고속카메라를 이용한 Drop-on-demand 방식의 정전 액적 토출 분석

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Analysis of Electrostatic Ejection of Liquid Droplets in Manner of Drop-on-demand Using High-speed Camera

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Abstract

An electrostatic inkjet head can be used for manufacturing processes of large display systems and printed circuit boards (PCB) as well as inkjet printers because an electrostatic field provides an external force which can be manipulated to control sizes of droplets. The existing printing methods such as thermal bubble and piezo inkjet heads have shown difficulties to control the ejection of the droplets for printing applications. Thus, the new inkjet head has been proposed using the electrostatic force. A numerical analysis has been performed to calculate the intensity of the electrostatic field using the Maxwell's equation. Also, experiments have been carried out to investigate the droplet movement using a downward capillary with outside diameter of 500μm. Gravity, surface tension, and electrostatic force have been analyzed with high voltages for a drop-on-demand ejection. It has been observed that the droplet size decreases and the frequency of the droplet formation and the velocity of the droplet ejection increase with increasing the intensity of the electrostatic field using high-speed camera.

Key Words : Electrostatic Ejection(정전 토출), Droplet(액적), Inkjet Printer Head(잉크젯 프린터 헤드)

1. Introduction

Experimental and theoretical investigations on the electro-spraying of liquids have been performed by many researchers. Scaling laws of spray were presented by using liquids with different viscosities, surface tension, electrical conductivities, and permittivity.(1) Sato et al.(2) measured the surface tension of liquid under applied D.C electric field and concluded that the surface tension decreased with increasing voltage, and the reduction was

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proportional to the square of the field strength. Uniformly sized droplets less than several micrometers of diameters have been produced by Vonnegut et al.(3) by using positive voltage applied to nozzle electrodes in air. They carried out experiments using aqueous electrolyte solution by varying the water conductivity and derived an equation to estimate the formed droplet sizes as a function of flow rate, surface tension, and electrical charge. They concluded that electrostatic jetting occurred by an electrical constriction force acting on a liquid meniscus.

A novel mechanism of electrostatic micro droplet formation and ejection of fluid is proposed in this study. The detailed jetting mechanisms and modes have been investigated to design the electrostatic jetting system optimally and to examine forces on the jetting mechanism for droplet-on-demand operation according to important physical parameters such as surface tension which is reduced by electrical conductivity of liquid due to applied voltages.

A micro-dripping mode is the optimum method for ejection of liquid for droplet-on-demand operation among a number of spraying modes which depend on many parameters such as applied voltages, liquid flow rates, and physical properties as well as electric field strength and configuration.(4) Thus, it is hard to search the suitable range for liquid ejection in micro-dripping mode by controlling various parameters. In this study, the change of droplet size has been observed according to the force for the droplet formation instead of the physical properties of the liquid. Also, equations have been derived for the various forces to compare with the experimental results.

2. NUMERICAL ANALYSIS

Former researchers have indicated that the process of dripping is essentially quasi-static in nature with negligible inertial and viscous effects of the fluid flow(5)(6). Therefore, a simple static force balance can be applied at all stages of the droplet formation from which the droplet diameter can be expressed as a function of the applied electric force (7).

The forces taken into account in the force balance are F_g due to the gravity, F_{st} due to the surface tension, and F_e due to the electric field. The following equation can be derived for the force balance (Fig. 1). The following equation can be derived for the force balance.

$$F_g - F_{st} + F_e = 0 \tag{1}$$

The electric field due to a potential applied to a semi-infinite wire with a rounded end and an infinite plate configuration(8) has been modified in this study as follows:

$$E = \frac{\sqrt{2}V}{r' \ln\left(\frac{4D'}{r'}\right)} \tag{2}$$

$$r' = \begin{cases} K_1(r-R)+R, & r \le R \\ K_2(r-R)+R, & r > R \end{cases} \tag{3}$$

