A Hybrid Inkjet Printer Utilizing Electrohydrodynamic Jetting and Piezoelectric Actuation

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Received March 19, 2010; accepted April 11, 2010; published online June 7, 2010

This paper reports a hybrid electrohydrodynamic (EHD) inkjet printing technique that offers better uniformity and stable operation in drop-on-demand (DOD) patterns compared to the conventional methods. This hybrid technique takes advantage of both electrohydrodynamic and piezoelectric methods where a piezoelectric actuator is used to supply a fixed volume of ink to the nozzle's exit for every jetting period, and the electrohydrodynamic technique is used to form ink droplets. Experimental results show that the print quality improves significantly when ink was supplied to the nozzle exit at a controlled rate using piezoelectric actuation.

DOI: 10.1143/JJAP.49.060216

Inkjet printing technology has received great attention to create microscale features due to the maskless printing, fewer environmental problems, lower fabrication cost, and good layer-to-layer registration for electronic and bio devices.[1–5] Performance factors such as high frequency jetting, high density of nozzle arrays, small droplet/pattern size, and uniformity of droplet size are needed to fulfill the requirements of various applications. An inkjet device based on thermal bubble or piezoelectric pumping, which has revolutionized the digital printing, has a number of limitations such as the size and density of the nozzle array as well as the ejection frequency due to thermal problem or lack of pumping energy.[6] In recent years, an electrohydrodynamic (EHD) jetting device has been suggested and developed as an alternative.[6–10] The EHD jetting is primarily based on instability of charged droplets in an electric field.[11]

In EHD printing, the electrical force acts directly on the meniscus to elongate it to an unstable shape, and finally breaks the meniscus into small droplets. Hence, the EHD printing can work with very small size nozzles to print high resolution patterns. Moreover, this technique can be used to print patterns from highly viscous ink. Recently, we reported some of the drawbacks of EHD printing technology, primarily focusing on the droplet flight behavior between the nozzle and target substrate. Depending on the droplet charge and applied electric field, droplets may deflect, reflect, or retreat to the meniscus.[12] And we demonstrated stable jetting by using the extractor electrode alone for an AC potential without aforementioned drawbacks.[13] Also this single potential technique allows ink droplets to be transferred to the substrate at a very small distance away from the nozzle to improve the precision of deposited patterns. Moreover, this technique simplifies the nozzle fabrication technique which is a delicate issue for inkjet printhead. The single potential technique can also be applied to form patterns on non-conductive substrates.

An EHD inkjet head can produce droplets smaller than the size of the nozzles used by micro dripping mode or short pulsation mode.[14] However, to obtain uniform size droplets, the same volume of liquid must be available at the nozzle tip for every period of jetting. In other words, for each jetting cycle the pulsating meniscus must move in the same manner (mainly same magnitude). To achieve this condition, vibration on meniscus must be damped out after a successful ejection or controlled during the jetting period with precise pumping of ink. Elimination of vibrations remains a major challenge in EHD printing. Therefore, the objective of this work is to control the meniscus and print uniform patterns by supplying fixed volume of ink using piezoelectric actuation, but forming ink droplets using EHD jetting mechanism. In the rest of the letter, we will use the term "hybrid inkjet printing" (HIP) to refer our proposed printing method.

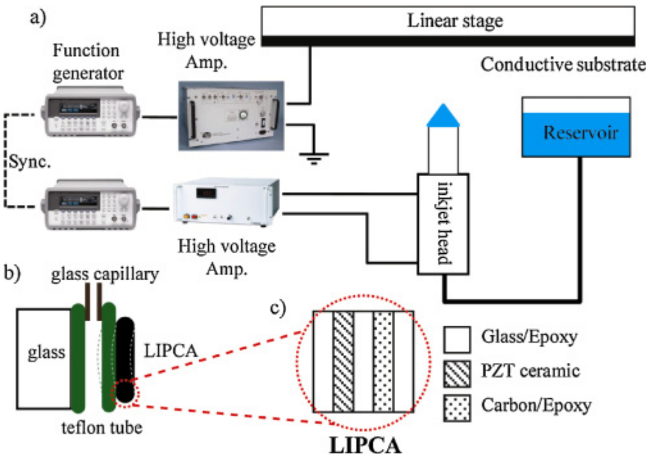

Fig. 1. (Color online) (a) Experimental setup for hybrid printing that employs two function generators, two high voltage power supplies, and a synchronizer. (b) The detail view of the hybrid inkjet head where a unimorph piezoelectric actuator (LIPCA type) pressing the Teflon tube to regulate the flow inside the tube. (c) The composition of the LIPCA.

