A Continuous Ink Jet Device on the Basis of Electrohydrodynamic Mechanism

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A new type of ink jet system is proposed on the basis of electrohydrodynamic (EHD) effect. On the application of high DC electric fields to some insulating fluids, a fluid jet with a velocity of about 1 ms^{-1} is generated from the positive electrode as a bulk flow. By controlling the EHD flow to issue across the free surface, the ink jet device is developed, of which the nozzle unit is simply composed of a needle electrode and capillary. When the fluids are subjected to high electric fields, the ink jet is generated above a critical threshold and the height increases with increasing voltage. The critical voltage strongly depends on the nozzle geometry. The height of ink jet at high voltages increases with decreasing viscosity and conductivity of fluids. The performance of ink jet based on the EHD jet can be improved by a combination of designs of nozzle geometry and material functions.

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Introduction

The ink jet printers have made remarkable progress in production of high quality images. In a current ink jet printing technology, uniformly sized droplets are ejected from a nozzle by breakup of fluids. The droplet formation process is initiated by application of pressure to the fluid in a reservoir. When subjected to mechanical vibration, the periodic disturbance leads to the instability of fluid motion and causes a jet to issue from the nozzle. The primarily important parameters controlling the breakup behavior of jet flow are the surface tension and viscosity of fluids, the mode of excitation signal, and the nozzle geometry.[1] The stimulation of fluids is generally introduced by the use of a piezoelectric transducer. In printing systems of the drop-on-demand type, the jetting rates are in the range of 6~12 kH, while the droplets with diameters around 15 μm are created at a rate of approximately 1 MHz in continuous ink jet. For high quality printing, the research trends are focused on the size reduction of droplets and recently a new continuous ink jet has been developed in which the fine droplets(mist) with an average diameter of 2.5 μm are ejected by ultrasonic waves at a frequency of 10 MHz.[2] The great advantage of this technique is that the droplet size can be changed by frequency of ultrasonic waves without a nozzle.

The application of high electric fields to insulating fluids often generates electric body forces due to the nonuniformity of electric conductivity and dielectric constant. In DC fields, the Coulomb force acting on a space charge dominates the dielectrophoretic force. Under certain conditions, the Coulomb force can cause hydrodynamic instability. The secondary motion of fluid, which is produced in high electric fields is known as the electrohydrodynamic (EHD) effect.[3–6] The EHD effect can give rise to interesting phenomena such as convection, turbulence, and chaos. In electric fields, ionic mobility has been reported[7,8] to be about 10^{-8} $m^2V^{-1}s^{-1}$ in dielectric fluids with viscosity of a few mPas. Based on the ionic mobility, the velocity of secondary flow can be estimated as 1×10^{-2} ms^{-1} in an electric field of 1 $kVmm^{-1}$. Numerical simulation and EHD experiments under microgravity conditions in space also show that the velocity of the flow is about 2×10^{-2} ms^{-1} at a DC electric Rayleigh number of 6000 where the Coulomb force dominates the viscous force.[9] Much work demonstrates that the velocity of the EHD flow is of the order of 10^{-2} ms^{-1} in electric fields of several kV.

In previous studies, we have found that on the application of high DC fields to some insulating fluids, a fluid jet with a velocity of about 1 ms^{-1} is generated from the positive electrode. In this process, electric energy is directly converted to kinetic energy of the fluid. Since the high energy density can be generated, the EHD jet is very attractive in applications to new fluid devices. By controlling the velocity and direction of EHD jet, the

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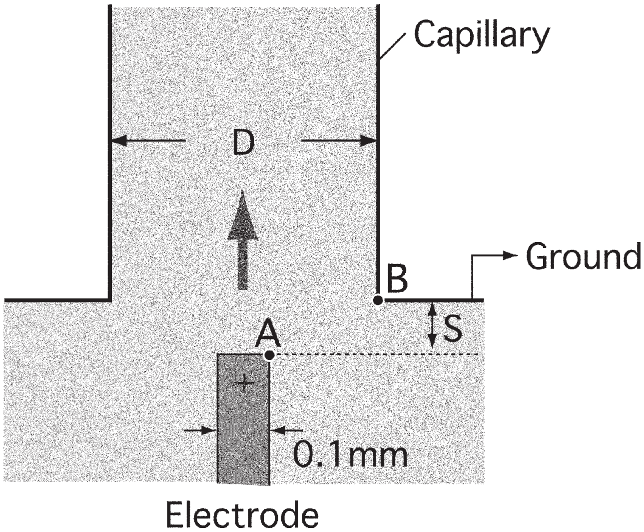

