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Analysis of Electrostatic Ejection for Liquid Droplets

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정전기력에 의한 액적 토출 분석

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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 using the electrostatic force has been proposed in this study. In order to prove the theory of the developed electrostatic inkjet head, the applicable and basic theory has been studied using distilled water and water with sodium dodecyl surfate (SDS). Also, a numerical analysis has been performed to calculate the intensity of the electrostatic field using the Maxwell's equation. Furthermore, experiments have been carried out using a downward glass capillary with outside diameter of 500μm. The gravity, surface tension, and electrostatic force have been analyzed with high voltages of 0 to 5kV. 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. The results of the experiments have shown good agreement with those of numerical analysis.

1. INTRODUCTION

There has been a tremendous increase in use of micro droplets in physical, chemical, biological and engineering research areas such as micro-detectors, combinatorial chemistry assays using high cost chemicals, and micro-dispensing of small sub-nanoliter volumes of fluids for sensors, flat panel displays, and biochips [1]. Since the conventional jetting devices based on thermal bubble or piezoelectric pumping have some fundamental limitations on the density of nozzle array as well as the ejection frequency, electrostatic jetting based on the direct manipulation of liquid by an electric field appears to be more promising [2].

Experimental and theoretical investigations on the electro-spraying of liquids have been performed by many researchers. Scaling laws of spray were presented using liquids with different viscosities, surface tension, electrical conductivities, and permittivity [3]. Sato et al. [4] 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 proportional to the square of the field strength. Uniformly sized droplets of less than several micrometers of diameters have been produced by Vonnegut et al. [5] using applied positive voltage 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 has been 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 a droplet-on-demand operation according to important physical parameters such as surface tension which is reduced by electrical conductivity of liquid by applied voltages.

A micro dripping mode is the optimum method for ejection of liquid by the 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, and electric field strength and configuration [6]. Thus, it is hard to search the suitable range for the liquid ejection of the micro dripping mode by controlling various parameters. In this study, the change of the droplet size has been observed by the force for the droplet formation instead of the physical properties of the liquid. Also,

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equations have been derived for the various forces to compare with the experimental results.

2. NUMERICAL ANALYSIS

A simple model to predict the droplet diameter in the dripping mode has been derived by Speranza et al. with measurements of droplet sizes and formation frequencies for highly conductive and viscous liquids [7]. However, the model of Speranza has shown discrepancies with the experimental results for the electric field with higher than 10^6V/m. The reduced amount of the droplet size increased with increasing the applied voltages for the experimental results while that decreased for the derived model. Thus, more accurate model has been proposed in this study considering the surface tension reduction which has not been included in previous researches, and confirmed with the experimental results.

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 [8]. 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 (Fig. 1). The following equation can be derived for the force balance.

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

The electrostatic force acting on the pendant drop is related to the geometry of the electrode which provides a nonuniform electric field. The electric field due to a potential applied to a semi-infinite wire with a rounded end and an infinite plate configuration [9] has been modified in this study as follows:

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

where r' is the modified radius of the droplet for the electric field, V is the electric potential, and D' is the modified distance between the wire end and the earthen electrode. The results of the three-dimensional electric field from the numerical analysis in the instant of the droplet formation have varied with the radius of the curvature at the surface of the liquid. Thus, the electric field depends on the radius of the formed droplet because the radius of the curvature at the surface of the liquid is very similar with the radius of the droplet. Equation (3) has been derived to consider this phenomenon.

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

where r is the radius of the droplet, r' is the modified radius of the droplet, R is the radius of the wire end, and K is the correction factor of the radius of the droplet with K_1 of 0.95 and K_2 of 1.2. Also, the distance between the wire end and the earthen electrode is a very important facot for the electric field intensity in the instant of the droplet formation. If the droplet size increases, the distance decreases when forming the droplet. Thus, Eq. (4) has been included in Eq. (2).

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

where D is the distance between the wire end and the earthen electrode and D' is the modified distance of D. It has been cofirmed 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. Because of the difference of the distribution of the electric field as shown in Fig. 2, the use of K has been divided into the droplet diameter>capillary diameter and the droplet diameter<capillary diameter. The electric field has the same direction with the droplet ejection (Fig. 2 (a)) while there is the opposite direction of the distribution of the electric field (Fig. 2 (b)) to make weak for the electrostatic force of the droplet ejection. Thus, 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.