Figure 1(a) shows the schematic of the experimental arrangement for hybrid printing. A conductive substrate is formed by coating indium tin oxide (ITO) on a plastic film, and the substrate is held on top of the nozzle or hybrid inkjet head. The hybrid inkjet head composes of a glass capillary with inner and outer diameters of 100 and 170 μm, respectively, which is connected to a soft Teflon tube for feeding ink to the glass capillary, as shown in Fig. 1(b). A LIPCA[15] (lightweight piezo-composite curved actuator) is placed on top of the Teflon tube to push the tube against a glass plate during its actuation [Fig. 1(b)]. The LIPCA provides high displacement and linear actuation which is suitable for squeezing the Teflon tube to control the amount of ink delivered to the nozzle. The composition of LIPCA is shown in Fig. 1(c), where the lead zirconate titanate (PZT) layer is placed off-axis to maximize the uni-morph displacement.

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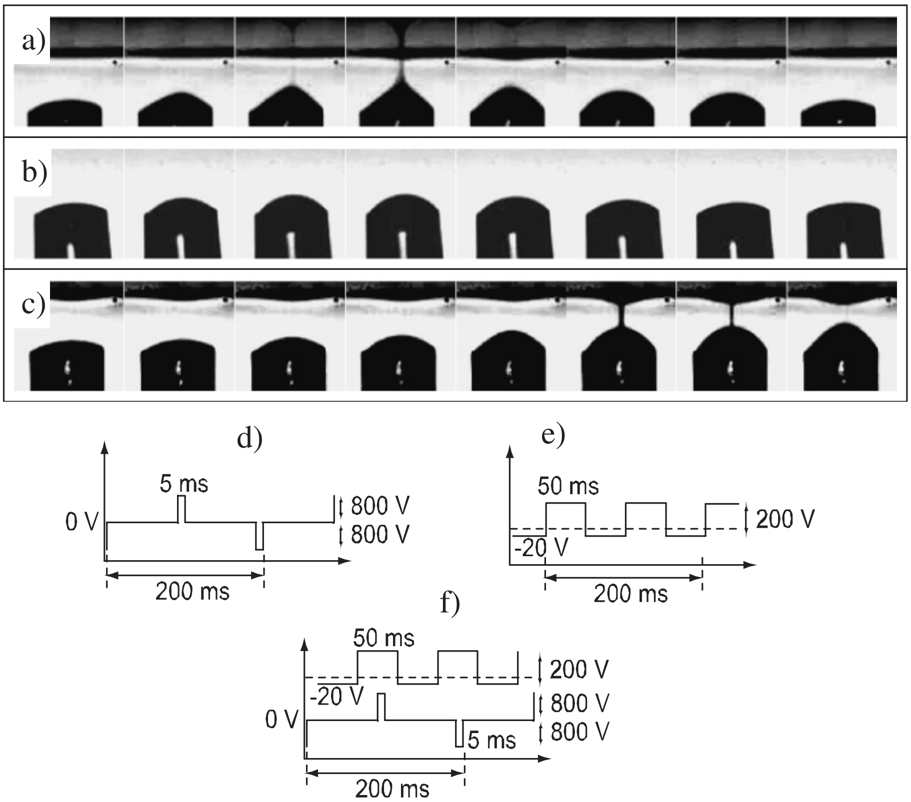

Fig. 2. Sequence of pictures: (a) EHD jetting caused by an AC electric potential; (b) expansion of meniscus due to piezoelectric actuation; (c) formation of droplets using hybrid jetting technique. The interval between frames is 1 millisecond. Applied electric potential for: (d) EHD printing; (e) piezoelectric actuation; and (f) combination of case (d) and (e) for hybrid technique.

To print droplets, a high voltage AC signal was applied to the conductive substrate using a function generator (Agilent 33250A) and a high-voltage amplifier (Trek 10/40A). The ink was supplied to the nozzle exit by the piezoelectric actuator which was controlled by another function generator (Agilent 33250A) and another high-voltage amplifier (Matsasuda AMT-1.5B40). Once the piezoelectric actuator receives an electric signal, it squeezes the Teflon tube and delivers a pressure wave to expand the meniscus. Depending on the fluid characteristic and channel structure, there was a time gap from the moment the actuator receives signal until the meniscus move. Therefore, the delay between two function generators was synchronized in such a way that the high electric field is applied for the EHD jetting when the meniscus reaches its maximum height.

A linear motor was used to move poly(ethylene terephthalate) (PET) substrates where patterns needed to be formed. A commercial silver ink (Inktec TEC-IJ-020), which uses methanol as solvent and composes of 20% of silver by weight, was used for this study. The viscosity, the surface tension coefficient and the density of the silver ink are 9–15 cP, 30–32 dyn/cm and 1.07 g/cm^3 at 25 °C. An LED lamp was used to illuminate droplets formed from jetting, and a high speed camera (Photron Fastcam Ultima APX) with a micro-zoom lens was used to visualize droplet ejection.

