MENISCUS DYNAMIC BEHAVIORS IN A SQUEEZE MODE
PIEZOELECTRIC INKJET DEVICE

Tzong-Shyng Leu¹, and Jan-Hua Lin ²

¹ Department of Aeronautics and Astronautics, National Cheng Kung University, Taiwan, tsleu@mail.ncku.edu.tw
² Department of Aeronautics and Astronautics, National Cheng Kung University, Taiwan, p4692104@ccmail.ncku.edu.tw

ABSTRACT  Meniscus dynamic behaviors, as well as its optimal waveform of driving signal, in a squeeze mode piezoelectric inkjet device are studied in this paper. To use the squeeze mode piezoelectric inkjet device as a drop on demand dispenser, the driving signal is trapezium waveform. The parameters in a trapezium waveform of the driving signal include rise time (t₁), dwell time (t₂), fall time (t₃), and voltage (Vₒ). Among these parameters, the most important parameter of driving signal is the dwelling time. To demonstrate the importance of dwelling time, a LED signal synchronized with the driving signal is used to visualize the instantaneous meniscus shape under a microscope. Experimental results show the meniscus oscillation at beginning and droplet ejection at the later phase. It is found there is an optimal dwelling time. At the optimal dwelling time, droplet ejects in a minimum time and its ejection velocity reaches the maximum. The optimal dwelling time can be further identified it relates to a pressure wave oscillation within the device. The optimal dwelling time can be approximated as the length (L) of the piezoelectric inkjet device divided by the speed of sound (C) in the dispensed fluid.

Keywords: piezoelectric inkjet, squeeze mode, meniscus, pressure oscillation

1. INTRODUCTION

Inkjet printing have been used in many application areas, such as office printing [1], [2], biofluid printing, fuel injection [3], drug dosage/micro dosing [4], IC cooling and direct writing. Reliable, high performance and low-cost inkjet devices are always in great demand. Recently, besides the previously mentioned applications, inkjet printing technology in various high-tech manufacture processes is very promising. The manufacturing research and development is being driven by the need for automation, miniaturization and reduction in costs and environmental impact. To meet these needs, inkjet printing technology is becoming an charming choice for the distribution and patterning of materials for a wide variety of applications.

Inkjet printing technology also has been explored to be applied to flat panel displays [5] fabrication. Organic light-emitting diodes (OLEDs) are one of the most promising technologies for the future. However, due to limitation on the solution selection, they are usually fabricated by using thin film deposition with an evaporation process and subsequent patterning through lithography. The processes, along with the required masks, are very expensive. Great benefits will be obtained if arrays of organic light-emitting materials can be deposited directly by inkjet printing methods. The current exercise for polymer light emitting diodes (PLEDs) is deposition through spin coating. With the application of inkjet printing technology, it is possible to deposit tiny pixels of red, green and blue elements to produce the color filters. Compared with the spin coating process, inkjet printing technology has the benefits of high resolution, low cost, simpler processing, a high rate of materials utilization and the capability to produce large panels. Inkjet printing technology also provides a unique process for micro-lithography and the fabrication of micro-lens arrays as well as complex three-dimensional structures [3].

A variety of actuation methods have been reported to eject micro droplets, including thermal bubble, piezoelectric [6], thermal buckling [7], acoustic wave [8] and electrostatic [9]. Among these methods, the actuations using piezoelectric and thermal bubble devices are the most mature and most popular for commercial inkjet printers. For thermal bubble devices, the ejection of liquid droplets from the nozzle is induced by the formation of a vapor bubble in the ink through the heating of a resistive film. For piezoelectric inkjet printing, there is no need to vaporize the fluid. The liquid droplets are ejected from the nozzle by the displacement of a piezoelectric diaphragm that is coupled to the fluid. Thus, this method can be used for the ejection and dispensing of polymers and liquid metals. The adoption of piezoelectric inkjet printing technology in the electronics manufacturing industry is thus very desirable.

The printing quality and resolution of an inkjet printhead are known to be closely related to the characteristics of the ejected droplet. Therefore, it is very desirable to gain insights into how the liquid droplet is formed, ejected and impacted onto the substrate in a piezoelectric inkjet printing device. Without detailed knowledge of the pressure response and velocity variation in the ink flow channel, optimal droplet ejection and therefore optimal printing quality cannot be assumed.

