Optimization of Inkjet Jetting for Ultra-Fine Droplets

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Abstract

Inkjet printing technology is used in many fields including display industry, due to its advantages such as high productivity, high quality, flexibility in patterning and scalability from a small to a large substrate. In particular, the conventional evaporation method for producing pixel displays has been becoming replaced by inkjet printing due to its less consumption of expensive materials and inclusion of particles for better efficiency and quality of display. As display resolution increases, it is essential to have a printhead with ultra-fine droplets, and to operate it in highly reproducible and stable conditions with optimal jetting quality plays a critical role in succeeding mass production. In this study, we investigated the jetting conditions such as jetting viscosity, circulation rate, meniscus pressure, printing speed, and incoming ink temperature, and their effects on jetting quality as well as facility for maintaining the printhead. We expect that such an optimizing process for jetting ultra-fine drops will contribute to the reliable printing process for high resolution displays.

Author Keywords

Inkjet printing; ultra-fine drop; drop position accuracy; drop volume uniformity; maintenance

1. Objective and Background

Inkjet printing technology is widely used in various fields such as graphic arts, textile, and the electronics industries as it can print on a variety of materials and produce high-quality prints with sophisticated patterns. In display industry, technology development has been in progress for a long time due to its high efficiency of material utilization, high resolution, and advantages of scalability and flexibility of substrates.[1] Inkjet printing is a non-contact process that uses a printhead to jet tiny ink droplets onto a substrate. Placing several millions of drops in designated pixels is a key technology for inkjet printing process, and an extremely precise control of jetting becomes more and more important especially with ultra-high resolution displays.

For the precise jetting control in high resolution displays, it is essential to first have a printhead with ultra-fine droplets, and to operate it in highly reproducible and stable conditions with optimal jetting quality is critical in succeeding mass production of high resolution pixel printing. Several factors such as drop position accuracy,[3] volume uniformity,[4] and a facilitized printhead maintenance play major roles in optimizing the jetting quality. In this study, we investigated the factors such as viscosity, circulation rate and temperature, meniscus pressure and printing speed, and their effects on jetting quality and maintenance.

2. Experimental

The printhead with nozzle level circulation was used in this study. A particle contained UV curable ink with a viscosity above 20 cP at room temperature was used, and heated down to the allowed jetting viscosity of 10~12 cP of the printhead by the internal heater of the printhead as well as the in-line heaters in the circulation system. The printhead was connected to the ink circulation system which is consisted of a reservoir containing ink, a pump which makes the circulating flow through the system, a meniscus pressure controller (MPC) which controls the pressure at nozzles, in-line heater for heating up the circulating ink, and a flow sensor to set the desired flow rate.

A drop watching system (ImageXpert) was used to measure the velocity of a droplet and to inspect the jetting quality such as a presence of mist and satellites, and the length of ligament for waveform optimization.[5] Drops were inspected at a distance of 400~800 ㎛ from the nozzle for the consistency with the printing gap. A 3D optical profiler and a line scan camera were used for analysis of volume and position accuracy, respectively, of the individual drops on a hydrophobic film. The position accuracy was quantified by calculating the error amount of each drop position from the average position of overall drops. A printing was carried out by positioning the printhead above the stage moving perpendicular to the nozzle direction of the printhead at a designated gap.

3. Results

Position accuracy optimization: A drop position accuracy is important in determining print quality and reliability, especially for the production of displays with ultra-high resolution.[2] The several parameters such as a drop volume and ejection speed, printing speed, and meniscus pressure affect the drop placement accuracy. A drop velocity is related with the energy of drop, and therefore, the straightness of drop trajectory. The higher the velocity, the higher the resistance to aerodynamic effect, thus it renders higher accuracy in drop placement. Therefore, it is important to first define the jetting condition for higher velocity. It was carried out by selecting three different viscosities, low A, medium B and high C, within the allowed range of the printhead by adjusting the temperature to relatively high, medium and low, respectively. At each viscosity, the velocities at different drop volumes were measured by adjusting the voltage. As shown in Figure 1, as the drop volume increases above i, satellites were generated in all viscosities, indicating the limitation in an adoptable drop volume with the given waveform. The relatively lower viscosities A and B result in similar velocity characteristics as well as higher velocities than viscosity C at the same drop volume. It is because the break-off of the ligament occurs far from the nozzle exit at higher viscosity, resulting in slower velocity. Based on the velocity and volume characteristics, viscosity B with medium heat-up temperature is better to choose over viscosity A, considering a relatively lower requirement of heating capacity, which can affect the stability and maintenance of printing system in overall. Figure 2 shows how the drop volume and velocity, printing gap, meniscus pressure and printing speed influence the drop position accuracy at viscosity B. The higher drop speed, and lower printing gap and speed have major effect on improvement of positon error. The meniscus pressure seems to have a minor impact on position error. However, for a long-term operation of the printhead, it may affect the drop position, especially with the ink with particles, due to the dryness of nozzles upon the level of meniscus pressure. It is important to keep the meniscus pressure not to overflow and to an extremely negative level.