The movements of liquid meniscus were recorded by the high speed camera with the exposure time of 100 μs. Figure 2 shows eight continuous frames for each case of EHD ejection, meniscus movement due to the piezoelectric actuator, and hybrid ejection. The patterns were made with the above-mentioned nozzle positioning at 200 μm from the substrate.

Figure 2(a) shows the sequence of ejection by an EHD inkjet device when a single AC potential was applied, as shown in Fig. 2(d). Under electric field by 5 ms pulse width, the meniscus was initially deformed into a cone [from second to sixth frames in Fig. 2(a)], and then the ink was deposited on the substrate as a jet [third and fourth frames in Fig. 2(a)]. After the first ejection, the meniscus was collapsed, and the ink either went back to nozzle or spread on the outer surface of the nozzle because of the lack electrostatic force. A good hydrophobic coating on the nozzle is required to prevent ink spreading at the outer surface of the nozzle and guide the remaining ink to retreat to the nozzle. Figure 2(b) shows eight frames with interval of 2 ms to demonstrate a controlled meniscus movement by piezoelectric actuation with AC potential [Fig. 2(e)]. Depending on the movement of piezoelectric actuator, the meniscus expands and retreats periodically. Meniscus expansion takes place when the piezoelectric membrane (LIPCA) flexes out, and this expansion is very stable even the nozzle is completely wet. During 50 ms of the applied positive pulse [Fig. 2(e)], the meniscus expands and maintains its highest position during 5 to 6 ms [from third to fifth frames in Fig. 2(b)]. Then, the meniscus retreats even the piezoelectric actuator is still pressing, because there is no valve or restrictor to prevent the fluid from flowing back after the stroke. Finally, the meniscus completely retreats to the glass capillary when the piezoelectric membrane becomes flat.

An ejection by the hybrid printing technique is shown in eight frames with interval of 1 ms [Fig. 2(c)], where the meniscus is first stretched out by the flexing of piezoelectric actuator. Next EHD electric field is activated [Fig. 2(f)] to rip out a jet of ink from the full developed meniscus. Here the role of electrostatic force is primarily to extract droplets as the meniscus is developed solely by the piezoelectric actuator. The piezoelectric actuator first sent the liquid ink to form a fully developed meniscus; it then maintained the stable meniscus until a jetting occurs; and, finally it guided the rest of the ink to go back to the nozzle after the jetting. On the other hand, in traditional EHD, when the electric force is off, the fully-developed meniscus collapses and gets back inside the nozzle. If the nozzle cannot accommodate that amount of liquid, ink overflow happens. Most of the time, an overflow of liquid prevents further ejection, and spoils the printing process. A number of such occurrences have been observed when the traditional EHD jetting was used for printing. This visible difference in dynamic ejection pattern leads to a clear distinction in jetting performance, which is shown in Fig. 3.

Figure 3(a) shows real images of patterns made by the HIP and EHD printing techniques. The dot patterns are much smaller than nozzle size used for this study. The printing was carried out in 10 Hz. The drops made by HIP are deposited in great uniformity. To analyse the printing quality, pictures of printed patterns were taken with a microscope and a digital camera. Then, the area of droplet was measured by contrast detection, and the diameter of the droplets was measured from a circular shape that has the same area as the patterned droplet. Droplet sizes printed by hybrid printing technique falls in the range of 39.8 to 75.9 μm, while the range for EHD printing is between 16.6 and 70.3 μm. Average values of droplet diameter are 54.17 and 48.95 μm for hybrid and EHD printing technique, respectively, and the average of the absolute deviations of droplet diameter are 5.47 and 7.84 μm for HIP and EHD, respectively. This demonstrates that the use of piezoelectric actuator improves the stability of ejection and makes uniform patterns.

The conventional inkjet systems generate circular droplets that can be captured visually to give information of droplet's size and volume. In 2009, Gan *et al.*[17] employed a piezoelectric inkjet system with a fine orifice of 50 μm inner diameter to generate droplets of PEDOT (has similar surface tension with the ink used in this article). For various applied control signal, the system could vary the volume of droplet ranging from 92.3 to 14 pl. Those PEDOT droplets were deposited on a silicon substrate with drop diameter ranging from 150.6 to 60.2 μm. In the EHD and hybrid printing systems, the liquid is pulled to the substrate at high speed resulting a blur thin jet that is difficult to measure liquid volume by visual method. Considering the size of patterns, the amount of liquid deposited can be estimated. In our experience, that droplets generated are much smaller than the outer nozzle diameter (around 1/5), while the conventional inkjet system gives bigger patterns compared to inner nozzle dimeter.[16,17]

EHD printing technique may improve pattern uniformity by using precise control of ink supplying system, which becomes the other challenge. Therefore, with the inclusion of piezoelectric actuator, the output from the hybrid printing improves significantly. This hybrid technique can be applied to small scale nozzle to obtain high resolution printing.