Figure 1. A schematic picture of a nozzle unit consisting of a needle electrode with a thickness of 0.1 mm and a capillary with a length of 5 mm.

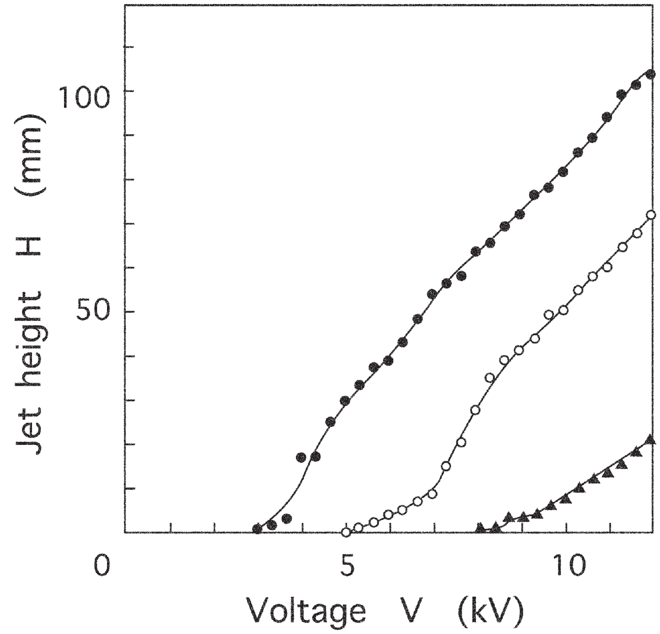

Figure 2. Jet height, *H*, plotted against the applied voltage, *V*, for the nozzle with a diameter of 0.2 mm at different gap distances; (●) 0, (○) 2.0, (▲) 4.0 mm.

authors have developed fluid motors[10] and electrorheological devices.[11,12] The electric fields acting on space charges produces not only the body forces in the bulk, but also the extra stresses across the interfaces. If the sufficiently high normal stresses are exerted, the continuous evolution of free surface from the nozzle exit can take place. In the present study, we have studied the EHD effect to generate the continuous liquid jet. The feasibility of providing a new basic technology for ink jet printing systems will be discussed in relation to fluid properties.

Experimental

Samples

Eight kinds of insulating fluids were used as models of ink media; dibutyl adipate (designated DBA; viscosity $\eta = 3.5 \times 10^{-3}$ Pas at 25°C, electrical conductivity $\sigma = 3.8 \times 10^{-9}$ Sm^{-1} in an electric field of 2.0 kV mm^{-1}), dibutyl decanedioate (DBS; $\eta = 7.0 \times 10^{-3}$ Pas, $\sigma = 1.4 \times 10^{-9}$ S m^{-1}), dibutyl maleate (DBM; $\eta = 3.7 \times 10^{-3}$ Pas, $\sigma = 3.3 \times 10^{-8}$ S/m^{-1}), dioctyl tetrahydrophthalate (DOTP, $\eta = 4.0 \times 10^{-2}$ Pas, $\sigma = 6.2 \times 10^{-10}$ S m^{-1}), triacetin (TA, $\eta = 1.4 \times 10^{-2}$ Pas, $\sigma = 3.6 \times 10^{-9}$ S m^{-1}), 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TMPD, $\eta = 4.0 \times 10^{-3}$ Pas, $\sigma = 6.2 \times 10^{-9}$ S m^{-1}), 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (TMPM, $\eta = 1.2 \times 10^{-2}$ Pas, $\sigma = 6.8 \times 10^{-8}$ S m^{-1}), and fluorinated fluid(FF-3 manufactured by New Technology Management, $\eta = 4 \times 10^{-4}$ Pas, $\sigma = 2.5 \times 10^{-9}$ S m^{-1}). All the sample fluids are Newtonian.