Development of inkjet printing systems for manufacturing processes is time-consuming and relies heavily on 'trial-and-error' experiments. In order to shorten the design cycle and accelerate establishment of the relevant technology, numerical simulation has been employed by many researchers. The first step in the
numerical simulation is to derive the pressure history at the nozzle end of the chamber due to the expansion and contraction of the chamber walls resulting from the application of a voltage pulse to the piezoelectric tube. The response of the piezoelectric crystal tube itself was studied by Bugdayci et al. [10], who calculated the inner cylindrical wall displacement of the tube for an applied voltage step. Bogy and Talke [11] deduced that the pressure at the inner face of the nozzle plate of a squeeze tube inkjet transducer is due to the constructive interference of acoustic pressure waves created in the fluid cavity by the expansion and contraction of the piezoelectric sleeve that surrounds the glass lining of this type of nozzle. A numerical solution for drop formation outside the nozzle based on the axisymmetric Navier–Stokes equations was presented by Fromm [12]. Several variations in the square wave pressure history applied at the nozzle inlet are discussed in relation to the drop velocities produced and the structure of ejected drops. Asai [13] employed a three-dimensional finite difference algorithm based on the volume-of-fluid (VOF) method to solve the Navier–Stokes equations and predict the drop ejection from a bubble jet printer. Liou et al. [14] applied a fluid dynamics simulation system named COMET to predict the meniscus position over time inside a SEAJet inkjet printhead (thermal bubble type) during the infusion and ejection stages. According to this literature, the flow behavior of the inkjet printing process depends strongly on physical design parameters and fluid. In this paper we present experimental results for a squeeze-type piezoelectric inkjet printing device and study the effects of operational characteristics including driving signal on the formation of liquid droplets. The efficiency of the droplet ejection is evaluated by the indices of the minimum energy input during ejection.

2. EXPERIMENTAL SETUP AND METHODS

2.1 Piezoelectric Inkjet Device

MicroJet (MJ-AT) device [15], manufactured by MicroFab Technologies, Inc is used in studying the meniscus dynamic behaviors of a squeeze mode piezoelectric inkjet device. The ‘MicroJet’ has been developed to dispense single drops of solvents, water-based fluids, and inks. With proper fluid preparation and device maintenance, the jetting device provides reliable delivery of fluid micro-drops. The MJ-AT jetting device design has successfully jetted a wide variety of fluids. Performance of the jetting device is closely tied to the characteristics of the fluid in use. Typical fluids successfully jetted in this device have viscosities less than 40 centipoise and surface tensions in the range of 0.02-0.07 N/m. Fluids with properties outside these limits can be jetted if changes to the properties can be achieved with solvents or changes in temperature. In this study, DI water is used for the current experiments. Physical dimensions of MJ-AT are shown in Figure 1. The jetting device orifice size is 80 microns. Depending on the operating parameters and the fluid, these devices can produce drops ranging from 50-200 picoliters in volume. The operating temperature of MJ-AT is between 20 and 150°C.

Figure 1  Squeeze mode piezoelectric inkjet device dimensions

2.2 Microscopic Visualization Techniques

To characterize the piezoelectric inkjet device and demonstrate its operation, microscopic visualization methods have been developed to show dynamic meniscus shape and the droplet ejection sequence. Note that the visualization of these droplets is nontrivial because of their small size (10–70 µm in diameter), their existence in free space (as opposed to on surface) and their fast speed. Furthermore, consider the difficulties involved with positioning the microscope objective lens. The lens needs to be close to the nozzle to resolve the micron size droplets but clear of the droplet path. The droplet trajectory provides an overall picture of the droplet ejection trajectory, while the droplet ejection sequence provides the more detail evolution of droplet formation and ejection. Droplet properties, such as ejection speed, droplet size, directionality, satellite droplets, flying distance and frequency response, can be quantitatively obtained.

Figure 2  The sketch of microscopic visualization experimental setup

To visualize the detail meniscus shape and droplet ejection sequence of the piezoelectric inkjet device in the nozzle region, a visualization system developed in house [16], [21] has been used. Figure 2 shows the sketch of experimental setup. An LED was placed under the inkjet device to back-illuminate the interface near the nozzle. Two
signals, are first synchronized with adjustable time delay by a pulse delay generator (STANFORD DG535). One of signals is sent to an arbitrary function generator to trigger the driving signal for piezoelectric inkjet device. The second signal is used to drive an LED. Both driving signal from arbitrary function generator and pulse delay generator are amplified by a high voltage power amplifier before they connect to the loads. The meniscus shape and droplet images can be frozen by the flashlight from the LED at specified time delays, as shown in Figure 3.

Figure 3 Photograph of experimental setup with the meniscus shape and droplet images captured by the setup

2.3 Driving Signal Waveform

In order to generate drops, a pulse is sent to the PZT surrounding the glass capillary. The shape of this waveform is shown in Figure 4. The driving signal in Figure 4 is trapezium waveform. The parameters in a trapezium waveform of the driving signal include rise time \( t_{\text{rise}} \), dwelling time \( t_{\text{dwell}} \), fall time \( t_{\text{fall}} \) and voltage \( V_p \). The rising time \( t_{\text{rise}} \) and the falling time \( t_{\text{fall}} \) represent for the initial rising time and final falling time between zero voltage and a high voltage \( V_p \). To minimize the driving voltage, the rise and fall times should be as short as possible. For current experiments, the rising time \( t_{\text{rise}} \) and the falling time \( t_{\text{fall}} \) equals to 1.3ns. Therefore, the most important parameter in the waveform of driving signal is the dwelling time \( t_{\text{dwell}} \).