$$D' = D - 2r \tag{4}$$

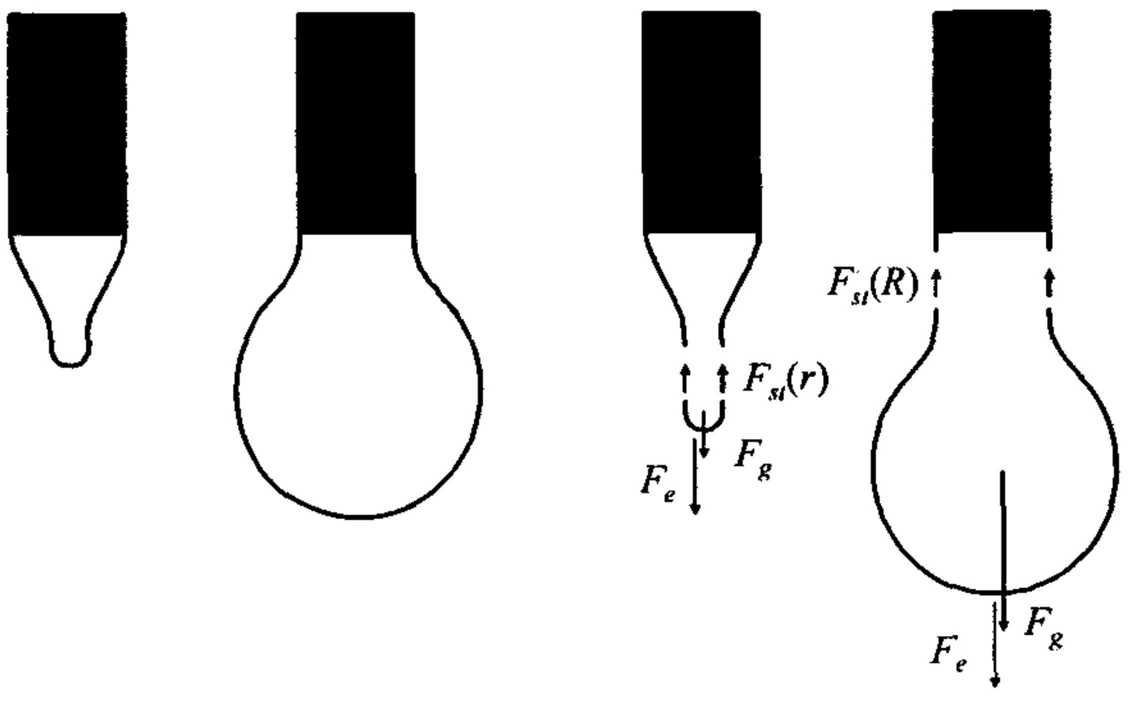


Fig. 1 Main forces acting on droplet

where r is the radius of the droplet, R is the radius of the wire end, V is the electric potential, D is the distance between the wire end and the earthen electrode and K is the correction factor of the radius of the droplet with $K1$ of 0.95 and $K2$

of 1.2.

It has been confirmed by the computational analysis that the electric field intensity is affected by the radius of the droplet as well as the radius of the wire end. Thus, the correction factor K has been introduced to obtain the electric field intensity considering both of the sizes(Fig. 2). The use of K has been divided into the droplet diameter>capillary diameter and the droplet diameter<capillary diameter. The equations (Eqs. (3) and (4)) have been derived to calculate the electric field and they have shown the good agreement with the results of the computer simulation as shown in Fig. 3.

The electrostatic force with the electric field acting on the pendant droplet can be evaluated in the following way.

$$F_e = \frac{1}{2} S\varepsilon_o E^2 \tag{5}$$

where S is the surface area of the droplet and ε_o is the permittivity of the air[(9)]. The force due to the surface tension can be obtained as follows:

$$F_{st} = \begin{cases} f(2\pi r)\gamma, & r \le R \\ f(2\pi R)\gamma, & r > R \end{cases} \tag{6}$$

$$\gamma = \gamma_o \left(1 - \frac{V^2}{{V_{ref}}^2} \right) \tag{7}$$

where γ is the constant of the surface tension with the applied voltage, γ_o is the surface tension constant without the applied voltage, f is the Harkins correction factor for the range of the considered droplet diameters with the value of 0.65, and V_{ref} is the reference value of the applied voltage. The surface tension also decreases with increasing the applied voltage and the reduction is proportional to the square of the applied field strength[(2)(10)]. Thus, Eq. (7) has been derived to calculate the surface tension with the applied voltage as shown in Fig. 4. The gravitational force F_g which is related to the droplet mass can be written as follows:

$$F_g = \left(\frac{4}{3} \pi r^3 \right) \rho g \tag{8}$$

where ρ is density of liquid, g is the gravitational acceleration.

The droplet radius r is the variable for all terms of the gravitational force, the surface tension, and the electrostatic force as shown by Eqs. (2) to (8). Therefore, the trial and error method has been used to calculate the droplet radius r at the state of the balance for three forces which are also affected by the droplet radius.