Measurements

Figure 1 shows a schematic picture of nozzle unit. The ink jet nozzle consists of a needle electrode with a diameter of 0.1 mm and a capillary with a length of 5 mm. Because the tip of needle electrode is polished by sandpaper, the surface is regarded as flat. Various nozzles made of stainless steel were used, of which diameters *D* are from 0.2 mm to 1.2 mm. The vertical distance between the tip of a needle electrode and bottom of nozzle electrode (called gap distance, *S*, in this article) are adjusted in the range of 0 ~4.0 mm. The ink jet unit was so immersed in the fluid that the bottom of the nozzle coincides with the fluid level. A DC voltage was applied to the needle electrode and the nozzle was connected to ground ($E = 0$). The height of jet was determined by image analysis of photographs.

Results and Discussion

Effect of Nozzle Geometry

First of all, the geometrical effect of nozzle on the ink jet behavior is examined by the use of fluorinated fluid which was newly formulated for the present study. On the application of high voltage, the continuous jet flow is almost instantaneously (within 50 ms) ejected from the nozzle. Figure 2 shows the jet height, *H*, plotted against the applied voltage, *V*, for the nozzle with a diameter of 0.2 mm at different gap distances. The jet issues when the voltage is increased above some critical level, which increases with increasing gap distance. Beyond the critical voltage, the plots are approximately correlated by a straight line. The height increase with decreasing gap distance although the annular entrance of fluid to nozzle becomes narrow. In this study, the maximum height was achieved at 12 kV by the use of nozzle with a diameter of 0.2 mm at zero gap distance and the value was about 100 mm. When the gap distance is increased up to 5 mm, the jet flow essentially disappears even at 12 kV. In the case of dielectric fluid motors,[10] the angular velocity increases with increasing applied voltage. However, there exists a critical value above which a steady rotation is achieved, and below which the rotor only oscillates with the amplitude of oscillation gradually decreasing. On the performance of ink jet and motors, similar effects of field intensity are confirmed. The internal convective flow in the bulk can be connected with the jet stream as the continuous evolution of free interface.

Figure 3 shows the jet height plotted against the applied voltage at zero distance for the nozzles with different diameters.

Image analysis enables us to determine the diameter of liquid jet at the nozzle exit when the jet height

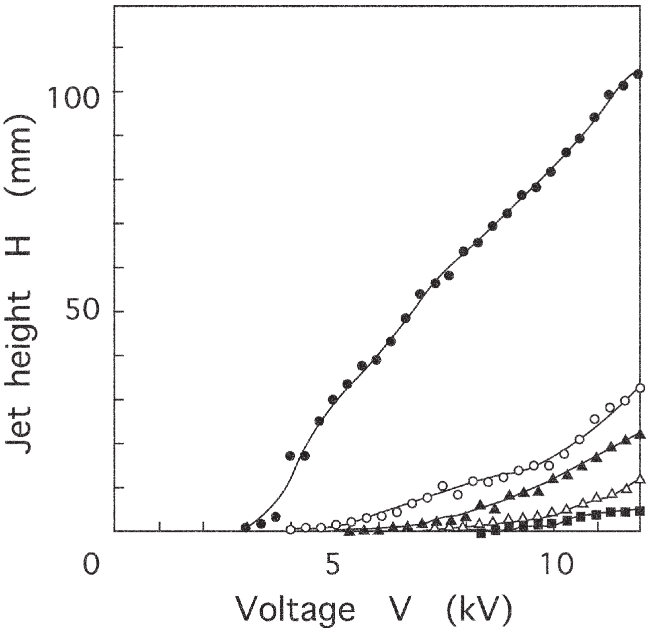

Figure 3. Jet height plotted against the applied voltage at zero distance for the nozzles with different diameters; (●) 0.2, (○) 0.4, (▲) 0.6, (△) 0.8, (■) 1.0 mm.

