Application of Electrostatic Inkjet Phenomena to Micro-Film Formation by Spraying Viscous Liquid from Multi-Nozzles.

Kazuyuki Tada, Nozomi Yoshida, Shunsuke Muraki, Takashi Nishiyama and Hiroyuki Kawamoto; Department of Applied Mechanics and Aerospace Engineering, Waseda University, Shinjuku, Tokyo, Japan

Abstract

Micro spray mode of electrostatic inkjet has been examined experimentally for the application of precision film coating. Critical issues of this technology lie in productivity and jetting viscous liquid. The former is that the amount of liquid jetted from a single nozzle is too small to obtain sufficiently high coating speed. The latter is that the stable jetting window of viscous liquid is narrow and the distribution of the droplet is not uniform. To overcome the situation, a possibility of jetting viscous solution from multi-nozzles was investigated in this report. As results, jetting from seven nozzles made of stainless steel was fanned out toward the opposite plate electrode. By intentionally clogging the both end-nozzles and making them as electrodes, the direction was remedied and parallel jets were obtained. According to the increment of applied voltage, jetting mode was varied from dripping mode to stable cone-jet mode. Although the variation of jetting mode was qualitatively the same as that of a single nozzle, for the multi-nozzle the higher voltage was required to obtain the stable jetting mode. Calculated results suggested that the electric field at the tips of the multi-nozzles were lower than that of a single nozzle so that the much higher voltage was required to obtain the same family of jetting mode. From coating experiments on a drum it was demonstrated that the multi-nozzles with dummy electrodes at high applied voltage could jet well-oriented fine droplets to acquire thick and flat film, although the droplets were not uniform. It was confirmed that the coating speed was improved according to the number of the nozzles but the more flowrate was indispensable to obtain thick film.

Introduction

Since the first inkjet printer appeared in market more than 50 years ago [1][2], the inkjet technology has progressed tremendously in quality and print speed. Although the electrostatic inkjet technology has not applied to commercial printers, it is attractive for the industrial application because of its versatility in jetting forms; an individual droplet on demand [3], fine droplets in micro spray state [4] and a thread for fabric [5]. Furthermore, it has the ability of jetting highly viscous liquid [6] and making (a) super fine, femtoliter-size, droplet(s) [3].

The authors are investigating the applicability of the micro spray state of electrostatic inkjet to precision film coating [7] [8]. Using a single nozzle, it was found that electrostatic inkjet system could jet femtoliter-size droplets even from a viscous liquid and by piling those droplets, quality coating was demonstrated. A critical issue for industrial application, however, lies in terms of productivity; the amount of liquid jetted from a nozzle was too small to obtain sufficiently high coating speed. To overcome the situation, scale-up study of multi-nozzle system with viscous liquid was tried in this report. At first, the most preferable jetting conditions were determined through experiments. Then, with those parameters examined, the possibility of high quality coating was explored through experiments.

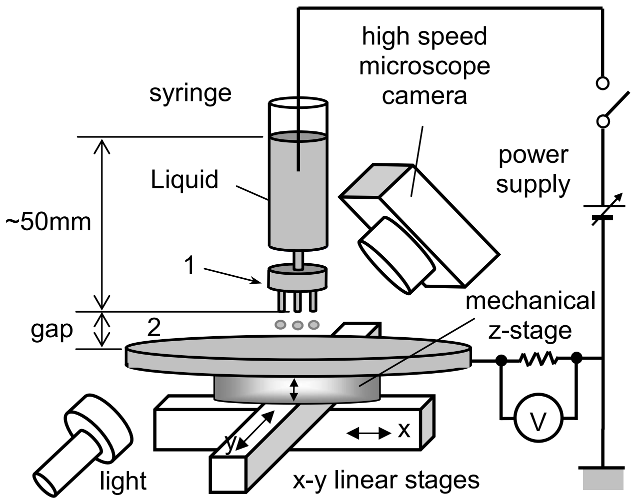


Figure 1. Experimental set-up of electrostatic inkjet jetting observation, 1: pin electrode=nozzle, 2: plate electrode.

Experimental

Experimental set-up

An experimental set-up for jetting observation is illustrated in Figure 1. During applying the voltage up to 30 kV by a high voltage amplifier, the jetting state was observed with a high-speed microscope camera. Nozzles, filled with liquid are assumed to be pin electrodes. The gap between the nozzle-tips and the plate electrode was controlled by a mechanical stage.

Figure 2 is an example of a head with seven nozzles. The nozzles are equally aligned as shown in the figure. All the nozzles and the body were made of stainless steel. The tips of the nozzles are tapered and the outer surfaces of the nozzles are coated with a conductive material. Both end-nozzles were intentionally clogged as dummy nozzles by a Tungsten wire to control the electric field. From the knwoledge of former study [8], the Tungsten wire protruded 1mm from the tips of the dummy nozzles was used.

