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Ultra Small Droplet Generation in Inkjet Printing by Higher Order Meniscus Oscillations

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Abstract

Piezo inkjet printing is a widely known technology to generate small droplets for accurate patterning of functional materials. The droplet generation is a complex interaction of the internal pump dimensions, the piezo electric driving characteristics and the liquid properties. For low viscosity inks standard drop formation is executed by employing the keynote mode of the waveguide type of print head. In such a print head the pump chambers are long, in order to allow for a close staking of the nozzles to end up with a large native drop per inch (DPI) number. This keynote mode produces droplets with a diameter that is of the order of the nozzle diameter. As there is a need for patterns with finer and finer features, especially for non-graphical applications, while still maintaining a robust printing process, i.e. without clogging of the nozzle, it is very interesting to generate smaller sized droplets while using a standard print head. In this paper it is shown experimentally and theoretically that such droplets can be made via higher order oscillatory meniscus modes. In such a mode the fluid motion is confined to the very close environment of the meniscus. When the print head and pulse are designed such that an overtone of the waveguide coincides with a symmetric resonance mode of the meniscus, it is possible to make stable droplets that are more than an order of magnitude smaller than the standard droplet.

Introduction

Piezo inkjet print heads are specified to produce droplets of a certain volume, speed and maximum driving frequency. These specifications are met by driving the print head with a specific pulse, the shape of which is tuned such that stable droplet emission is obtained and that satellite droplets are as good as possible avoided [1].

The basic timing of the pulse shape is related to the keynote of the print head. So if the keynote frequency is 50 kHz a pulse timing of 10 µs is found, for 200 kHz 2.5 µs; the higher the keynote frequency the smaller the nozzle diameter. The droplet size is metered by the nozzle cross-section.

In a multi-nozzle piezo-electrically driven print head a large number of miniature and valveless pumps are integrated and all connected to a main ink supply channel. In order to have a design with the smallest native nozzle pitch (DPI) possible the pumps are placed as closely as possible next to each other. This implies that the length of such a miniature pump has to be long compared to its cross-sectional dimensions in order to generate enough volume displacement by the piezoelectric actuator. The layout of such a pump is referred to as of the waveguide type.

In a waveguide type print head two almost independent dynamical phenomena are active.

The first one concerns waves that travel back and forth through the pump upon actuation. The evolution of these waves in course of time depends on the reflection properties at the beginning and the end of the pump, the beginning being the connection to the main ink supply channel and the end being the nozzle. The attenuation depends on the viscosity of the ink used. In a waveguide type of print head with a restricted connection to the main supply channel the keynote frequency belongs to a half wave length oscillation, for a print head of which the pump chambers have an open connection to the main supply channel, this mode is a quarter wavelength oscillation [1].

The second dynamical phenomenon is related to the capillary forces originating from the meniscus at the end of the nozzle facing ambient and pinned to the nozzle rim. When the meniscus retracts over a small distance (small compared to radius nozzle) further into the nozzle, its curvature increases and the capillary pressure increases. This effect forces the meniscus to move back to its original position. During outflow over a small distance the same happens. With increasing outflow the curvature increases and the capillary force opposing the motion increases accordingly. The capillarity builds a kind of mechanical spring action. This spring action together with the mass of all the fluid in the pump forms a mass-spring system with its own oscillatory behavior. The corresponding characteristic resonance frequency is the so-called slosh mode, all the fluid contained in the pump moves against the surface tension spring. For most designs the slosh mode frequency is considerably lower than the keynote frequency.

For higher order modes meniscus modes, however, the fluid motion is confined to the very close environment of the meniscus [2]. As now much less mass is involved the associated higher order meniscus resonance frequencies are very high. This means that for low frequencies like the slosh mode and the keynote frequency the meniscus shape is determined by the fluid displacement in the nozzle and follows the mechanical spring picture sketched above.

A wave guide is characterized by its keynote and overtones. Specific frequencies in the spectrum of the pulse used to drive the print head may activate overtones of the waveguide. When the print head and the pulse are designed such that an overtone of the waveguide coincides with a symmetric resonance mode of the meniscus it may be possible to make droplets that are much smaller than the standard droplet. The higher order meniscus wave forms resemble the wave forms of the surface of a drop sitting on a surface with pinned contact line [3].