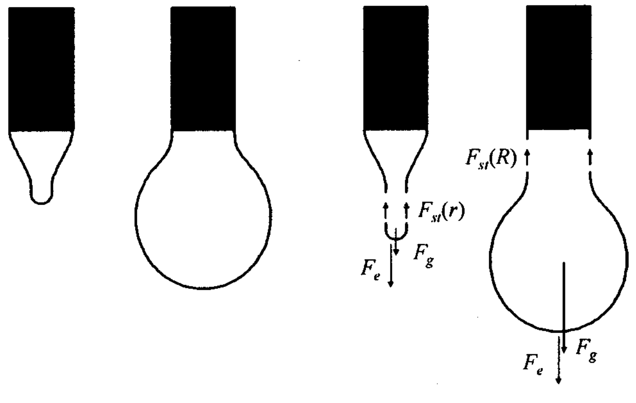
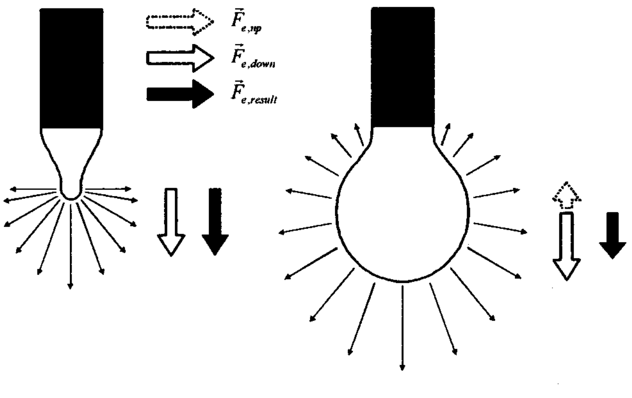


Fig. 1 Main forces acting on droplet



(a) r < R (b) r > R

Fig. 2 Electrostatic force caused by electric field distribution around meniscus of liquid

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 [10]. According to Takamatsu et al. [11], the electrostatic force acting on the pendant drop can be considered to be equivalent to the electrostatic force acting on the formed drop with a small margin of error. 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 [12], and V_{ref} is the reference value of the applied voltage. The assumption of f allows the error of below 10% for the analytical result in the evaluation of the force due to the surface tension. The surface tension is proportional to the droplet size if the droplet diameter is smaller than the capillary diameter, otherwise it depends on the capillary diameter (Eq. (6)). The surface tension also decreases with increasing the applied voltage and the reduction is proportional to the square of the applied field strength [4]. Thus, Eq. (7) has been derived to calculate the surface tension with the applied voltage. 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 the droplet density and 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.

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 500 μm including a pole made by Pt wire as shown in Fig. 3. The images of the droplet ejection (Fig. 4) 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.

Table 1 Liquid properties

Liquid	Density [kg/m^3]	Surface tension [N/m]	Electric conductivity [S/cm]
distilled water	998	0.0725	1.0580×10^{-5}
distilled water + SDS 1wt%	1000	0.039	3.8676×10^{-4}

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 the water 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 10 μl/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. 5 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 10 μm to 400 μm 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. 5.

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 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. 4 and 5.

The derived model in this study has shown the good agreement

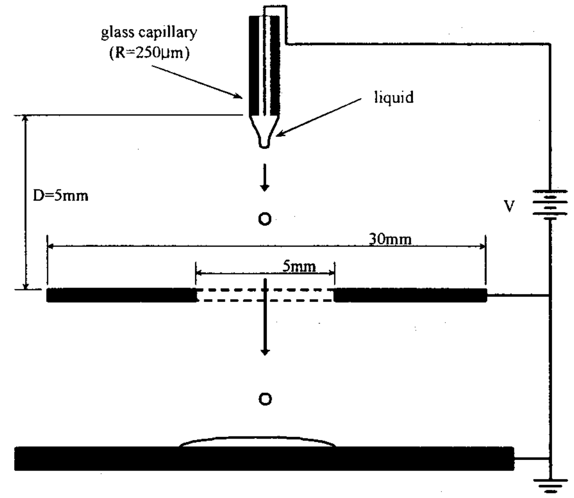


Fig. 3 Experimental setup

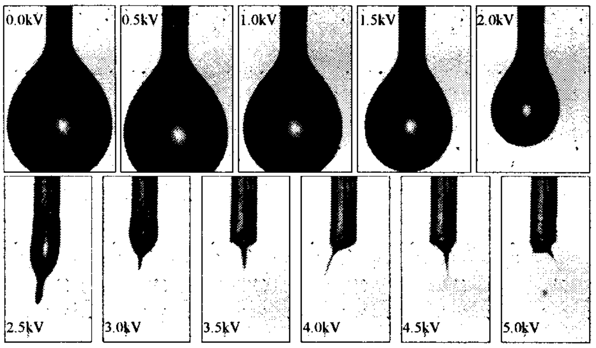


Fig. 4 Meniscus of SDS 1wt% with droplet formation for various applied voltages

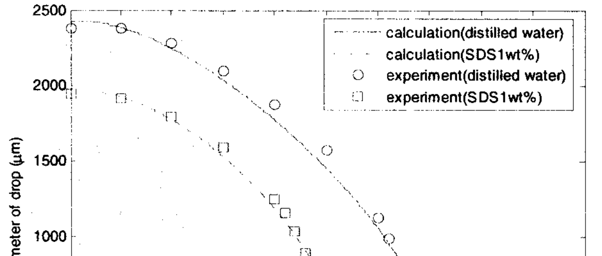


Fig. 5 Distribution of droplet size with applied voltages

with the experimental results for the distilled water and the SDS 1wt% before the unstable ejection (Fig. 5) 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.

5. CONCLUSION

The 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 inaccuracy of the previous studies. The results of the proposed model have shown the good agreement with the experimental results to calculate the accurate sizes of the formed droplets. More experiments and analyses are required to optimize the constants for the reacting forces especially for the irregular ejection which has been observed in this study.

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