.

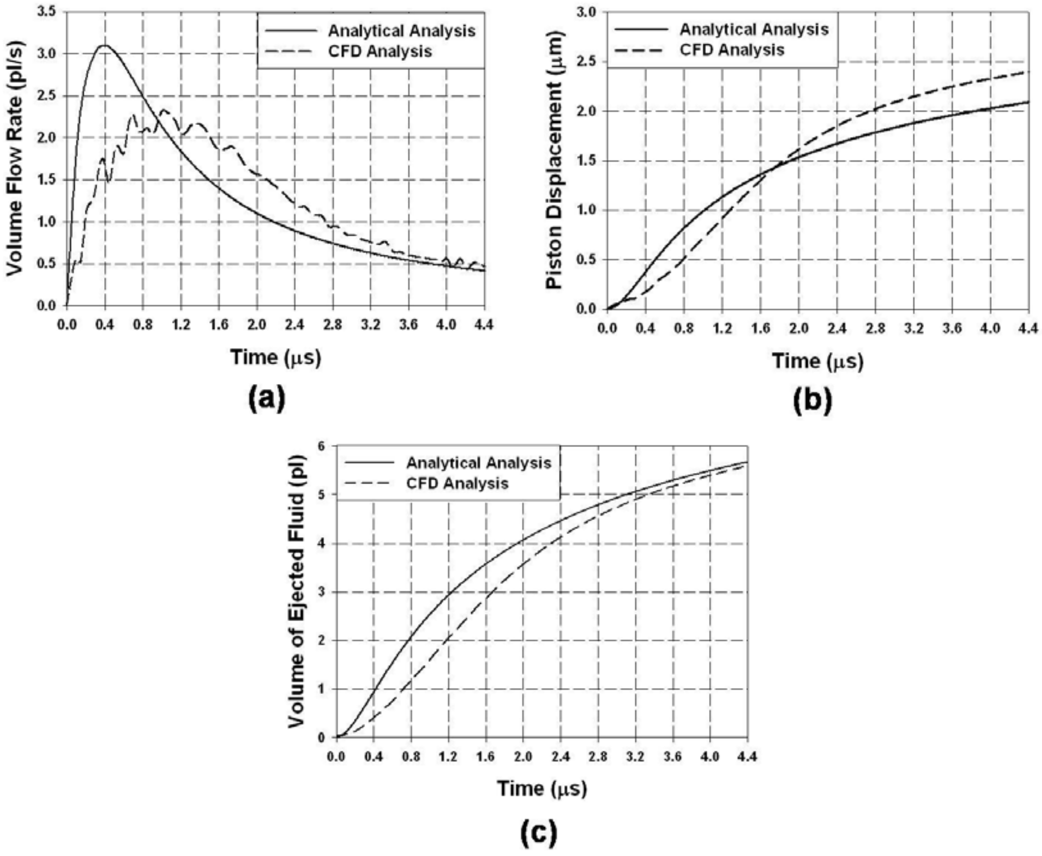

Fig. 3. Comparison of analysis: (a) volume flow rate; (b) piston displacement; and (c) ejected volume.

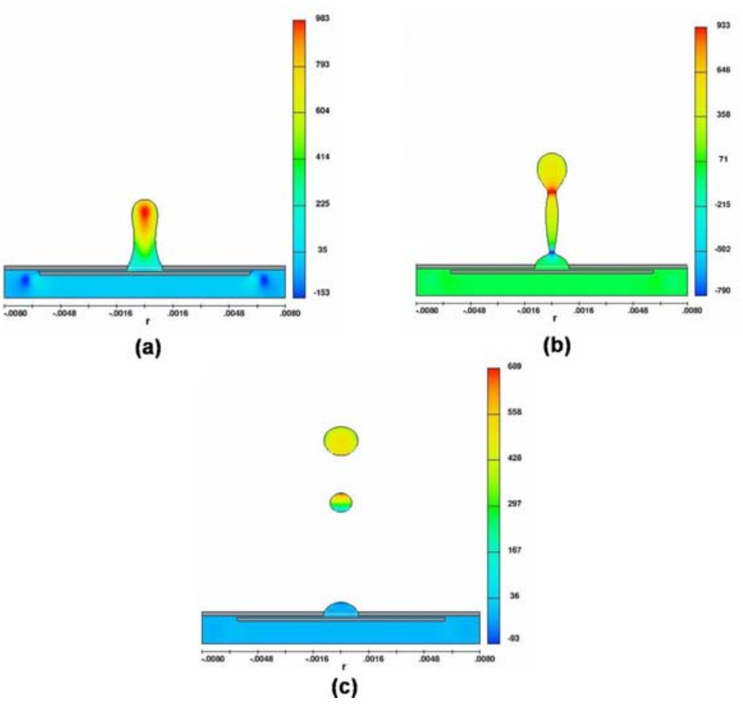

Fig. 4. CFD simulation of drop ejection: (a) t = 4.4 µs, (b) t = 10 µs, and (c) t = 20 µs.

