In Situ Measurement of Instantaneous Jetting Speed Curve

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Abstract

The jetting speed of an inkjet droplet from an inkjet head has been measured, and is widely used in industry to improve jetting performance. The measured jetting speed is used to control the inkjet head by modifying the driving waveform voltage. In jetting speed measurements, the travel distances of an inkjet droplet during two pre-defined timings are used. However, the jetting speed varies significantly during drop formation. If there is a ligament or satellite, the jetting speed is significantly affected. Thus, measured jetting speed using the current methods can differ according to the selection of the two timings. We proposed an instantaneous jetting speed curve to overcome the shortcomings of previous techniques. By determining the instantaneous jetting speed curve, we can understand jetting speed variation during drop formation. Also, the relative jetting speed of satellites with respect to the main droplet during drop formation can be using the proposed approach.

Introduction

Inkjet printing uses ink droplets to form required patterns on a substrate. With inkjet technology, the volume of a droplet from the inkjet printhead can be controlled to an accuracy of picoliters and the droplet can be placed onto the substrate to an accuracy of micrometers. Due to these capabilities, inkjet technology has been used for patterning electronic devices such as large area display applications, radio frequency identification (RFID) devices and printed circuit boards (PCBs) [1,2].

As inkjet applications broaden, various types of jetting materials are required to be precisely dispensed from the inkjet head. Therefore, droplet behavior from the inkjet head must be well controlled and proper measurement of jetting performance is increasingly important. Measured jetting behavior can be used to improve jetting performance by modifying either the functional ink properties or the driving waveform voltage.

To evaluate jetting performance, jetting speed and droplet volume is measured from droplet images. In this study, by using light emitting diode (LED) lights synchronized to the firing signal, droplet images appear to be frozen in the acquired CCD camera image. Then, image processing techniques were used to measure ink droplet locations at two different timings for jetting speed measurement [3, 4]. Droplet volume can be calculated using the droplet diameter, which can be obtained from a droplet image assuming that the droplet shape is spherical [3]. However, as jetting speed increases, the inkjet droplet does not remain spherical since the droplet is likely to have ligaments and satellites.

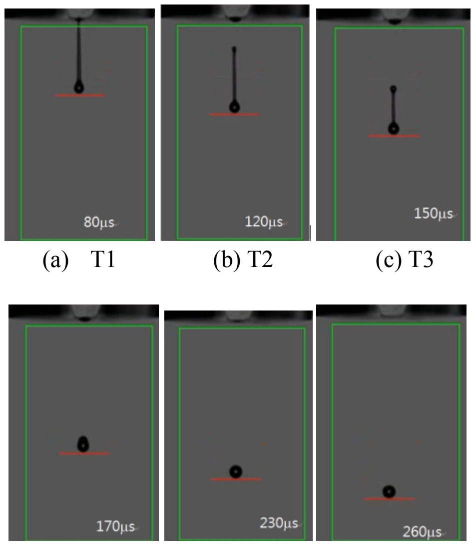
The measured droplet volume may have errors because the measured results differ according to the threshold value needed for binary image conversion, the LED light intensity and lens focusing [3]. In practice, the measured jetting speed is considered to be more reliable, and jetting speed has been widely used for the following purposes:

1) Normalizing jetting performance among many ejectors in a multi-nozzle head [1]
2) Evaluation of jetting performance [5]. If the jetting speed is low, then the jetting accuracy is likely to be poor and the jetting performance could easily be affected by many factors.
3) Waveform design (by seeking the dwell time and jetting speed relationship) [5]

However, inkjet droplet jetting speed can vary significantly during the drop formation. Thus, there are two major drawbacks in the conventional speed measurement method: 1) It cannot measure the jetting speed variation during drop formation. As a result, the measured jetting speed can differ according to the selection of two timings for images. 2) It is difficult to understand the relative jetting speed of the main droplet with respect to satellites during drop formation. It is important to understand the relative jetting speed of the main droplet with respect to satellites since this can help determine whether or not the satellite will merge with the main droplet. Satellites that do not merge with main droplet can result in placement errors during printing.

Dong *et al.* used the so-called drop-on-demand (DOD) drop formation curve to understand satellite and ligament behavior [6]. However, efforts were needed to obtain the DOD drop formation curve since the droplet locations are determined by postprocessing of many sequential images. Thus, *in situ* automatic measurement methods are required for practicality. Also, the jetting speed variation has not been considered in detail in previous works. For these reasons, *in situ* measurement techniques are presented in this study such that the DOD drop formation curve and instantaneous jetting speed can be measured during jetting. By measuring the instantaneous jetting speed curve, we can understand the relative jetting speed of the satellite with respect to the main droplet during the entire drop formation. Also, the jetting speed curve during drop formation can be easily obtained without the need to postprocess numerous sequential images.