Figure 4 Typical driving signal waveform for a piezoelectric inkjet device

3. EXPERIMENTAL RESULTS AND DISCUSSION

According to piezoelectric effect, the displacement of the piezoelectric tube is proportional to input voltage. Therefore, the actuation of the piezoelectric inkjet device can be controlled by the following parameters including back pressure, voltage, dwelling time of signal and driving frequency. For the convenience of describing meniscus shape, meniscus height \( H_m \) is defined as interface location along the centerline of the nozzle. \( H_m \) is defined as a positive (negative) value when meniscus is convex (concave). For examples, Figure 5 shows an image of meniscus shape. Meniscus height \( H_m \) is defined as a negative value in Figure 5 since its meniscus is concave shape.

Figure 5 Meniscus image with a negative meniscus height \( (H_m < 0) \)

3.1 Back Pressure Test

Before any dynamic investigation, meniscus shape at different back pressure is first tested in piezoelectric inkjet device. The meniscus heights for various back pressure are plotted in Figure 6.

Figure 6 Meniscus height \( H_m \) at different back pressure
Figure 7 Sequence images of meniscus near the nozzle for (a) $V_p=12.8$ volt and (b) $V_p=50$ volt. The time delay between two adjacent images is 4 $\mu s$.

It is noticed that the meniscus is convex shape and its meniscus height is positive for positive back pressure greater than 19.6 Pa. For back pressure between -150 and 19.6 Pa, the fluid meniscus is flush with the device front face. The meniscus height is close to zero since it is very hard to notice any meniscus movement within this range of back pressure. Once the back pressure is smaller than -150 Pa, the meniscus shape retreats and meniscus height becomes negative. When the back pressure reaches -249.2 Pa, the meniscus height $H_m$ equals -33.5 $\mu m$. If the back pressure decreases beyond -249.2 Pa, the meniscus will be unable to be held near the nozzle. The nozzle will suck the air into the devices. In this study, all the cases are tested when the back pressure equal to zero.

3.2 Voltage Test

To investigate the effect of every operation parameters to the performance of piezoelectric inkjet device, the driving signal waveforms, fixed at dwelling time $t_{\text{dwell}}=125\mu s$, frequency $f=500$Hz, and voltage $V_p =12.8$, 50 or 70 volt, are tested. Figure 7 shows the sequence images for the cases of $V_p=12.8$ and 50 volt. It is easily to verify that meniscus for $V_p=12.8$ volt only oscillates without any droplet ejection, and droplet breaks up at 176 $\mu s$ for the $V_p=50$ volt case.

The dynamic behaviors of meniscus for all cases can be seen clearly if the meniscus height $H_m$ is plotted in Figure 8. When the delay time is zero, driving signal just input into the inkjet device. The voltage increases from ground to a positive voltage within 1.3ns. At this time, piezoelectric tube diameter increases and ejection chamber volume expands. The meniscus height $H_m$ becomes negative. This situation keeps for about 125$\mu s$. The ejection chamber volume returns to its original size and
squeeze the liquid out of the device when the voltage drops to ground. For \( V_p=12.8 \) volt case, the meniscus shape hardly moves before \( 125 \) µs, but it oscillates after \( 125 \) µs and reaches to its maximum at \( T_{\text{delay}}=160 \) µs and \( 216 \) µs. The meniscus height \( H_m \) changes between 0 and \( 50 \) µm for about two cycles before diminishing. Eventually, the droplet can not be ejected out the nozzle for \( V_p=12.8 \) volt case. On the other hand, the meniscus heights for \( V_p=50 \) and \( 70 \) volts cases show the constructive pressure waves build up before \( 125 \) µs and the droplets immediately shoot out from nozzle after \( 125 \) µs.

In the voltage tests, it is confirmed that there is pressure wave propagation and interference within the piezoelectric tube. The higher the voltage, the larger the amplitude is. With high enough voltage, the constructive pressure wave may build up. It is also suggested that dwelling time relate to the buildup of a constructive pressure wave closely.