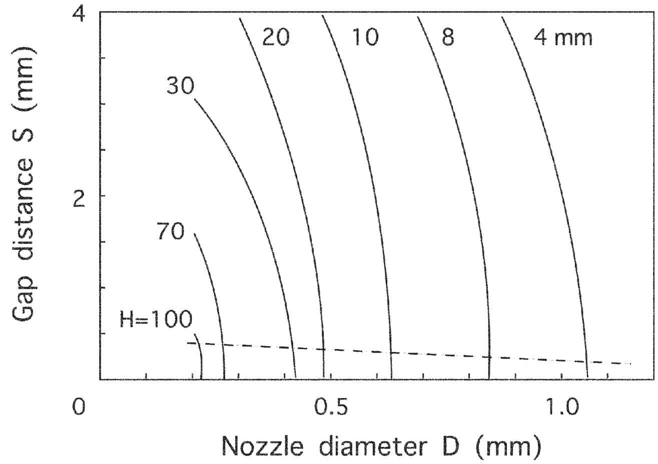

Figure 4. Contour lines showing jet heights at 12 kV as a function of nozzle diameter and gap distance. The broken line is the equifield intensity curve at 24 kV mm^{-1}.

exceeds 5 mm. The jet diameters are almost the same as the nozzle diameters and independent of applied voltage. Above the critical voltage, the jet height slowly increases at first and then begins to rapidly increase. Since the threshold voltage increases, the jet height rapidly decreases with increasing diameter. When the diameter increases above 1.0 mm, the height approaches zero. The thick nozzles hardly generate the effective jet flow. The velocity at nozzle exit is about 0.5 ms^{-1} for jet with the maximum height. The close relationship is established between the velocity and height. The geometrical parameters determining the ink jet performance are the gap distance and nozzle diameter. To examine their contributions, jet heights at 12 kV are shown as contour lines in Fig. 4. The jet height decreases with increasing gap distance and nozzle diameter. We consider that the field intensity plays an important role in generating ink jet. The field intensity is generally defined as the difference between voltages at two electrodes divided by their separation. Referring to Fig. 1, we can use the distance between points A and B to characterize the field intensity in nozzle. The broken line in Fig. 4 represents the equifield intensity curve at 24 kV mm^{-1}. The solid lines showing constant height and the broken line showing constant field intensity have quite different profiles. The results clearly indicate that the jet formation process is not scaled on the field intensity.

The jet height is much more sensitive to horizontal separation.

Figure 5 shows the jet height at 12 kV plotted against the reciprocal cross section of nozzle at zero distance. The plots are approximated by a straight line with a slope of 1. The product of jet height and cross section of nozzle is almost constant and this value can give a measure of pressure locally generated to raise the fluid elements. For formation of upward flow, vertical force must be exerted on the fluid column in the nozzle. As a simplified approach, the force F can be estimated by the following equation;

$$F = P(\pi D^2/4)\, Hg = (\pi D^2/4)P$$

where ρ is the density of fluid, P the pressure induced, and g the acceleration due to gravity. The density of fluorinated fluid was taken as 1.430×10^3 kgm^{-3}, and the values of force and pressure are obtained as $F = 40$ μN and $P = 1.4$ kPa, respectively. In piezoelectric stimulation technique, to impose a periodic disturbance onto the jet issuing from a nozzle, typical pressures are reported to be about 0.5 MPa. The estimate for the proposed device is considerably lower, compared with the experimental data for widely used systems. The forces induced by EHD jet from the positive electrode may be effectively converted to vertical flow of the fluid column, although the nozzle is much thicker than the needle electrode. When the fluid column above the needle electrode starts to flow vertically, the fluid element in an annular space is subjected to upward traction. Therefore, continuous flow is maintained in DC fields.