Figure 3 is a schematic of a bench for coating experiments. A metal cylinder was used as a coating substrate. Liquid is jetted from the multi-nozzle head which is mounted above the rotating cylinder. Whole area of the cylinder surface could be coated by traversing the multi-nozzle head into the x-direction in the figure by a linear stage. The position of the nozzle was controlled by a

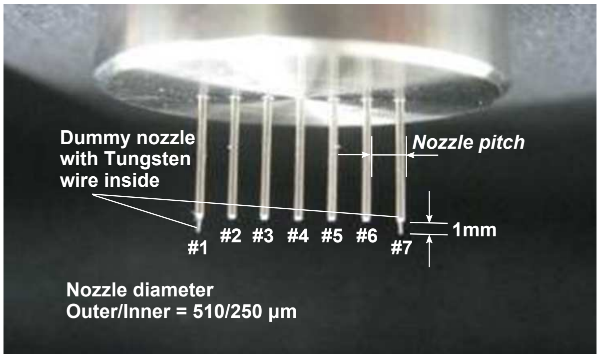


Figure 2. Multi-nozzle head made of stainless steal.

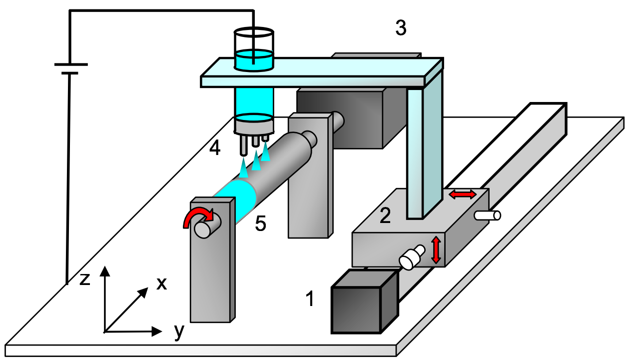


Figure 3. A schematic of a cylinder coating bench. 1: x-axis linear stageC2: y-z mechanical stage, 3: motor for rotation, 4: multi-nozzle head, 5: a metal cylinder (coating substrate grounded).

mechanical stage.

Liquid

The examined liquid was a viscous solution. The solid components consist of equal amount of polycarbonate and an arylamine-type low molecular component. These solid components were solved into cyclohexanone. The properties of the viscous solution are as follows; solid contents= 15.0wt%, conductivity= 1.55×10^{-6} S/m, viscosity= 172.0mPa·s and surface tension= 35.74mN/m. The conductivity is in the range of spray mode of electrostatic inkjet system, withiin $10^{-3}-10^{-11}$ S/m, reported by Drozin [9].

Calculation of Electric Field

To understand the mechanism of jetting, electric field surrounding the multi-nozzle was calculated. Only the domain in the Figure 4 was examined because of its symmetricity. Three dimensional Cartesian coordinate system was used. Laplace equation (2) as the basic function was solved with its boundary conditions described in the equation (2),(3),(4) by finite difference method.

$$\nabla^2 U = 0 \tag{1}$$

$$U = 1 \quad \text{on Surface of nozzle} \tag{2}$$

$$U = 0 \quad \text{on Surface of bottom electrode} \tag{3}$$

$$\mathbf{n}\cdot\nabla U = 0 \quad \text{on other surfaces} \tag{4}$$

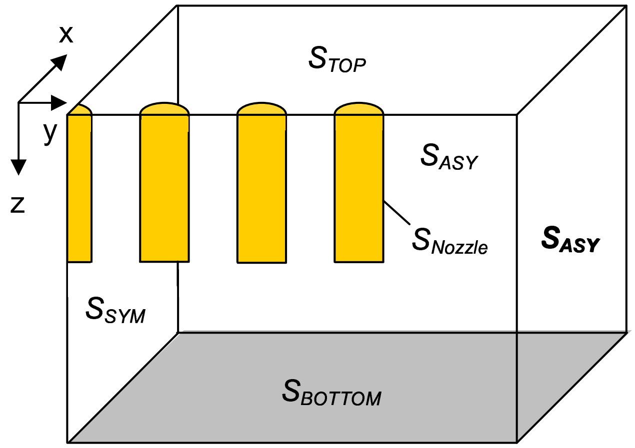


Figure 4. Calculated domain of the electric field sourrounding multi nozzles.

Results and Discussion

Jet direction

Figure 5 shows an example of the jetting from the multi-nozzle. With the dummy nozzles at the ends of the aligned nozzles to control the electrical field, it is clear that the favorable parallel jetting was obatained.