Experimental

Using a MicroDrop (www.microdrop.de) single nozzle print head with a 50 µm nozzle the influence of the wave form on the droplet size has been tested. An example is shown in Figure 1, the drop formation process using the standard pulse provided by the manufacturer. The test liquid in all experiments reported about in this paper is a 0.88% solution (by volume) of a light emitting polymer in tetralin (density $\rho = 0.97$ kg/l, surface tension $\gamma = 35.5\ \mathrm{mN/m}$ and shear viscosity tuned to $\mu = 10$ mPas by the amount of polymer). Tetralin has been chosen because this solvent has a high boiling point and it is therefore possible to measure accurately the weight of a fixed number of jetted drops without using a correction of the evaporated volume during the experiment.

The shape of the waveform was an ordinary rectangular waveform (pulse time 20-30 μs, pulse height 100-150 V as prescribed by the manufacturer). The drop volume with this waveform was about 180 pl (note that this volume is considerably larger than the volume metered by the nozzle, 65 pl). This pulse complies with the basic resonance frequency of such a head being equal to roughly 20-30 kHz.

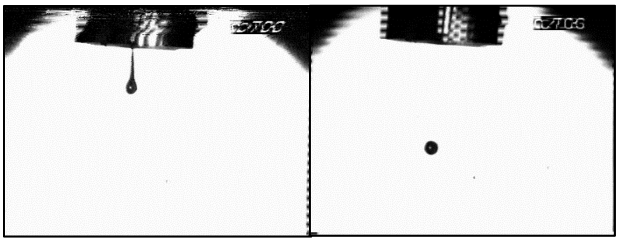


Figure 1. *Drop formation out of a 50 μm diameter nozzle with a standard waveform at different delay times with respect to the leading edge of the pulse. Drop size is ≈ 180 pl.*

By changing the waveform the drop volume can be reduced considerably. Figure 2 shows the drop formation process with an adapted pulse shape. At 1000 Hz driving a drop volume of 14 pl has been measured, meaning a more than an order of magnitude reduction in volume! Clearly is visible that the meniscus shows a higher order meniscus oscillation.

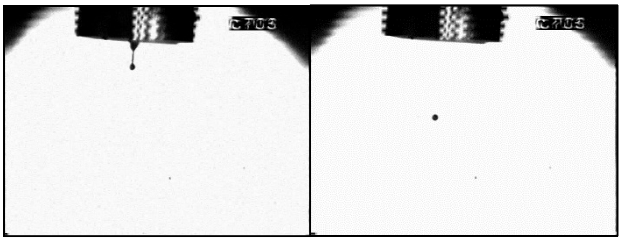


Figure 2. *Drop formation process in a 50 μm nozzle diameter single nozzle head with optimized pulse shape. Drop volume is 14 picoliter at 1000 Hz.*

The drop formation process appeared to be very stable and no satellite drops were observed. The waveform, however, is more complicated. It is sketched in Figure 3. The head has been driven in the “negative” mode, i.e. the liquid is first sucked in the nozzle (plateau 1), then it is driven out of the nozzle (plateau 2) and then it is cut-off (plateau 3). The up and down times are of the order of 1 μs.

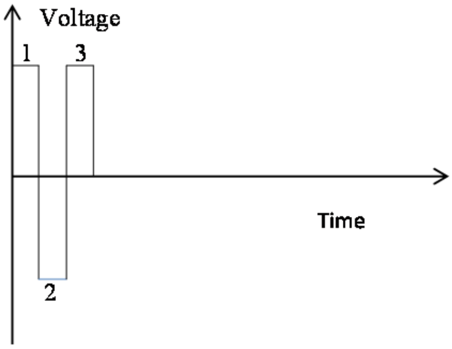
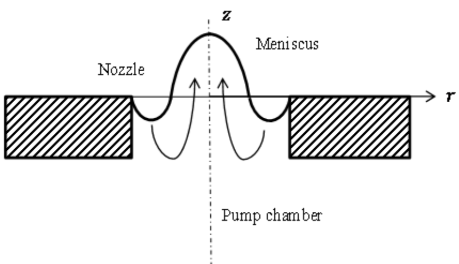


Figure 3. Waveform used to reduce the drop volume. The up and down times are of the order of a few μs.