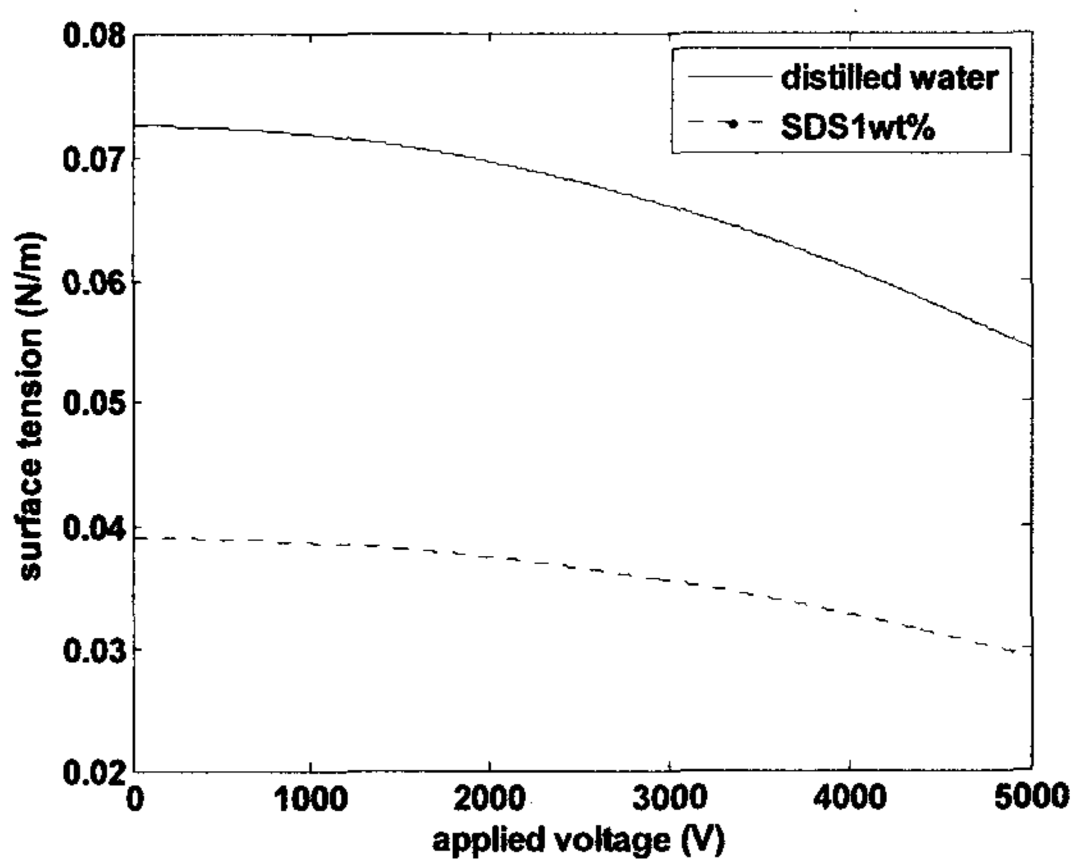


Fig. 3 Electric field intensity with diameters of droplets

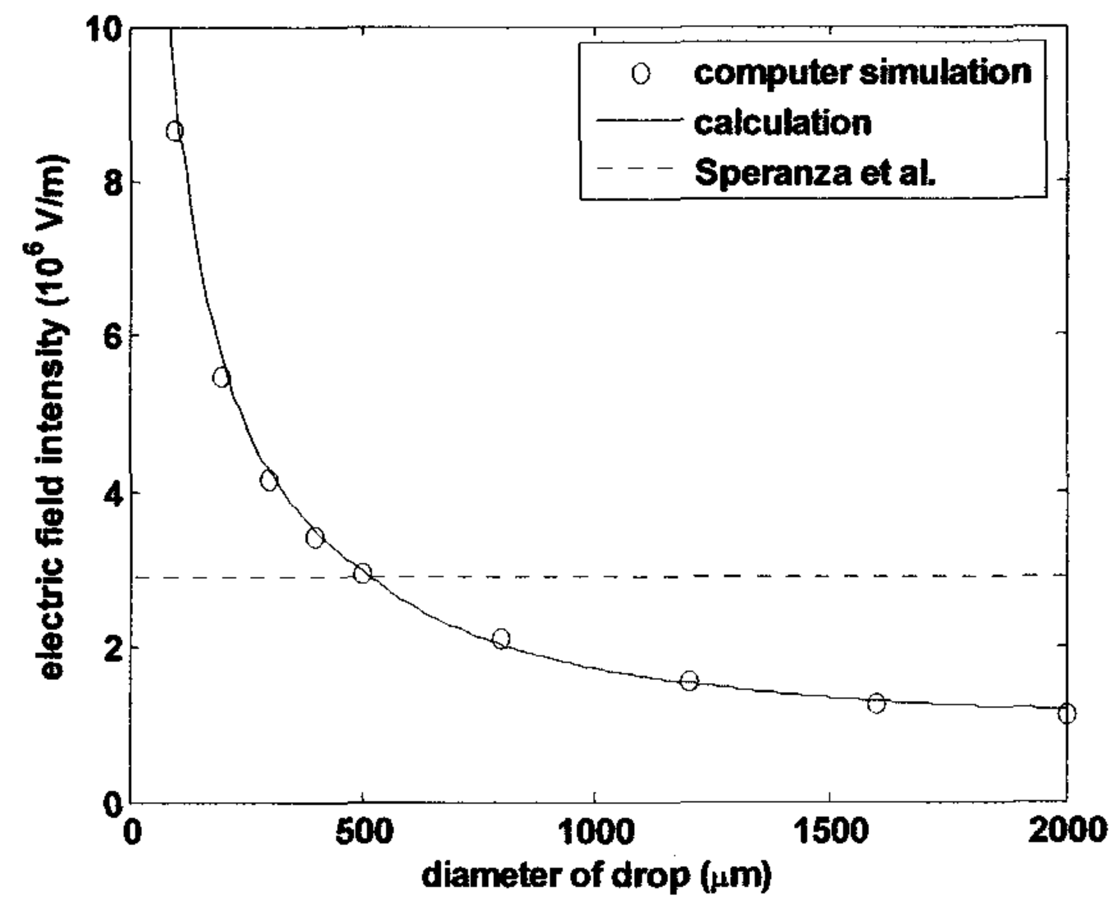


Fig. 4 Surface tension with applied voltages

Table 1 Liquid properties

Liquid	Density [kg/m^3]	Surface tension [N/m]	Electric conductivity [S/cm]
distilled water	998	0.0725	1.0580x10^{-5}
distilled water + SDS 1wt%	1000	0.039	3.8676x10^{-4}

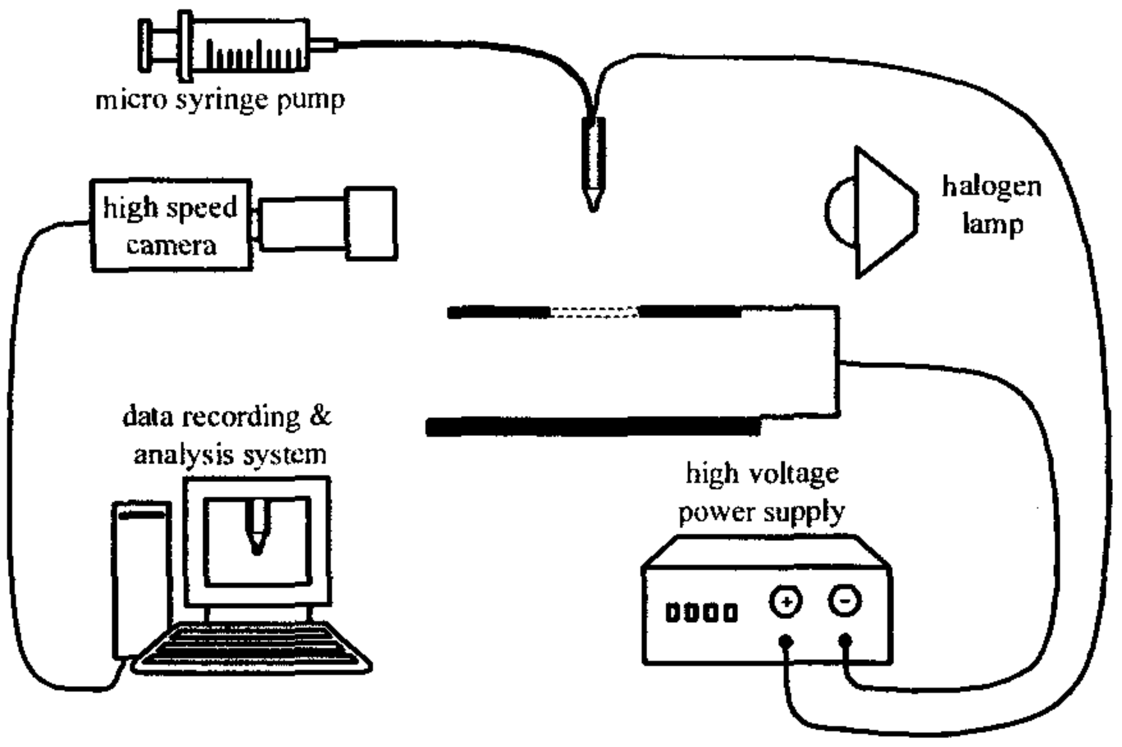
3. EXPERIMENTAL SETUP

The droplet has been formed and ejected by a pair of electroplates with a hole (5mm) at the center and a micro glass capillary tube with an outside diameter of 500μm including a pole made by Pt wire as shown in Fig. 5. The images of the droplet ejection (Fig. 6) have been captured by a high speed camera (IDT XS-4) with 5000 frames in a second and a 512x512 pixel resolution, a micro-zoom lens (infinity K2), and a 100W halogen lamp. A high voltage power supply system with the maximum voltage of 5.0kV has been used to control the electrostatic field. Liquids have been supplied into the glass capillary by a micro syringe pump. Table 1 shows the properties of the used liquids in this experiment.