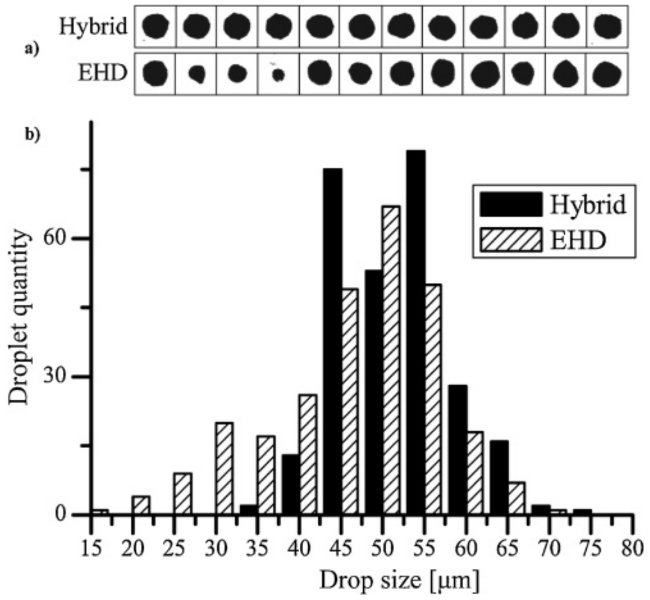

Fig. 3. (a) Pattern of dots printed by the hybrid system and EHD inkjet system (without the use of LIPCA). The distance from nozzle to substrate is 200 μm. Electrical potential applied at the substrate is AC pulse, 10 Hz, 800 V peak-to-peak. (b) Drop size distribution for EHD and Hybrid system. Number of drops measured is 269×2.

Acknowledgments This work was funded by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2009-0074875 and 2010-0015174). VDN acknowledges partial support from the Korea Research Foundation (KRF-2007-211-D00019) and Professor Dutta acknowledges the Konkuk University Brain Pool Program.

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1) E. R. Lee: *Microdrop Generation* (CRC Press, Boca Raton, FL, 2002) p. 252.
2) T. Aernouts, T. Aleksandrov, C. Girotto, J. Genoe, and J. Poortmans: Appl. Phys. Lett. **92** (2008) 033306.
3) T. R. Hebner, C. C. Wu, D. Marcy, M. H. Lu, and J. C. Sturm: Appl. Phys. Lett. **72** (1998) 519.
4) H. Sirringhaus, T. Kawase, R. H. Friend, T. Shimoda, M. Inbasekaran, W. Wu, and E. P. Woo: Science **290** (2000) 2123.
5) T. Goldmann and J. S. Gonzalez: J. Biochem. Biophys. Methods **42** (2000) 105.
6) S. Lee, D. Byun, D. Jung, J. Choi, Y. Kim, J. H. Yang, S. U. Son, S. B. Q. Tran, and H. S. Ko: Sens. Actuators A **141** (2008) 506.
7) J. Choi, Y. J. Kim, S. Lee, S. U. Son, H. S. Ko, V. D. Nguyen, and D. Byun: Appl. Phys. Lett. **93** (2008) 193508.
8) Y. J. Kim, H. S. Ko, S. Lee, S. U. Son, D. Jung, and D. Byun: J. Korean Phys. Soc. **51** (2007) 42.
9) D. Y. Lee, Y. S. Shin, S. E. Park, T. U. Yu, and J. H. Hwang: Appl. Phys. Lett. **90** (2007) 081905.
10) D. Byun, Y. Lee, S. B. Q. Tran, V. D. Nguyen, S. Kim, B. Park, S. Lee, N. Inamdar, and H. H. Bau: Appl. Phys. Lett. **92** (2008) 093507.
11) J. Zeleny: Phys. Rev. **10** (1917) 1.
12) H. T. Yudistira, V. D. Nguyen, P. Dutta, and D. Byun: Appl. Phys. Lett. **96** (2010) 023503.
13) V. D. Nguyen and D. Byun: Appl. Phys. Lett. **94** (2009) 173509.
14) M. Cloupeau and B. Prunet-Foch: J. Electrostat. **25** (1990) 165.
15) K. J. Yoon, S. Shin, H. C. Park, and N. S. Goo: Smart Mater. Struct. **11** (2002) 163.
16) J. Perelaer, C. E. Hendriks, A. W. M. de Laat, and U. S. Schubert: Nanotechnology **20** (2009) 165303.
17) H. Y. Gan, X. Schan, T. Eriksson, B. K. Lok, and Y. C. Lam: J. Micromech. Microeng. **19** (2009) 055010.