Jetting mode

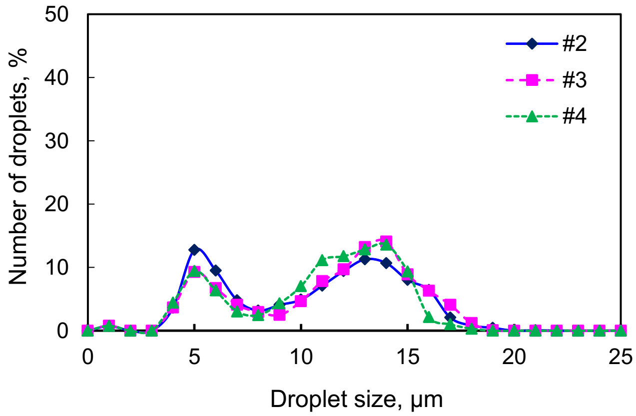
As of mentioned elsewhere [7][8], the forms of jets varied from dripping mode to cone-jet mode along increasing the applied voltage. Much higher voltage was required for the mode change in case of multi-nozzle than that of a single nozzle as in Figure 6. The onset voltage of mode change for each nozzle was slightly different as shown in Figure 5. The applied voltage for the mode change of #2 and #6 (not shown in the figures) nozzle was always lower than the nozzles in the middle and the highest voltage was required for the moddle nozzle #4.

Drop size and distribution

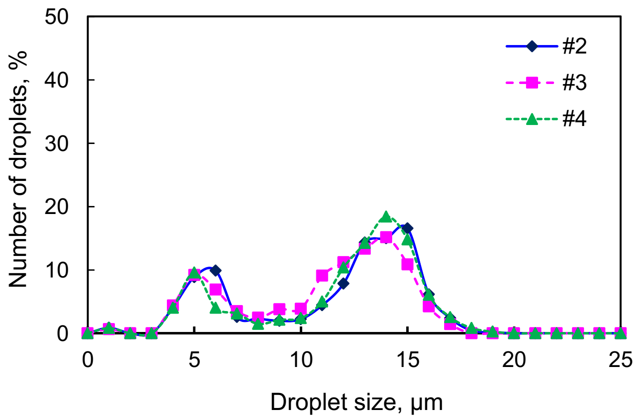
Figure 7 is the distribution of jetted droplet-sizes from deposited dots on a photo quality inkjet paper in the range of cone-jet mode. Although the applied voltage was increased to 15 kV, the distribution of the droplets were not significantly improved, two peaks appeared around 5 μm and 14 μm. Note that the corona discharge already occured in this range of voltage. In the case of single nozzle, required voltage to obtain Taylor cone was much lower, such as 4.0kV, the mode-diameter was small as 6 μm and the distribution was relatively mono-disperesed. Such difference between single and multi-nozzle came from the strengh of electric field at the tip of the Taylor cone.

Coating experiments

With the jetting condition in Figure 7, cylinder coating trials were carried out with the coating bench as shown in Figure 3. The travese speed of the multi-nozzle and the rotation speed of a aluminum cylinder were 0.12mm/s and 100rpm As a result, although the droplets were not jetted mono-dispersely as in Figure 7, more than 10 μm thickness of high quality film was obtained. The arithmetric surface roughness was less than 0.05 μm. Because the flowrate were multiplied by the number of nozzle, the



(a) 13kV, distribution of number



(b) 15kV, distribution of number

Figure 7. *Droplet size distributions. Owing to the symmetricity, only three nozzles out of five jetting nozzles are shown. Nozzle-pitch= 3 mm. Gap = 30 mm.*