The electric fields generated in the liquid column between the tip of the electrode and the nozzle are nonuniform and the lines of electric force are curved. However, the degree of nonuniformity may be larger in the liquid under the line connecting points A and B in Fig. 1, because the radius of curvature may be smaller. The EHD motion often occurs by the force in the direction perpendicular to the lines of electric force. The perpendicular motion is governed by the radius of curvature. Thus the upward flow in the nozzle can be explained by the force induced by the nonuniformity of electric fields.

The flow patterns of EHD convection is very complicated and strongly depends on the geometry of vessel, electrode arrangement, field strength, and fluid properties. The EHD flow can form cell structures consisting of a collection of small circulation. In a previous article,[13] we have reported the performance of fluid motors, which are composed of a rotor with a diameter of 2 mm and stator (cylindrical case) with diameter of 3~4 mm. The motors can rotate at speeds of 3,000~15,000

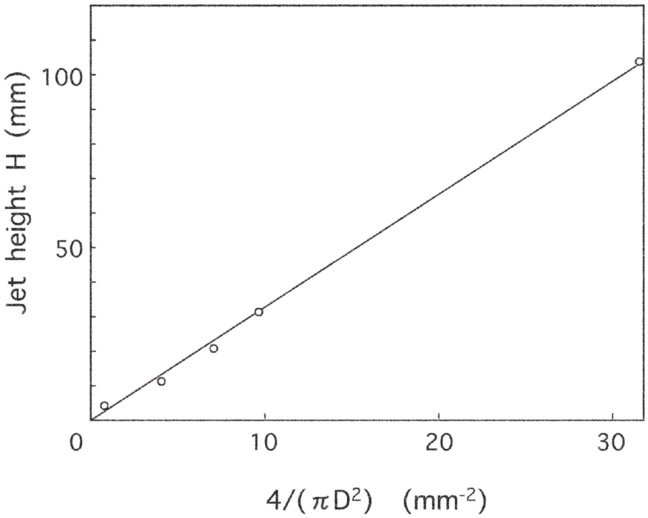

Figure 5. Jet height at 12 kV plotted against the reciprocal cross section of nozzle at zero distance.

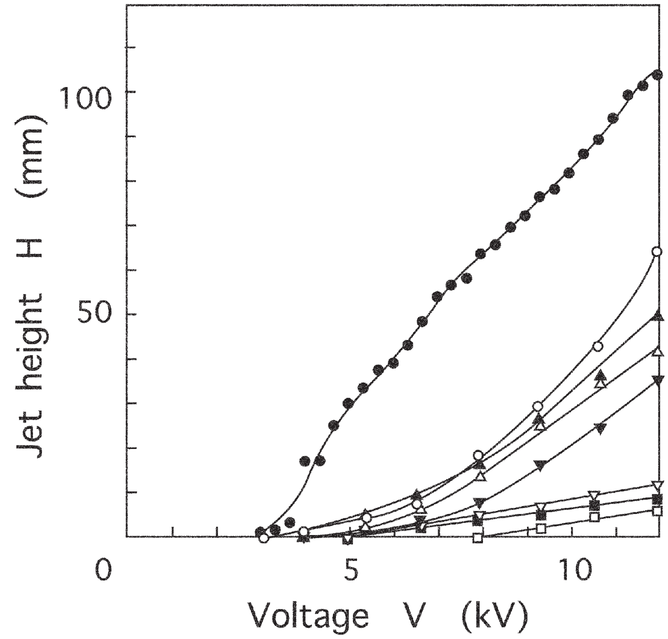

Figure 6. Jet height plotted against the applied voltage for various fluids; (▲) DBA, (○) DBS, (△) DBM, (▽) DOTP, (□) TA, (▼) TMPD, (■) TMPM, (●) FF-3.