Volume uniformity optimization: A high uniformity of drop volume between nozzles is important for high quality printing especially over a large-area panel which is usually processed by single or minimal number of scans. If the uniformity of drop

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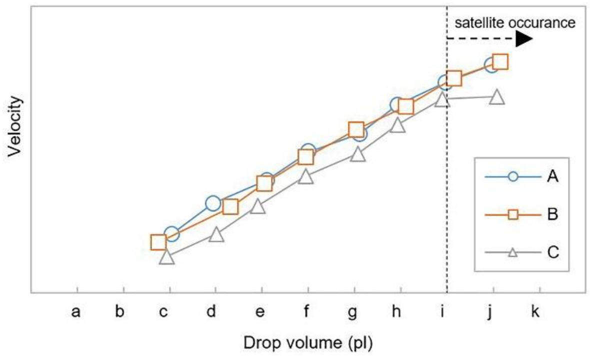

Figure 1. Measured velocities versus different volumes at 3 viscosities.

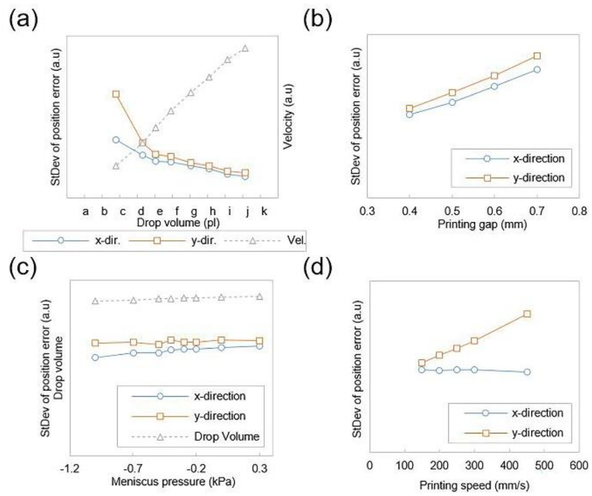

Figure 2. Analysis of influential factors for drop position accuracy (a) drop volume and velocity, (b) printing gap, (c) meniscus pressure, and (d) printing speed.

volume is low, it can cause stains on the panels due to low uniformity of thickness between ink-filled pixels. This becomes more critical especially with a high resolution display, of which pixel size is so small that it is filled with only a few ultra-fine drops. Ideally, using printheads with the function of drive-per-nozzle is beneficial in terms of forming a uniform drop volume across the nozzles, however, such printheads are not easily available and usually low in nozzle density and, thus, it requires an integration of an extremely large quantity of printheads to cover the panel. Therefore, for conventional printheads, it is important to understand the operating conditions to optimize the volume uniformity. Here, the effect of heating the incoming ink was investigated. In addition to heating up ink by the internal heater of the printhead, the ink can be also pre-heated by the in-line heaters in circulating system. Figure 3 shows the volume uniformities across nozzles with and without preheat at a recommended flow rate. The volume deviation decreases by ±5% with preheat due to the improvement in volume deviation at the inlet and outlet sides where the heat sink occurs the most in the

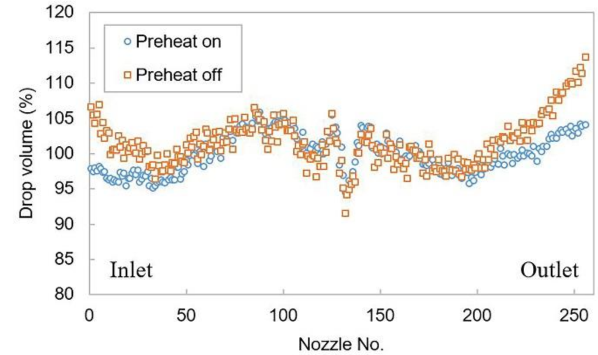

Figure 3. Volume uniformities across nozzles with and without preheat.

printhead. With preheat, it forms a similar temperature, thus the similar viscosity, of the incoming ink with the ink in printhead, and as it circulates through the heated printhead, the temperature becomes maintained throughout it. Therefore, preheating the ink before the printhead is beneficial to improve the volume uniformity.