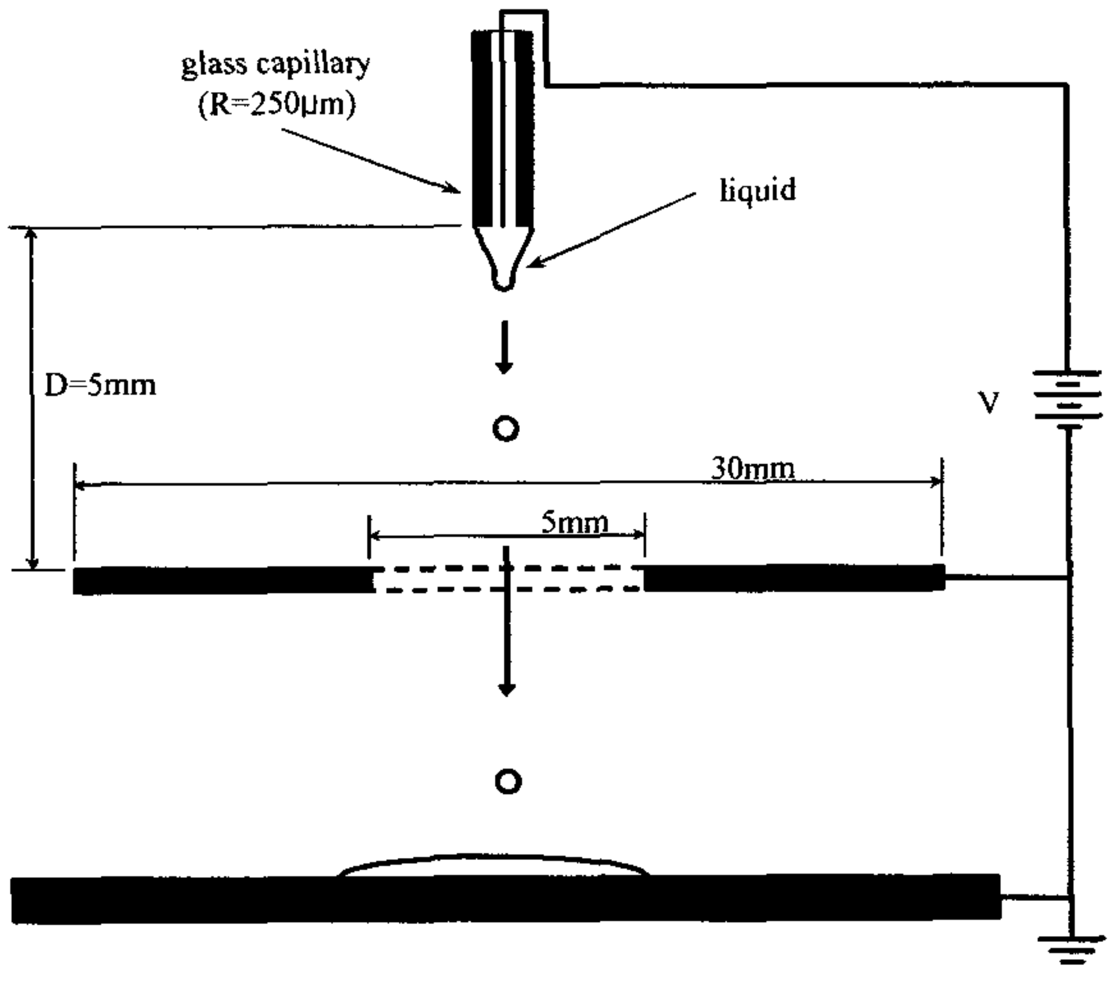
The gravitational force is not so significant in this experiment because the size of the capillary and the formed droplet are small. Thus, the main forces such as the surface tension and the electrostatic force have been observed with the voltages of 0 to 5kV and the distilled water and thewater mixed with the sodium dodecyl sulfate (SDS) which is one of the surfactants have been used to investigate the surface tension.

4. RESULTS AND DISCUSSION

The liquids have been supplied to the micro capillary with the constant velocity of 10μl/min by the micro syringe pump and the voltage has been provided to the electrodes. If the voltage increases, the droplet size decreases and the reduction rate increases as shown in Fig. 6-7 because the electrostatic force increases and the surface tension decreases to reduce the droplet size for the balance of both forces. Initially, the uniform droplet size has appeared with the regular formed frequency for the stable ejection until 3.3kV for the distilled water. The droplet size has decreased rapidly and the ejection has become unstable with the irregular frequency and the various droplet sizes including 10μm to 400μm from 3.3kV to 5kV since the ejection frequency of the droplet becomes shorter than the relaxation time of the liquid to make the charge for the liquid unstable. The biggest and the smallest values of the observed droplets at the same voltage have been drawn in the graph of Fig. 7.



(a) overview



(b) sectional view

Fig. 5 Experimental setup

The similar phenomenon as the distilled water has occurred for the SDS 1wt% until 2.5kV. However, the droplet size has not varied at the