A similar waveform has been applied to a MicroDrop single nozzle print head with a 30 μm nozzle diameter. Now it is possible to make drops with a volume of ≈ 3-4 pl at 1000 Hz, where ≈ 60 pl is the size with the standard waveform. Again more than an order of magnitude reduction in volume, very stable drop formation, no satellites and very good start-and-stop accuracy are achieved.

Analysis

The full analysis of the action of a piezo driven inkjet print head concerns the internal acoustics, droplet formation dynamics and droplet-substrate interaction [1]. In this paper only the meniscus dynamics are considered. The shape of the meniscus shown in Figure 3 suggests that the mode to be considered is a symmetric mode visualized in ***Figure 4.*** *Symmetric higher order meniscus motion, fluid is transported back and forth*



*underneath the meniscus from the rim to the center and causes the meniscus to deform. The arrows symbolize the material displacement involved. The cylindrical co-ordinates are denoted by r and z.*Figure 4.

Figure 4. *Symmetric higher order meniscus motion, fluid is transported back and forth underneath the meniscus from the rim to the center and causes the meniscus to deform. The arrows symbolize the material displacement involved. The cylindrical co-ordinates are denoted by r and z.*

During oscillation the surface of the meniscus is perturbed in time. If the perturbation is axisymmetric and harmonic such a periodic change in height $z(r,t)$ can be represented by:

$$z(r,t) = A\left(\cos\frac{\pi}{2}\frac{r}{R_1} + \lambda\cos\frac{3\pi}{2}\frac{r}{R_1}\right)\sin\omega t.$$

Here R_1 is the radius of the nozzle and A amplitude. In the case that there is no net material transport to and from the nozzle, the constant λ is defined such that the meniscus motion satisfies the incompressibility condition:

$$\int_0^{R_1} A\left(\cos\frac{\pi}{2}\frac{r}{R_1} + \lambda\cos\frac{3\pi}{2}\frac{r}{R_1}\right)2\pi r dr$$

$$= 2\pi A R_1^2 \frac{1}{\left(\frac{\pi}{2}\right)^2}\left[\frac{\pi-2}{2} - \lambda\left(\frac{1}{6}\pi + \frac{1}{9}\right)\right] = 0,$$

$$\lambda = \frac{9(\pi-2)}{(3\pi+2)} = 0.899303.$$

The value for λ is universal, in the sense that it does not depend on the amplitude A. For small meniscus motions, the maximum increase in surface area of the deformed meniscus is given by (the numerical pre-factor has been found by numerical calculation):

$$\Delta A_{max} = A_{meniscus,max} - \pi R_1^2$$

$$= -\pi R_1^2 + \int_0^{R_1} 2\pi r dr\sqrt{1 + \left(\frac{dz}{dr}\right)^2}$$

$$\approx -\pi R_1^2 + \int_0^{R_1} 2\pi r dr\left[1 + \frac{1}{2}\left(\frac{dz}{dr}\right)^2\right] = \pi\int_0^{R_1} r\left(\frac{dz}{dr}\right)^2 dr$$

$$= 13.23A^2.$$

The fluid motion close to the meniscus is approximated by considering a kind of toroidal motion (note that the torus cannot move like a rigid body). Close to the centre the velocity of the torus is given by the mean velocity of the meniscus between $r = 0$ and $r = R_1/2$ $(0.8377\omega A)$. In the rim region the velocity is taken equal to the mean velocity between $r = R_1/2$ and $= R_1$ $(-0.2792\omega A)$. The centre circle of the torus is located at $r = R_1/2$.

A local co-ordinate system is defined with r^* giving the distance from the centre of torus to some point in the fluid and θ the angle running from the surface close to centreline of the meniscus to the rim of it. The velocity field is approximated by:

$$v_\theta = A\omega\left[0.8377\,\frac{\pi-\theta}{\pi} - 0.2792\frac{\theta}{\pi}\right]\cos\omega t.$$