Conventional Jetting speed measurement



(a) T1 (b) T2 (c) T3

(d) T4 (e) T5 (f) T6

Fig.1. Jetting images at different times.

A mixture of ethylene glycol (EG) and isopropyl alcohol (IPA) was used as the jetting material. A Microfab head (MJ-AT-50) was used for the printhead. Figure 1 shows jetting images acquired at different timings. Conventional jetting speed measurement uses droplet center locations at two timings [3]. Note that the droplet might not be spherical. In such cases, the droplet location at the lowest point in the jetting direction can be used for the measurement. Table 1 shows calculated jetting speeds from the images in Fig.1.

Table. 1 Jetting speeds using conventional methods

Time 1(μs)	Time 2(μs)	Jetting speed (m/s)
(a) 80	(b) 120	2.2
(b) 120	(c) 150	1.7
(c) 150	(d) 170	1.5
(e) 230	(f) 260	1.9

As seen in Table 1, the jetting speed can vary significantly according to the selection of timings (time 1 and time 2). Therefore, it may be difficult to determine the "true" jetting speed that represents the jetting performance. In addition, if there are satellites, the jetting speed behavior will be even more difficult to measure using the conventional approach. Therefore, in this study, the use of instantaneous jetting speed is proposed such that the jetting behavior can be fully understood during drop formation.

Instantaneous Jetting Speed Measurement

We developed a software algorithm for *in situ* measurement of the DOD drop formation curve and instantaneous jetting speed curve. The proposed algorithm was implemented in a laboratory-developed drop watcher system [5]. In most printing systems for printed electronics applications, there is a drop watcher module to measure jetting speed and droplet volume [1], and the proposed algorithm can be implemented in any drop watcher system. Thus, the proposed method does not require additional hardware.

To understand jetting speed variation during jetting, sequential images must be obtained. Each sequential image is then processed to extract inkjet drop information before the next image is acquired. A method of obtaining sequential images using a CCD camera was discussed in detail in the author's previous work [5].

The acquired images from the CCD camera have eight bit image pixels that can appear as grey with values ranging from 0 to 255 according to the brightness of the image as shown in Fig. 2(a). The grey image can be converted into a binary image in which the pixels have values of 0 or 1. Using the converted binary image, the ink droplet information can be extracted since the ink droplet's pixels have a value of zero (or one) and the background can be one (or zero).

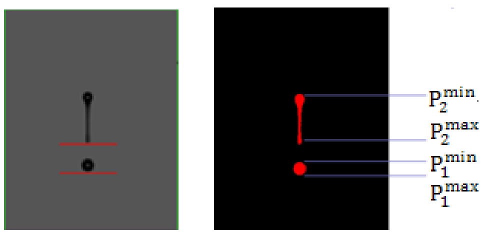
The number of droplets including the main droplet and satellites can be obtained from an analysis of binary images. In addition, the maximum and minimum locations of the k_{th} droplet in the y direction, denoted as $P_k^{max}(t_d)$ and $P_k^{min}(t_d)$, can be obtained as shown in Fig. 2(b). The superscripts "max" and "min" denote maximum and minimum locations, respectively. The DOD drop formation curve was updated by adding the calculated the maximum and minimum locations of each droplet $P_k^{max}(t_d)$ and $P_k^{min}(t_d)$, respectively, in the graph before acquiring the next sequential image.

The instantaneous jetting speeds of each droplet, $V_k^{max}(t_d)$ and $V_k^{min}(t_d)$ of k_{th} droplet can be obtained as

$$V_k^{max}(t_d) = \frac{\Delta(P_k^{max}(t_d))}{\Delta(t_d)} \text{ and}$$

$$V_k^{min}(t_d) = \frac{\Delta(P_k^{min}(t_d))}{\Delta(t_d)} \quad k=1,2,\ldots n$$

where $\Delta(t_d)$ is the incremental time of trigger delay between the two consecutive images and $\Delta(P_k^{max}(t_d))$ and $\Delta\left(P_k^{min}(t_d)\right)$ are the travel distance of the maximum and minimum locations of the k_{th} droplet, respectively, during the time duration of $\Delta(t_d)$. In most printing applications, the maximum location of a droplet $P_k^{max}(t_d)$ is important in a printing application since it is placed on the substrate first. Therefore, the behavior of the jetting speed at the maximum location $V_k^{max}(t_d)$ rather than $V_k^{min}(t_d)$ is discussed for an explanation of drop formation. However, the actual droplet jetting speed is difficult to define because the speed of the maximum locations in a droplet can differ significantly from the speed of the minimum location if the droplet has a long ligament.