Table 2. CFD analysis: drop volumes and velocities.

Drop Volume (pl)/DropVelocity (m/s)			
	R_p (µm)		
	50	60	70
h_0 (µm)			
3.5	3.0/0.86	3.7/2.0	3.13/4.40
4.0	3.56/2.1	4.78/3.24	3.78/5.54
4.5	4.0/3.12	4.95/3.8	4.35/6.6

It should be noted that the drop volumes and velocities predicted here are comparable with a similar analysis performed using the finite-element based GOMA code developed at Sandia National Laboratories.

4. Device Performance

Prototype ejectors as illustrated in Fig. 1 were developed and characterized at Sandia National Laboratories. The tested devices produced picoliter-sized droplets with velocities of approximately 10 m/s at kHz repetition rates [14]. The energy required to eject a drop was on the order of 3 nJ/pl.

Several critical factors were identified for robust operation of the ejector. The most fundamental issue involves electric breakdown of the fluid. Specifically, the E field in the fluid needs to be kept below the breakdown value, nominally 30 V/µm for H_2O at microscale dimensions. If a fixed actuation potential is applied between the piston and the nozzle during ejection, the E field will increase as the gap between the two decreases, which can lead to breakdown. This can circumvented using a current source, or dynamic voltage control wherein the voltage is reduced during ejection.

Another operational issue is electrolysis and gas bubble generation. Specifically, the applied E field can cause electrochemical reactions at the interface between the electrodes (i.e., the piston and orifice plate) and the liquid. This can lead to power dissipation and the production of gas bubbles. Gas bubbles are compliant and can reduce ejection efficiency. Furthermore, cavitation can occur during bubble nucleation and this can cause structural damage. Electrochemical reactions are reversible and can be suppressed using a continually alternating bipolar voltage pulse [14]. Additives can also be used to reduce electrolysis.

A third operation issue is undesired heating of the fluid. Aqueous fluids have a finite conductivity σ, and therefore joule heating takes place within the fluid during ejection. The heating power density is $P = \sigma E^2$. This heating can degrade the fluid or ink, and additives may be used to suppress it.

5. Conclusions

We have studied the operation of a MEMS squeeze-film dominated electrostatic drop ejector. Prototype ejectors that are capable of producing picoliter-sized droplets at kHz repetition rates have been developed at Sandia National Laboratories. We have discussed the fundamental physics governing drop ejection and presented a lumped-element model for estimating device performance. The model needs to be calibrated using a limited number of fully-coupled CFD simulations in order to provide accurate estimates of the orifice flow rate and total ejected volume. Once calibrated, the model enables rapid parametric analysis of device performance as a function of key parameters including the piston size, orifice diameter and initial gap beneath the nozzle. The model should be of considerable use in the development and design of novel squeeze-film based electrostatic MEMS DOD ejectors.