The torus extends over $0 < r^* < R_1/2$. The maximum of the kinetic energy follows from (again the result has been obtained by numerical integration):

$$T_{max} = \frac{1}{2}\pi\rho_0\int_0^{\pi}\int_0^{R_1/2}\left(\frac{1}{2}R_1 - r^*\cos\theta\right)v_\theta^2 r^* dr^* d\theta$$

$$= 0.03\rho_0 A^2 R_1^3$$

The resonance frequency belonging to the axisymmetric mode following Rayleigh reads:

$$\omega^2 \approx \frac{13.23A^2\gamma}{0.03\rho_0 A^2 R_1^3} = 441\frac{\gamma}{\rho_0 R_1^3}$$

$$f \approx 3.34\sqrt{\frac{\gamma}{\rho_0 R_1^3}}$$

For the 50 µm nozzle and the test fluid defined under the heading experimental, the basic higher order resonance is given by: $f \approx 160$ kHz. This frequency can be generated by a pulse with steep leading and trailing edges ($t_r, t_f <$ 0.1 µs) and pulse time of the order of 3 µs. In that case, instead of exciting the whole meniscus, a higher mode is touched generating much smaller droplets.

It is also possible to generate a simple expression for the volume reduction of the droplet. From the expression for the height $z(r,t)$ we can find an analytical expression for the non-trivial position r_0 where $z(r_0,t) = 0$, i.e.

$$r_0 = \frac{2}{\pi}R_1\cos^{-1}\sqrt{\frac{3\lambda-1}{4\lambda}}$$

Which results in $r_0 \approx 0.5179R_1$. Assuming a droplet volume that will be scaled with the new "effective" nozzle diameter we expect a droplet volume of ≈ 7 times smaller, which is in agreement with the measured reduction of ≈10 times.

Discussion

It has been shown experimentally that a standard print head like the Microdrop single nozzle print head can be driven in such a way that a wide range of droplet volumes can be generated. Around the standard setting droplets are generated employing the basic key tone resonance of the print head (in the case discussed around 30 kHz) and the meniscus deforms upon actuation as a dome of liquid attached to the rim of the nozzle. There are two almost independent modes that control the action of the print head, namely, the so-called low frequency slosh mode for which all the fluid in the print head pump moves as whole against the capillary action of the meniscus and the keynote mode. In a waveguide type of print head for a system with a throttle the keynote frequency belongs to a half wave length oscillation, for a print head of which the pump chambers have an open connection to the main supply channel, this mode is a quarter wavelength oscillation [1]. For a pump with a throttle the keynote frequency is often referred to as the Helmholtz frequency. Although the compressibility of the fluid contained in the pump chamber is dominant, the keynote frequency slightly depends on the capillary action of the deforming meniscus as well. For higher order modes of the meniscus, however, the fluid motion is confined to a thin layer of fluid close to the meniscus. This implies that the associated resonance frequencies are high, much higher than the keynote frequency of the waveguide, and far much higher than the slosh mode frequency. Such a mode can only be set in motion by a high frequency. Such a high frequency can be found in the spectrum of a pulse of short duration, for the MicroDrop print head it is about µs. The pump chamber of a MicroDrop print head is long and therefore of the waveguide type. By actuation not only the key tone can be touched but also high frequency overtones. The interplay of frequencies in the spectrum of the short duration pulse, specific resonances of the wave guide type of print head and higher order meniscus resonances makes it possible to generate very small droplets.

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Authors Biography

Paul C. Duineveld *graduated and did his PhD at Twente University under supervision of Leen van Wijngaarden on bubble dynamics. After his service as Navy officer he started at Philips Research working, together with Frits Dijksman, mainly on inkjet printing for display and bio-sensor applications. In 2004 he moved to Philips Health Tech where he started working on what is now Philips AirFloss. In 2007 he became a director of Engineering in the field of Fluid Dynamics and in 2008 a DFSS BB. He is the principal in a team of 8 people working on fluid dynamic applications in household appliances from vacuum cleaners, irons, air purifiers, baby bottles, toothbrushes, fruit juicers, respiratory care, coffeemakers etc.*

J. Frits Dijksman *obtained his masters in mechanical engineering at the Technical University of Delft in The Netherlands in 1973. He finished his PhD within the groups of Professor. D. de Jong and Professor W.T. Koiter (Technical University of Delft, The Netherlands, 1978) focussing on the engineering mechanics of leaf spring mechanisms. He worked with Philips Research Laboratories in Eindhoven, The Netherlands for 32.5 years. In a number of projects he worked closely together with Paul Duineveld. After his retirement he continued his work as part time professor at the University of Twente, The Netherlands and as an inkjet consultant. The topics include inkjet printing of viscoelastic inks, design of inkjet print heads and printed biosensors. He is now emeritus professor at the University of Twente.*