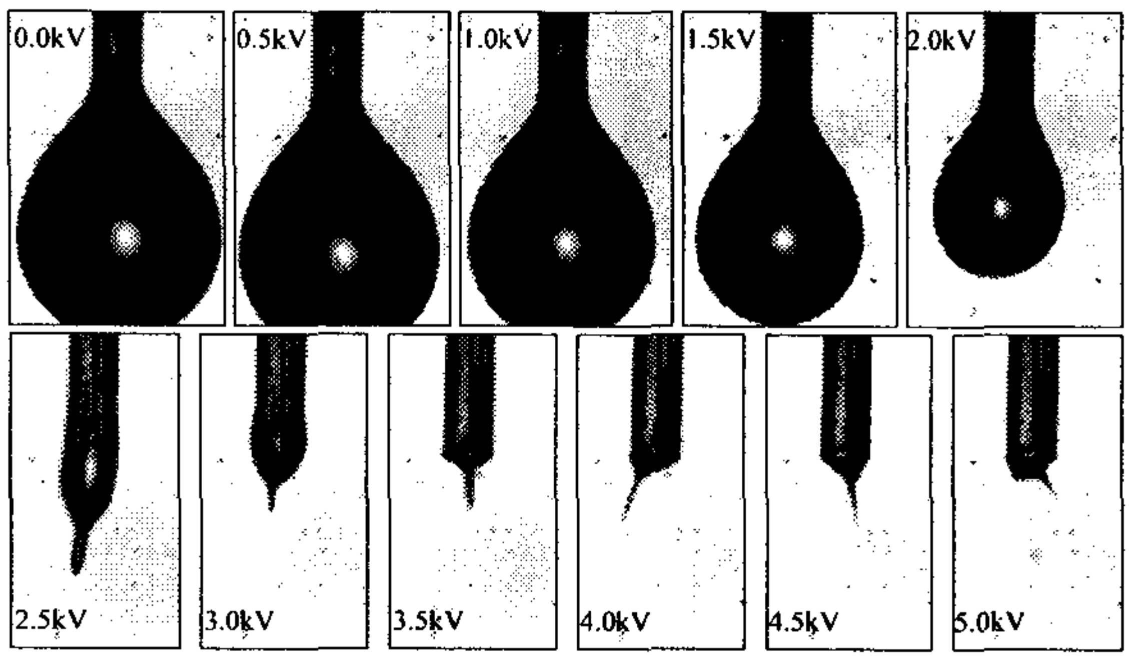


Fig. 6 Meniscus of SDS 1wt% with droplet formation for various