(a) Grey image (b) Binary image

Fig. 2 Image processing of droplet image

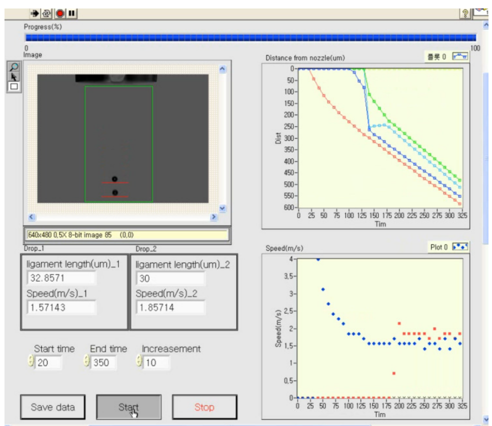
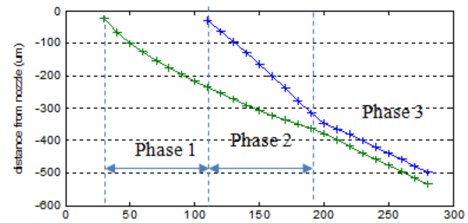


Fig. 3 Developed software menu [7]

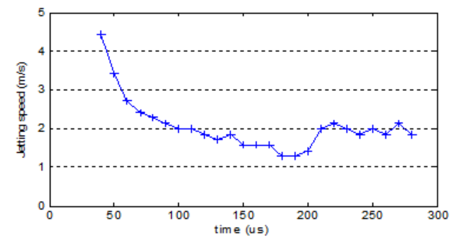
Figure 3 shows the menu of the developed software during measurement of the jetting behavior of mixture of EG and IPA. Using the software, the DOD drop formation curve and the instantaneous jetting speed can be obtained during jetting without requiring postprocessing of a large number of sequential images. For more information, a video clip is available in [7]. Three different cases will be discussed to demonstrate the effectiveness of the proposed method: a single droplet with a long ligament, a faster satellite and a slower satellite.

Case Study: Long Ligament

Drop formation behaviour can differ significantly according to jetting fluid and the driving waveform voltage. In the case of using EG (volume fraction of 0.75) and IPA (volume fraction of 0.25), we obtained a single droplet with a long ligament using a waveform with a dwell time of 23µs. Figure 4 shows a measured DOD drop formation curve and an instantaneous jetting speed curve.



(a) DOD drop formation curve



(b) Instantaneous jetting speed

Fig. 4. Jetting behaviour with no satellites (dwell time: 23µs, voltage magnitude: 32V)

From the measured jetting behavior shown in Fig.4, the drop formation can be analyzed using three different phases:

1) Phase 1 (from 30 µs to 120 µs): A partial of droplet is extruded from the nozzle. During the jetting process of phase 1, the instantaneous speed of the extruded part, $V_1^{max}(t_d)$, is significantly reduced from 4.5m/s to 2m/s. This effect may be due to the viscoelasticity of the fluids: the still-attached fluid at the nozzle may pull back the extruded fluid from the nozzle before the fluid is pinched off.

2) Phase 2 (from 120 µs to 190 µs): In phase 2, after pinch-off, the ink droplet drops in a condition of free-flying jetting, but still has a ligament. During phase 2, the instantaneous jetting speed of the leading end, $V_1^{max}(t_d)$, was about 1.5-2m/s as seen in Fig. 4 (b). The jetting speed variation at the free-flying condition was small compared to the jetting speed variation in phase 1. Note that the ligament length was reduced because the speed of the tail end, $V_1^{min}(t_d)$, was faster than $V_1^{max}(t_d)$.

3) Phase 3 (from 190 µs): Finally, the lengthy ligament reconciles with the leading end of the droplet, resulting in a spherical droplet. During the reconciliation, the faster tail end (or minimum location) will increase the final jetting speed of the droplet from 1.5m/s to 2m/s as shown in Fig.4. We note that the final jetting speed became almost constant (about 2 m/s) only after the shape of the droplet became spherical. Thus, when measuring the jetting speed by the conventional method using two different timings, it was required to measure the speed when the droplet became spherical. Otherwise, the measured speed may not represent the jetting performance since the measured jetting speed can be different according to the selection of the two timings.

