Experimental Studies of Bubble Dynamics with Thermal Bubble Valve in Micro Nozzle Channel

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Abstract
In this paper, dynamic behaviors of thermal bubbles are studied inside a micro-nozzle channel. Within the micro-nozzle channel, different chamber neck designs for controlling bubble growth are used, including conventional structural chamber neck as well as virtual chamber neck. Dynamics of bubble growth rates under different input signals and chamber neck configurations are measured using a high speed microscopic imaging system. The experimental results show that with the help of virtual chamber neck at upstream, the bubble interface will tend to move downstream which will enhance the actuation force of the liquid toward the nozzle direction.

Keywords: Thermal bubble; Bubble growth; High-speed microscopic image

1. Introduction
Inkjet printing is a process that material is deposited onto a substrate by ejection of liquid droplet from a nozzle. According to different actuation forces, there are many types of inkjet printheads including thermal bubble, piezoelectric, acoustic and electrostatic types. Among all these types, thermal bubble inkjet printhead is the most commonly used for document printing application. The basic principle of thermal bubble printhead is very simple, but its dynamics is very complicated. Figure 1 illustrates the processes of thermal bubble printhead [1-3]. Firstly, thermal bubble is first generated by applying an impulse signal to a heater inside a microchannel. Heterogeneous boiling occurs above the heater and the liquid above heater starts to nucleate (Figure 1(a)). Secondly, Nucleation bubbles will merge into a single thermal bubble above heater (Figure 1(b)). Thirdly, the bubble growth inside a microchannel pushes surrounding liquid toward nozzle direction. The liquid ejects from the nozzle (Figure 1(c)). Once the input signal is off, the bubble collapses and droplet breaks (Figure 1(d)). The droplet breaks off and forms meniscus interface near the nozzle. Liquid from ink reservoir refills into microchannel through surface tension of the meniscus. The challenge of a thermal bubble inkjet printhead is the design of high actuation force with high repetition frequency. These two goals somehow contradict each other. To have high actuation force, chamber neck structure is commonly designed to reduce backward flow and force bubble to grow forward, thus enhance the actuation force. Figure 2 is SEM image of the chamber structures inside HP 51626A printhead [4]. Chamber neck design is used in HP printheads to limit the backward liquid flow which prevents pressure cross talk problem between adjacent ejection nozzles and enhance the forward actuation force. However, the chamber neck design also retards refilling process from ink reservoir to micro channel and causes the low repetition frequency.

Figure 1. The processes of thermal bubble inkjet actuation [1-3]
To design thermal bubble inkjet printheads with both high actuation force and high repetition frequency, virtual chamber neck design has been proposed by Tseng [1,2,4,5]. Figure 3 shows the concept of virtual chamber neck design. Instead of using chamber neck structures, virtual chamber neck design uses a thermal bubble generated with time lead before main actuation bubble to enhance the actuation force during ejection process. This thermal bubble is also designed to collapse earlier to allow fast liquid refilling and thus achieve higher repetition frequency.

Although virtual chamber neck design concept has been proposed, the bubble dynamics with virtual chamber neck design was not fully tested in previous literatures. In this paper, virtual chamber neck, as well as structural chamber neck, is tested in a micro-nozzle channel. The thermal bubble growth behaviors with structural chamber neck and virtual chamber neck are compared to demonstrate the different effects between bubble dynamics of virtual chamber neck and structural chamber neck design.

2. Design and Fabrication of Microfluidic Chips

To study bubble dynamics with virtual chamber neck, micro-nozzle channels with different chamber neck configurations are designed and fabricated, as shown in Figure 4. There are three types of micro-nozzle channels. Types A, B and C are micro-nozzle channels with no chamber neck, structural chamber neck and virtual chamber neck, respectively. For micro-nozzle channels with virtual chamber neck (Type C) in Figure 4(c), two heaters are integrated within micro-nozzle channels. Heater 1 is heated first to generate bubble which serves as virtual chamber neck for thermal bubble for Heater 2.
Figure 5 illustrates fabrication processes of micro-nozzle channels chip. The width, height and length of microchannel are 60 μm, 50 μm and 960 μm, respectively. The exit of micro nozzle is 30 μm in width. For Type B, micro-nozzle channel with structural chamber neck, a narrow channel region with width of 30 μm is designed and used as chamber neck to prevent bubble growth toward upstream direction.