applied voltages

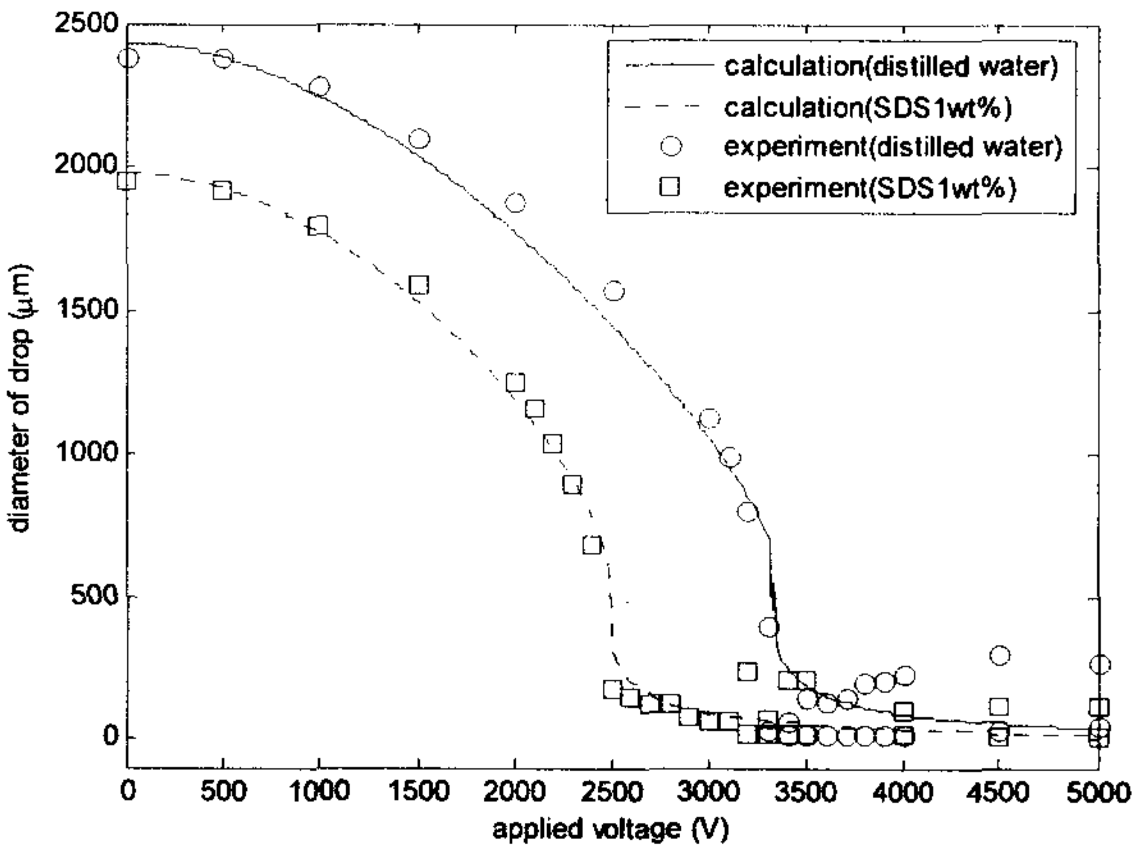
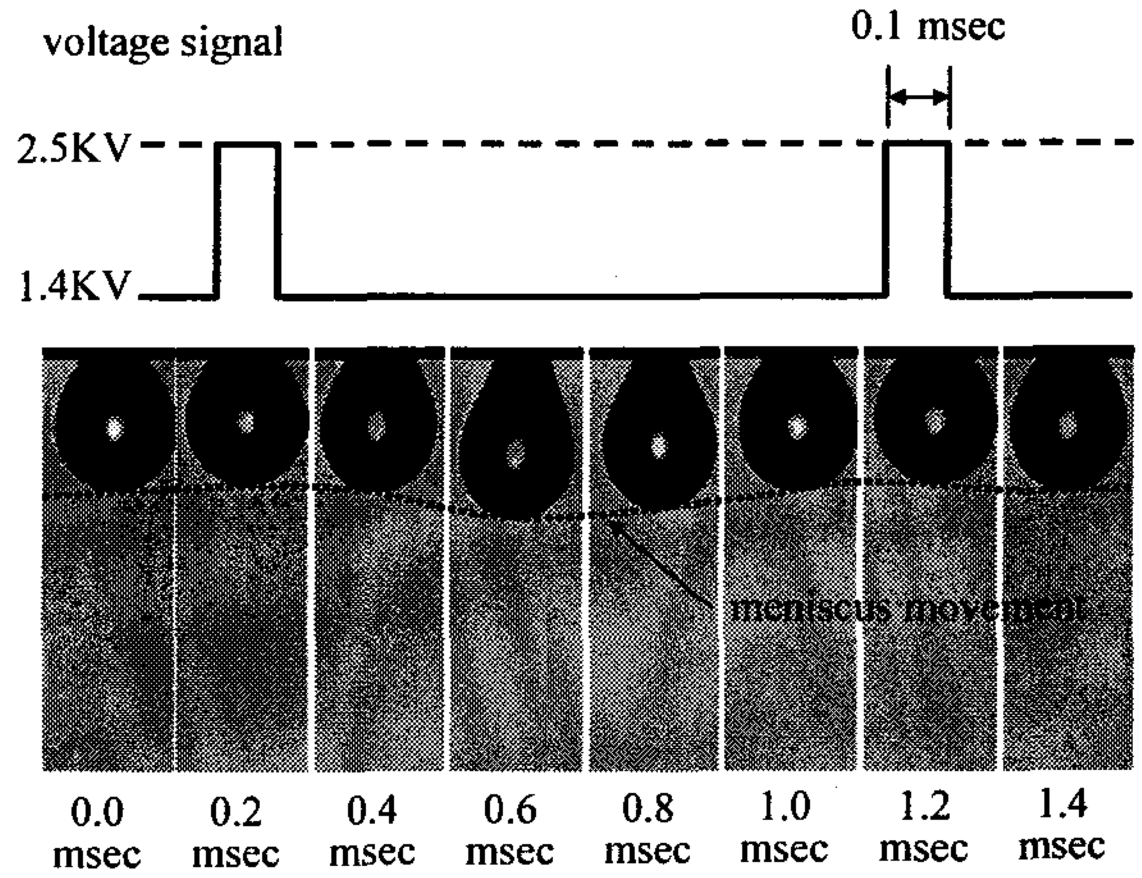