Head maintenance: In display industry, several tens to a few hundreds of printheads are integrated into a printer depending on the size of panel and printing mechanism. Maintaining the jetting quality and characteristics throughout the usage and maximizing the lifetime of printheads are important in terms of cost and production. Inkjet process is considered to be cost effective due to a less consumption of material compared to the conventional photolithography or evaporation deposition. However, occasionally it consumes a considerable amount of material, as much as 100 ~ 1000 $\mu\ell$, by pushing out the ink through nozzles at high pressure (i.e. purge) to recover the jetting quality after a length of idle time due to the dryness at nozzles, which sometimes leads nozzle clogging with particle containing ink. Here we investigated the benefits of nozzle level circulating printhead in terms of material usage at different viscosities after an idle time, and the long-term maintenance of jetting quality.

Table 1 shows the ink consumption by dummy jet required to recover the drop position accuracy to the level before idle time at viscosities A (low), B (medium) and C (higher) from the previous section. In all cases, no purge was required but only dummy jet of drops was carried out, unlike the non-circulating printhead which generally requires a purge after a few hours of idle time for recovery.

Table 1. Ink consumption required to recover the drop position accuracy.

Viscosity	Consumed ink at idle time ($\mu\ell$)				
	2.5 min	5 min	10 min	30 min	≥ 15 hrs
A	0	0	< 0.01	< 0.02	N/A
B	0	0	0	< 0.01	< 0.2
C	0	0	0	< 0.01	< 0.07

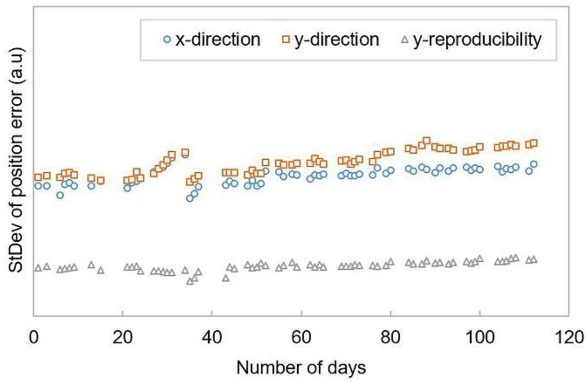

Figure 4. A long-term measurement of drop position error.

Even after more than 15 hours of idle time, it only required less than 0.2 $\mu\ell$, about 500~5000 times less than the non-circulation printheads. It is also indicated that the higher viscosity consumes less amount of ink for recovery. It may be due to the faster speed of sedimentation of particles and dryness at nozzles at lower viscosity (i.e. higher temperature). The optimal ink viscosity can be determined in perspectives of both drop placement accuracy (i.e. drop velocity) and head maintenance.

Figure 4 shows a long-term measurement of drop position error with approximately 20~30 $\mu\ell$ of discharging dummy drops regularly to mimic it close to the printing process. The position error was maintained below acceptable range throughout the measurement. Without an additional ink consumption for printhead maintenance, if the idle time is shorter than 30 minutes and it jets regularly, such printhead can sustain the jetting quality for an extended length of time.

4. Impact

In this study, we investigated several factors influencing the jetting quality and maintenance. For drop placement accuracy, a higher ejection velocity is important for a better jetting straightness and it can be achieved by adjusting the viscosity of ink first and then by tuning the drop volume to a stable ejection without satellites and minimal mists. A lower printing gap and speed have major effect on improvement of positon error, and a meniscus pressure is foreseen to play an important role in maintaining jetting quality in a long-term operation. For an optimization of uniform volume, it was evidenced that heating the circulating ink to the similar level with the temperature of ink in printhead reduces the volume deviations at inlet and outlet sides of the printhead by minimizing the deviation of temperature from heat loss. For a facilitized maintenance of printhead, it is beneficial to use a printhead with nozzle level circulation since they can be operated with a long-term sustained jetting quality with minimal ink consumption. This benefit is magnified when integrating a massive number of printheads especially for a large area printing. The control of precise jetting of ultra-fine drops with the optimized parameters is expected to contribute to the printing process for high resolution displays.

5. References

1. Kwon, B. H., & Joo, C. W. (2023). "Trends in Display Technology Development Applying Inkjet Printing Principles." *Electronics and Telecommunications Trends*, **38** (1), 26-35.

2. Liu, Y., & Derby, B. (2019). "Experimental study of the parameters for stable drop-on-demand inkjet performance." *Physics of Fluids*, **31** (3): 032004.

3. Park, J. A. et al. (2017). "Freeform micropatterning of living cells into cell culture medium using direct inkjet printing." *Scientific reports*, **7** (1), 14610.

4. Heilmann, J., & Lindqvist, U. (2000). "Effect of drop size on the print quality in continuous ink jet printing." *Journal of Imaging Science and Technology*, **44** (6), 491-494.

5. Ogunsanya, M., Isichei, J., Parupelli, S. K., Desai, S., & Cai, Y. (2021). "In-situ droplet monitoring of inkjet 3D printing process using image analysis and machine learning models." *Procedia Manufacturing*, **53**, 427-434.