Figure 6 shows the photo of micro-fabricated micro-nozzle channel with integrated micro heaters.

3. Experimental Setup and Methods

High speed microscope imaging system is set up for this study. Figure 7(a) is the schematic sketch of the experimental setup for micro-nozzle channels with virtual chamber neck. As shown in Figure 7, high speed camera (CASIO EX-F1) is used on a microscope to image thermal bubbles at 1200 frame per second. Since there are two micro heaters micro-nozzle channels with virtual chamber neck. Heater 1 located at upstream is used as virtual chamber neck and Heater 2 at downstream is the main actuation bubble generator. The driving signals for two micro heaters, as well as the LED light source, are controlled with following equipments. First, two identical impulse signals are issues from a function generator. One of impulse signal is used to drive LED light and can be served as time stamp of the image sequence. The second impulse signal is connected to the trigger input of pulse delay generator (Standford, DG535). Pulse delay generator outputs two signals upon trigger. Two signal outputs with a controlled time delay between them are used to drive Heater 1 and Heater 2 after amplification by home-built amplifier circuits. Since there is no built-in power fabricated by sputtering TaAl (Ta : 70%, Al : 30%) thin film alloy with thickness 2 μm on glass substrate. TaAl micro heaters are patterning by using lift-off process of AZ4620 photo-resist. Each heater has length 240 μm and width 30 μm. Finally, PDMS micro nozzle channels are bonded with micro heater glass substrate by using O2 plasma. Seals are watertight under ambient pressure conditions.
supply in home-built power amplifier, power supply (Model: LPS-305) is used as source for each home-built amplifier. For micro-nozzle channels without chamber neck and with structural chamber neck, only one heater is inside the micro-channel. The heater is driven by one impulse signal and this signal is synchronized with LED light driving signal.

The control parameter for each heater input is the total energy input \((E)\). The total energy input \((E)\) to a heater with an impulse signal duration \((t_p)\) can be formulated as

\[
E = t_p \frac{V_{op}^2}{R}
\]  

The time delay \((t_d)\) between Signal A and Signal B is 5 to 10 ms which can be precisely controlled by the delay generator. DI water is working fluid used in the device.

4. Experimental Results and Discussion

The experimental results start with image sequence acquisition by using high speed microscopic imaging system. Figure 9 is image sequence when bubbles generate, grow and interact inside micro-nozzle channel with virtual chamber neck configuration. The driving signal waveform parameters are \(t_p=30\) ms and \(t_d=5\) ms. The total energy input \((E)\) to each heater is \(E=0.03\) J for this case. Figure 9 shows bubble dynamics on Heater 1 (left) and Heater 2 (right). At \(t=3.32\) ms, the bubble on Heater 1 starts to grow. At \(t= t_d=5\) ms, Heater 2 is actuated by input signal B. A small bubble above Heater 2 can be seen at \(t=6.64\) ms. Then two bubbles on Heater 1 and 2 start to interact with each other. The length \((L_b)\) of elongating bubble is used to study the bubble growth rate inside micro-nozzle channels with different chamber neck configurations. The bubble interface locations \((D_i)\) are also investigated to illustrate the bubble dynamic behavior.

To understand bubble dynamics of micro-nozzle channels with different chamber neck configurations, the bubble interface locations \((D_i)\) for Type A: no chamber
neck, Type B, structural chamber neck and Type C: virtual chamber neck are illustrated in Figure 10. The center of heater (Heater 2 for the case of virtual chamber neck) is defined as \( D_c = 0 \) in Figure 10. For each bubble, there are two interfaces. Positive \((D_c > 0)\) interface represents forward bubble interface moving toward nozzle direction, and negative \((D_c < 0)\) interface location if bubble interface moves toward reservoir direction. As shown in Figure 10, positive bubble interface will temp to move faster when virtual chamber neck is applied. Therefore, Type C with virtual chamber neck is proven to be able to enhance the actuation force for liquid ejection from nozzle.

![Figure 10. Bubble interface locations \( (D_c) \) for Type A: no chamber neck, Type B, structural chamber neck and Type C: virtual chamber neck \( (t_p=30\text{ms}, t_d=5\text{ms}, P=1\text{W, } E=0.03\text{J}) \)](image)

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