### 3.3 Dwelling Time Test

From previous section results, it indicates the dwelling time is an important parameter for the buildup of constructive pressure wave. In this section, the driving signals, fixed at voltage \( V_p=35 \) volt, back pressure \( 0 \) Pa, frequency \( 500\)Hz and dwelling time \( t_{\text{dwell}}=13, 25 \) or \( 50 \) µs, are tested to study the dwelling time effect. Figure 9 shows the meniscus height \( H_m \) for dwelling time \( t_{\text{dwell}}=13, 25 \) and \( 50 \) µs. For meniscus height of \( t_{\text{dwell}}=13 \) µs case, \( H_m \) starts to retreat at \( 13 \) µs and reaches its negative maximum at \( 20 \) µs. After time at \( 20 \) µs, the meniscus changes from a negative value to a positive value and arrive to its peak at \( 48 \) µs. It oscillates until a valley at \( 76 \) µs. After \( 76 \) µs, the meniscus shape expands outward and finally droplet ejects after \( 80 \) µs. If dwelling time is further increased to \( 25 \) µs, the dynamic behaviors of meniscus are different from the case of \( t_{\text{dwell}}=13 \) µs case. The meniscus reaches its negative maximum at \( 28 \) µs and the droplet ejection immediately after \( 40 \) µs. It does not have any meniscus oscillation like \( t_{\text{dwell}}=13 \) µs case. The \( t_{\text{dwell}}=50 \) µs case has similar dynamic behaviors like \( t_{\text{dwell}}=25 \) µs case, but the droplet ejection time is delayed until \( 60 \) µs.

From meniscus height diagram for different dwelling time setting, one can identify there is an optimal dwelling time for the inkjet device. When the dwelling time is shorter than the optimal dwelling time, the meniscus oscillates. The droplet ejection time is delayed. If the dwelling time is longer than the optimal dwelling time, the droplet ejection time is delayed, too. To depict the optimal dwelling time, pressure wave propagation within the piezoelectric tube is sketched in Figure 10.

In Figure 10, the pressure wave is initiated at \( T=0 \). The pressure wave propagates forward and backward. When the forward (or backward) pressure wave reaches nozzle (or inlet) at \( T=t \), it will bounce back and arrive to the center at \( T=2t \). If the dwelling time of driving signal equals to \( 2t \), the piezoelectric tube generate another pressure wave because of the contraction of piezoelectric tube. These
two pressure wave will interact. Constructive pressure wave can be generated if the dwelling time is optimal. Based on this model, the optimal dwelling time can be approximated as:

\[
\text{Optimal dwell time } t_{\text{dwell}} = \frac{L}{C}
\]

where \(L\) is the length of the squeeze mode piezoelectric inkjet device and \(C\) is the speed of sound in the dispensed fluid.

By more detailed experiments, the optimal dwelling time can be found to be about 20\(\mu\)s. For MJ-AT inkjet device, the length \(L\) equals 2.235cm and speed of sound for water medium at 25\(^\circ\)C is about 1435 m/s. Therefore, the optimal dwelling time can be estimated to be about 16\(\mu\)s, which is very close to experimental results.

4. CONCLUSION

In this paper, meniscus dynamic behaviors, as well as its optimal waveform of driving signal, in a squeeze mode piezoelectric inkjet device are studied. To use the squeeze mode piezoelectric inkjet device as a drop on demand dispenser, the driving signal is trapezium waveform. The parameters in a trapezium waveform of the driving signal include rise time \((t_{\text{rise}})\), dwelling time \((t_{\text{dwell}})\), fall time \((t_{\text{fall}})\), and voltage \((V)\). The rising time \((t_{\text{rise}})\) and the falling time \((t_{\text{fall}})\) represent for the initial rising time and final falling time between zero voltage and a high voltage \(V\). To minimize the driving voltage, the rise and fall times should be as short as possible. The most important parameter in the waveform of driving signal is the dwelling time \((t_{\text{dwell}})\).

In order to demonstrate the importance of dwelling time, a LED signal synchronized with the driving signal and have an adjustable delay from the beginning of the pulse is used to visualize the instantaneous meniscus shape, as well as the droplet ejection process, under a microscope when different dwelling time signals are used to drive the squeeze mode piezoelectric inkjet device. One can see the meniscus oscillation at beginning and droplet ejection at the later phase. The meniscus heights \((H_m)\) are studied for different dwelling time settings. One can find there is an optimum valve for the dwelling time. At the optimal dwelling time (~20\(\mu\)s), droplet ejection in a minimum time period and the ejection velocity reaches the maximum. The optimum dwelling time can be further identified that it relates to a pressure wave oscillation within the device. The length of the piezoelectric inkjet device dictates the dwelling time and the dwelling time can be estimated by \(t_{\text{dwell}} = L/C\), as shown in Equation (1).

5. NOMENCLATURE

\begin{center}
\begin{tabular}{ll}
C & sound speed \ [m/sec] \\
H_m & meniscus height \ [\mu m] \\
L & length of tube \ [cm] \\
t_{\text{rise}} & rising time \ [sec] \\
t_{\text{dwell}} & dwelling time \ [sec] \\
t_{\text{fall}} & fall time \ [sec] \\
V_p & voltage \ [volt] \\
\end{tabular}
\end{center}

6. REFERENCES