Case Study: Faster Satellite

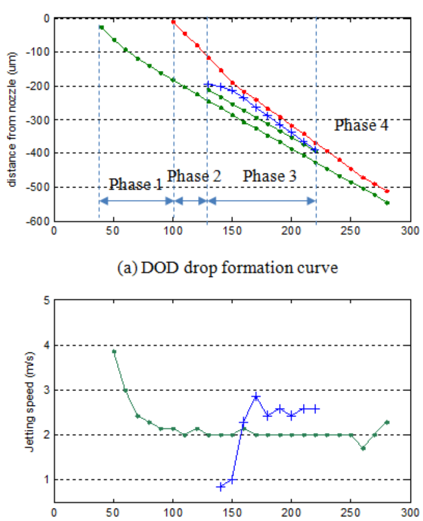
In many cases of ink jetting, satellites are unavoidable. Then, the relative jetting speed of satellites with respect to the main drop becomes important. The faster jetting speed of the satellite with respect to the main droplet is desirable because the satellite can eventually merge with main droplet. A simple trapezoidal waveform was used [5]. Here, only dwell time and the magnitude of the voltage were modified to control jetting performance whereas the rising and falling time of the waveform were fixed at 6 μs. For jetting material, a fluid mixture of EG (0.25) and IPA (0.75) was used. For a faster satellite condition, a waveform with a dwell time of 30μs and a magnitude of 25V was used.

Figure 5 shows the typical jetting behavior of faster satellites. As seen in the figure, a satellite takes form by separating from the main droplet at 125 μs. Note that the initial speed of the satellite is very slow. Then, its speed became even faster than that of the main droplet when it became spherical in shape at 160 μs. This phenomenon is the opposite of the main droplet's speed, which is very fast at the beginning and then slows as it become spherical in shape. The jetting speed variation of both the main droplet and satellite during drop formation can be understood using Fig. 5. As seen in the phase 3 data shown in Fig. 5, the jetting speed of the satellite droplet was measured to be 2.5m/s, and the jetting speed of the main droplet was 2m/s. Due to the higher jetting speed of the satellite, the satellite eventually merged with the main droplet as shown in Fig. 5 (phase 4)

Case Study: Slower Satellite

Figure 6 shows the typical jetting behavior when the jetting speed of the satellite is slower than the main droplet. To make a slower satellite jetting speed, only the dwell time of the waveform was modified (17 μs), keeping other conditions the same as described in the previous section.

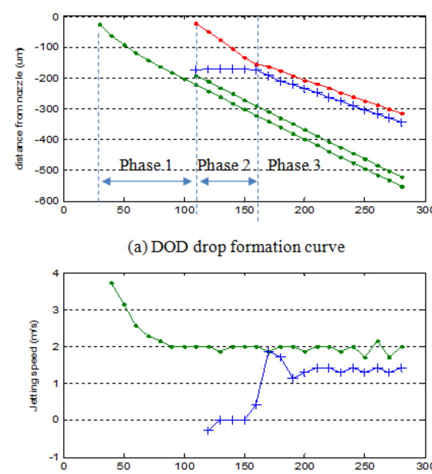
Similar to the faster satellite, the jetting speed of the satellite was very slow (even negative) when a single droplet broke into a main droplet and a satellite at 110 μs. The satellite continued at low speed until it became spherical. After being spherical in shape, the jetting speed became almost constant (phase 3 in Fig. 6). As seen in phase 3 of the figure, the final jetting speed of the main droplet was 2m/s whereas the satellite jetting speed was about 1.2m/s. If the jetting speed of a satellite is slower than the main droplet, the satellite droplet can produce serious placement errors during printing. Therefore, the jetting speed of the satellite should be measured and evaluated in relation to the jetting speed of the main droplet as seen in Fig.6(b).



(a) DOD drop formation curve

(b) Instantaneous jetting speed

Fig.5 Jetting behavior of faster satellite(dwell time: 30 μs, voltage magnitude: 25V)



(a) DOD drop formation curve

(b) Instantaneous jetting speed

Fig.6 Jetting behavior of slower satellite (dwell time 17 μs, voltage: 25V)

Conclusions

In situ techniques to measure jetting behavior were developed such that DOD drop formation and the instantaneous jetting speed curve can be obtained during jetting. Unlike previous inkjet speed measurements, the proposed instantaneous jetting speed curve has advantages because the speed variation during drop formation can be fully understood. From the measured instantaneous jetting speed, we were able to investigate the relative jetting speed of the satellite relative to the main drop.

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Author's Biography

Kye-Si Kwon has been an assistant professor at Soonchunhyang University in Korea in the department of mechanical engineering since 2006. He received his BS degree in mechanical engineering from Yonsei University, Seoul, Korea in 1992. He holds a master's degree (1994) and a PhD (1999), both in mechanical engineering from Korea Advanced Institute of Technology (KAIST), Korea. Before joining Soonchunyang University, he was a member of the research staff at the Samsung Advanced Institute of Technology. His current work is focused on the development of measurement methods for controlling inkjet head.