Fig. 7 Distribution of droplet size with applied voltages

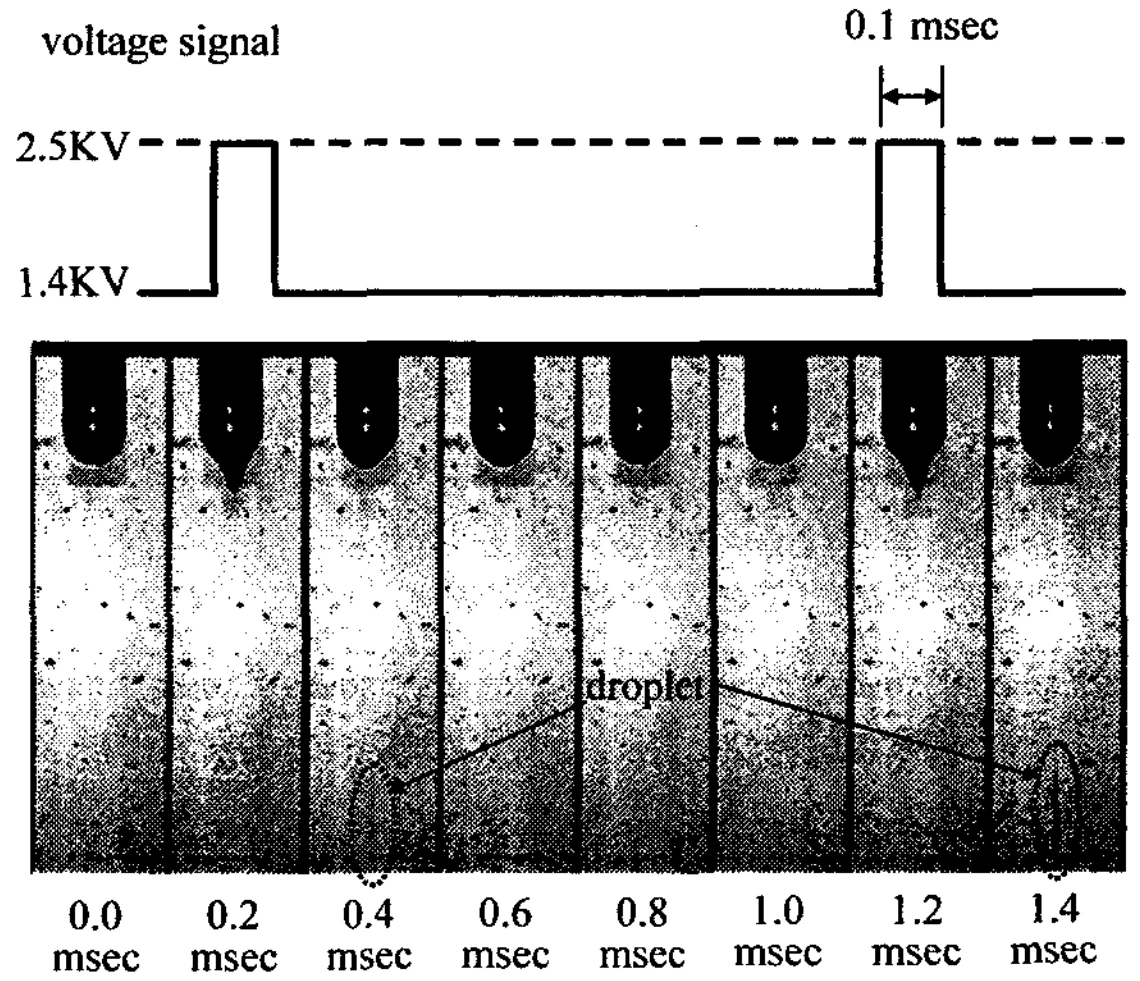
same voltage after 2.5kV for the stable droplet formation of the micro dripping mode although the droplet size has decreased significantly with increasing the voltage. The similar phenomenon with the distilled water after 3.3kV has been observed for the SDS 1 wt% at the 3.2kV, which has shown the various droplet sizes. A spindle and oscillating mode and a multi-jet mode have appeared for the SDS 1 wt% at 3.5~4kV and 5kV, respectively as shown in Figs. 6 and 7.

The derived model in this study has shown the good agreement with the experimental results for the distilled water and the SDS 1wt% before the unstable ejection (Fig. 7) compared with the previous studies which have not expressed the great reduction of the droplet size appropriately for the range of the high voltage because the proposed model has used the variables for the various electric field intensities and the surface tension constants. Thus, it has been realized that the prediction of the accurate electric field and the surface tension is very important for the electrostatic ejection of the droplet. The additional experiments and analyses should be required to investigate the irregular and unstable ejection phenomena for the region of the high voltages.

A drop-on-demand experiment has also been performed in this study to investigate the developed electrostatic inkjet head. A voltage waveform of 1.1kV at 1kHz pulsed signal with10% duty ratio has been applied and 1.4kV bias has been added. The outer diameter of capillary nozzle is 170 μm. A shape of an initial meniscus has been found to



(a) Large curvature of meniscus



(b) Small curvature of meniscus

Fig. 8 Movement of liquid meniscus.

be a key factor for the electrostatic drop-on-demand jetting. Different jetting modes have been observed by various geometries, flow rates, applied voltages, etc., respectively, under same other conditions.

In the case of large curvature of meniscus on the outer wall of the capillary nozzle, the intensity of the electric field decreases drastically. Thus, the separate droplet has not been generated and the formed meniscus has moved up and down as shown in Fig. 8 (a). The meniscus has grown and formed a large droplet in the dripping mode.

The outer wall of the capillary nozzle has not been wetted for the case of the small-meniscus shape. The electric-field intensity has increased greatly so that the end of the liquid meniscus can form a droplet in micro-dripping mode as shown in Fig. 8 (b). Therefore, the ejection mode has been affected by the shape of the initial meniscus in the drop-on-demand jetting.

5. CONCLUSION

A new model considering the change of the electric field and the surface tension has been derived and confirmed with the experimental results in this study, to overcome the inaccuracies of the previous studies. The distilled water and the SDS 1wt% have been used to construct the model for the analysis of the electrostatic ejection of the droplet. The results of the proposed model have shown the good agreement with the experimental results in calculating accurate sizes of the formed droplets. The tiny droplets in the drop-on-demand and micro-dripping modes have been generated by the small curvature of the initial meniscus and the dry outer wall of the capillary nozzle.

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