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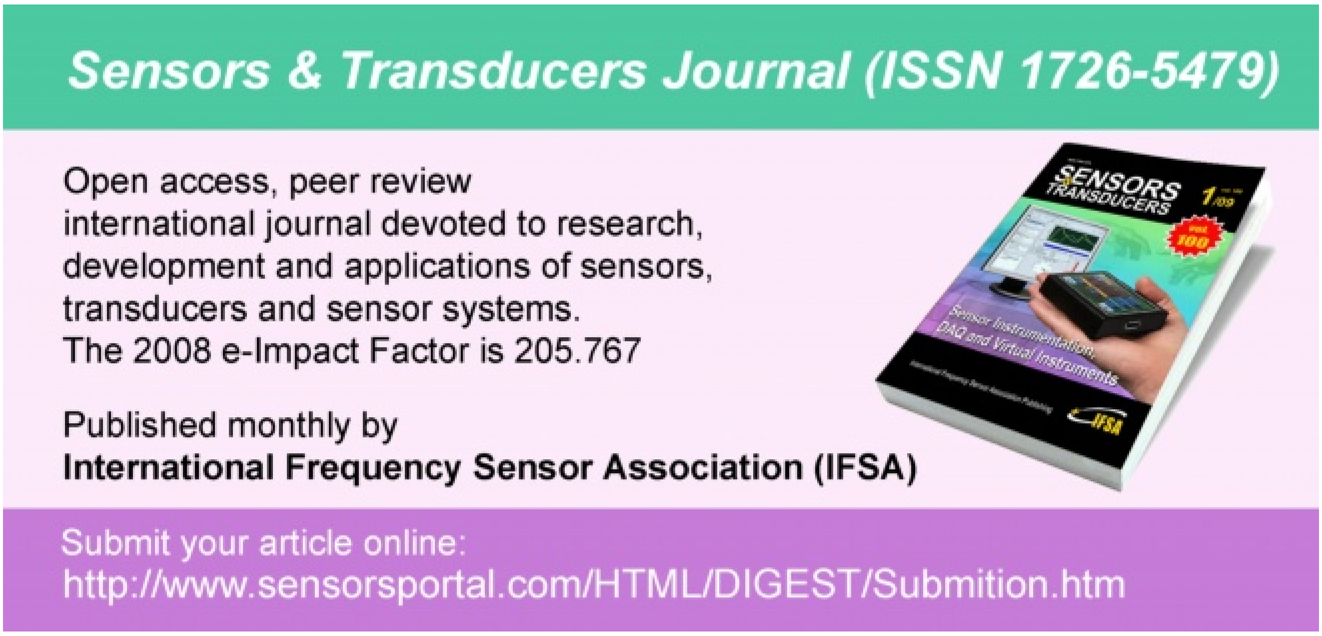

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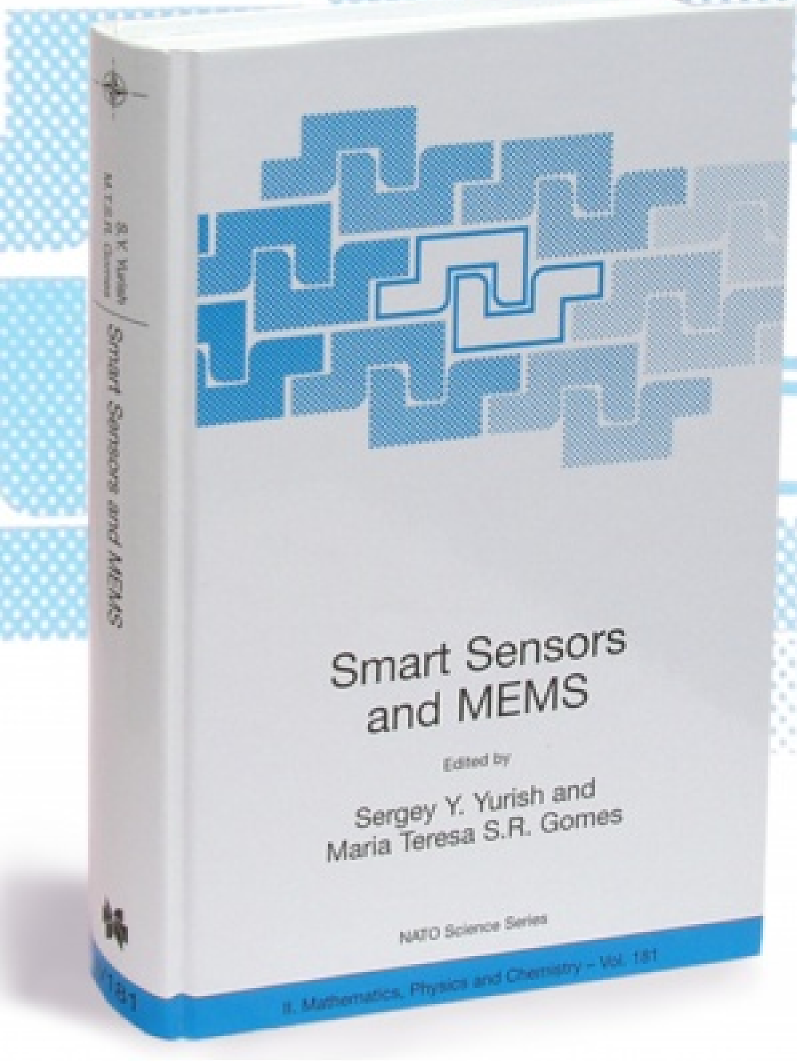
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