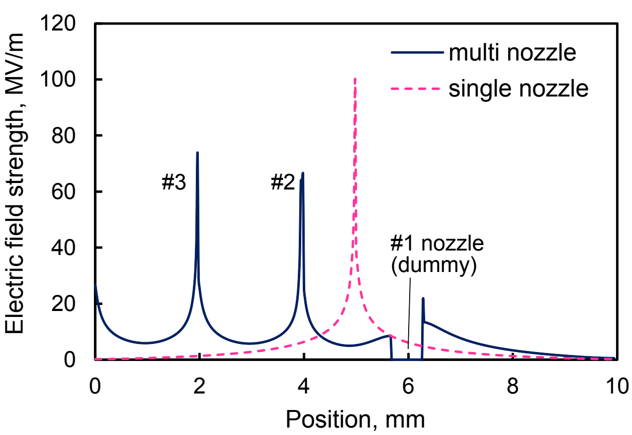
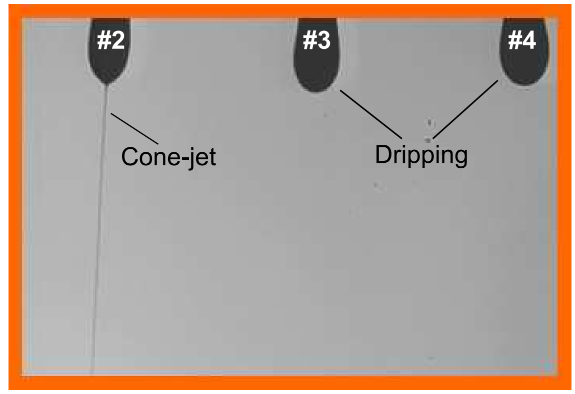
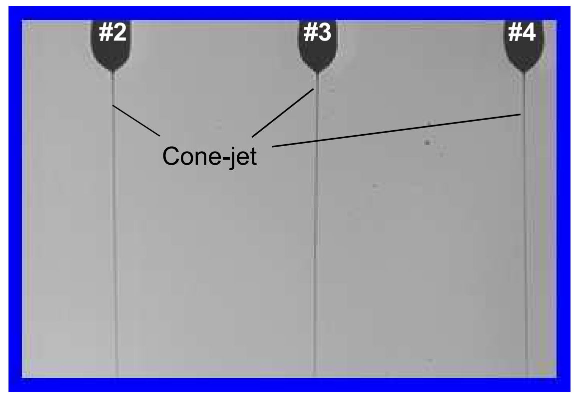


Figure 8. *Strength of electric field at the line including tips of pseudo cone-jet. The applied voltage for single and multi nozzle were 4.0kV and 9.0kV, respectively.*



(a) 8.6kV



(b) 10.6kV

Figure 5. *Voltage evolution of jetting mode of viscous solution from a multi-nozzle by applying voltage. Owing to the symmetricity, only three nozzles out of 5 jetting nozzles are shown. Gap= 30 mm.*

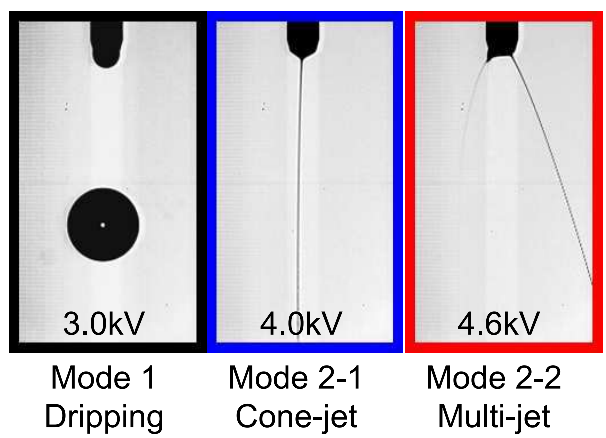


Figure 6. *Jetting mode of viscous solution from a single stainless nozzle. Gap= 30 mm. Nozzle inner/outer diameter= 250/510 μm.*

coating speed was increaesd according to the number of nozzle.

Strength of electric field

Figure 8 is the strength of electric filed near the artificial tip of Taylor cones. Applied voltgae of singl and multi-nozzle were 4.0kV and 9.0kV, respectively. In the Figure 8, the strengh of the multi-nozzle is smaller than that of the single nozzle even though the applied voltage of the multi-nozzle was much higher. Concentration of electric field at the tip of Taylor cone is required to jet uniformly and efficiently.

Concluding remarks

Ability of jetting fine droplets of viscous solution from multi nozzles and applicability of the spray state of electrostatic inkjet to quality and high-speed coating of thick film were examined experimentally. It was found that,

1. By adding intentionally clogged dummy nozzles to both ends of aligned multi nozzles, well oriented parallel jet could be obtained.
2. Mono-disperse droplet distribution could not be achieved. Still, the diameter of the droplets are small enough to satisfy the drops-on-drops concept to coat thick film, high quality coating was possible.
3. Concentration of electric field at the tip of Taylor cone without applying high voltage is required to obtain finer droplets without corona discharge. In this case, however, the flowrate is likely reduced so that the productivity of coating could be worsen.

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Author Biography

Kazuyuki Tada started his professional career as an engineer in 1990 following completion of a M.S. degree at Keio University. Since then he has been working in a manufacturing engineering division of Fuji Xerox. From 1997 to 1999 he had a chance to study coating science and technology in University of Minnesota where he received another M.S. degree. During the stay in Minnesota, he participated in NIP14 at the first time as an audience in Toronto, CANADA. This is his fourth consecutive presentation at NIP/DF conference from 2008. Currently he enjoys double statuses of his career, a corporate engineer and a doctoral-course student at Waseda University.