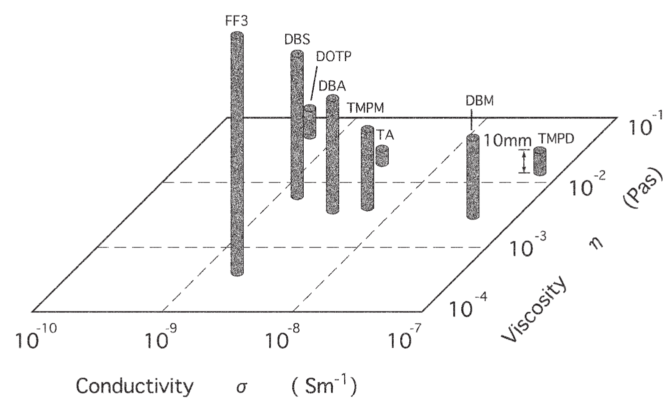

Figure 7. Jet height at 12 kV as a function of viscosity and conductivity for various fluids.

rpm. This implies that the high speed circulation takes place in the gap range of 0.5~1 mm. The volume of fluid in the motors is comparable to that in an ink jet nozzle.

Therefore, the domain size of EHD circulation may be about 1 mm. Since the jet height is less sensitive to the distance between the tip of electrode and bottom of nozzle than to the nozzle diameter, the EHD convection which develop into upward jet flow is induced near the electrode. The constant force independent of nozzle size can be attributed to the cooperative motion of fluid in the limited region just above the needle electrode.

Effect of Fluid Properties

A rapid reversible change in viscosity of fluids on the application or removal of electric fields is referred to as the electrorheological effect, and fluids exhibiting such an effect have come to be known as electrorheological or ER fluids. In previous studies,[11,12] we have reported that the pure fluids whose viscosity hardly changes in uniform fields between metal electrodes with smooth surfaces can be ER-active when subjected to nonuniform fields in electrodes, e.g., comprising flocked fabrics. For example, the viscosity is increased by a factor of 100 at a shear rate of 10 s^{-1} under an electric field of 4 $kVmm^{-1}$ for typical ER fluids. The ER effect arises from the EHD convection enhanced by the fibers on the electrodes. The ER behavior obtained by the use of electrodes with flocked fabrics can be summarized as follows: (a) The parameters determining the ER effect are the viscosity and conductivity of fluids. (b) The relative viscosity, defined as the viscosity of fluid in electric fields divided by that in the zero field, increases with decreasing fluid viscosity and conductivity. To establish the ink formulation for the ink jet mechanism proposed in the present study, it is essential to understand the EHD jet behavior as a function of material properties.

Figure 6 shows the jet height plotted against the applied voltage for various fluids. The experiments were carried out by the 0.2 mm nozzle at zero gap distance. For all fluids, the jet height shows a rapid increase above the critical voltage. Although the jet height at high voltages widely varies with the fluids, the critical voltages lie in the range of 3.0~5.0 kV except for TA. From Figs. 2, and 3, the critical voltage strongly depends on the nozzle geometry. Once the ink jet issues from the nozzle, the performance is determined by the physical properties of the fluid. In conditions where the rapid EHD convection is induced, the material functions play an essential role in producing the force across the free surface.

Figure 7 shows the jet height at an electrode voltage of 12 kV as a function of viscosity and conductivity for all fluids used in this work. The data were obtained at zero gap distance by the use of 0.2 mm nozzle. With decreasing viscosity and conductivity, the jet height increases as expected from the ER experiments. The ER effect in pure fluids with the electrodes comprising flocked fabrics can be attributed to the disturbance of EHD convective motion with periodic structure by external shear. Since the interactions or cooperative motion between EHD convection and applied shear require additional energy dissipation, the viscosity of liquids can effectively increase due to their combined effects. In EHD ink jet, the vertical force is exerted on the liquid column in the nozzle. The force in ink jet formation may be comparable to that required to maintain the domain structures under static conditions in the electrodes used for ER experiments. Similar dependence of ink jet height and ER viscosity on material functions indicates that both effects are controlled by the same mechanism. Although detailed experiments are required to establish the EHD dynamics quantitatively, we can reach very important conclusions, namely that the practical method of providing good inks involves reduction of viscosity and conductivity of medium fluid.

In practical application of EHD ink jet device, the engineering of fluids and nozzle geometry are essential in order to satisfy many requirements. The critical voltage can be reduced by the nozzle design and the height of the ink jet can be increased by the selection of material properties. Their combination may be critical to fabrication of high performance ink jet.

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