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Formation of liquid cone jet dependent on rise time of driving voltage

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ABSTRACT

This paper reports on transient dynamics of electrospray driven by high step voltage and its dependence on voltage rise time. Three rise times (50 ns, 1.8 μs, and 400 μs) were used to compare influence on liquid dynamics. It was found that, when the applied voltage exceeds a certain level, minute differences in voltage rise time significantly affect jet formation time. A rise time of 50 ns accelerates the jet ejection by about 20% compared with other rise times. These results indicate that optimization of rise time may enable drastic improvement of controllability of drop-on-demand electrospray.

1. Introduction

Atomization of liquid by application of high voltage to a liquid meniscus at a thin nozzle is known as electrospray, or electrohydrodynamic-spray, which has been deeply studied due to its broad applicability in fields such as space thrusters, chemical analyses, and thin film deposition [1–3]. Several spraying modes exist depending on electrical and hydrodynamic conditions [4–6]. Pulsation and cone-jet atomization processes, both highly controllable, are widely used in practical application. In these modes, meniscus of dripping liquid at the nozzle tip is deformed into a conical shape, called a “Taylor-cone” [7]. A thin liquid jet spit out from the apex of the conical meniscus is finally isolated to become charged micro-droplets owing to hydrodynamic instability [8]. Although mechanisms of conventional DC-electrospray and those of steady-state operation in AC-electrospray have been discussed and mostly clarified theoretically and experimentally [4–10], there exist few studies on transient behavior of the liquid meniscus [11,12]. This transient mode occurs in cases immediately after voltage application or when driven by pulsed voltages.

A number of novel applications such as a printing technology and microarray fabrication [13,14] require the highly repetitive drop-on-demand operation driven by pulsed voltages. Because of the pulsed voltage can be changed duty ratio optionally, ejection volume and repetition frequency are controlled individually and smaller ejection volume compared with conventional pulsation mode can be achieved. These advantages enable more flexible patterning. Recent research about drop-on-demand electrospray obtained only 18 kHz repetition frequency in maximum although commercially available piezoelectric inkjet printer obtained over 50 kHz driving frequency [15]. Thus, elucidation of the transient dynamics of electrospray is required. Drop-on-demand repetition frequency is determined by the time required to form the Taylor-cone from the beginning of the voltage application, which depends on several factors. Increase in applied voltage definitely reduces formation time [12], but it may change the spraying mode, which brings about depression of jet controllability. Literature regarding DC-spraying indicate that spray features are determined primarily by the relationship between dielectric relaxation time and hydrodynamic characteristic time, which is correlated to the Taylor-cone formation time [16]. Hence, the influence of the voltage rise time much shorter than these time constants has been thus far neglected [11]. Here, we report on the influence of voltage rise time on initiation of atomization.

2. Material and methods

A stainless steel flat-tip needle (NN-1838R, Terumo) with respective inner and outer diameters of 0.94 and 1.2 mm was used

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as a high-potential spraying nozzle. Ethanol was used as a test liquid and delivered to the needle using a syringe pump (PHD 2000, Harvard Apparatus) with a flow rate of 5 ml/h. The parameters of the ethanol are as follows: density is 790kg/m^3, viscosity is 1.2×10^{-3} Pa·s, surface tension is 22×10^{-3} N/m, electrical conductivity is 1.3×10^{-4} S/m, relative permittivity is 24. The relatively large diameter of the nozzle and the ethanol were selected in order to simplify the experiment and observation. An 80 mm diameter copper plate as a counter electrode was located 25 mm from the nozzle tip and grounded through a 1 MΩ internal resistance of the oscilloscope for current measurement. The voltage applied between the needle and the plate electrodes was obtained by subtracting voltage drops due to circuit components from the measured voltage using a probe (P6015A, Tektronix).

The nozzle was provided with a step functioned voltage with a variable rise time using a pulse circuit consisting of a DC high voltage power supply (HAR-30R10, Matsusada Precision), a 1 nF buffer capacitor, a MOSFET module (HTS 221-06, Behlke) and a register–capacitor combination (RC) circuit. Fig. 1 shows schematic of the experimental setup. Resistance and capacitance of the RC circuit were 10 kΩ or 1 MΩ and 100 pF, respectively. Rise times, defined as the time for the voltage to be from 10% to 90% of the final voltage, were 50 ns, 1.8 μs, and 400 μs.

A Q-switched Nd:YAG laser (Minilite, Continuum), a magnification projection optics, and a digital CCD camera were used to obtain a time-resolved microscopic image around the nozzle tip by means of the shadowgraph scheme. For the consistent initial condition of the meniscus at the voltage application, the position of the liquid surface was precisely monitored using a thin laser beam (He–Ne laser: V05LHR991, Suruga Seiki) which passed approximately 0.5 mm below the nozzle tip. The change in the photodiode signal due to laser beam interruption by dripping meniscus triggered the MOSFET switch of the voltage application circuit and the laser observation system.

3. Results

Fig. 2 shows typical behaviors of the ethanol meniscus from the beginning of the voltage application to the jet ejection for the different voltages of 4.86 (a), 4.75 (b), and 6.84 kV (c). Voltage rise time in these cases was 50 ns. The initial condition of the liquid surface at the beginning of voltage application (0.0 s) was consistent over every shot as described. Voltage amplitude is clearly found to be a most important factor in determining the behavior of the meniscus. 4.8 kV is the critical value to produce the Taylor-cone without meniscus oscillation, as shown in Fig. 2(a). The electric field strength at the nozzle tip is estimated to be 31 kV/cm in this condition [17]. Cone formation took approximately 4 ms. Fig. 2(b) shows voltage slightly less than the critical value, where the surface fluctuated up and down before constructing the cone. Conversely, voltages higher than the critical value constructed cones more quickly. However, much higher voltages altered the spraying mode to multi-jet mode, as shown in Fig. 2(c). The half angles of the Taylor-cone immediately before jet ejection were obtained by drawing tangential line at apex of the Taylor-cone in all pictures. The range of the half angle was approximately 30°–45°.

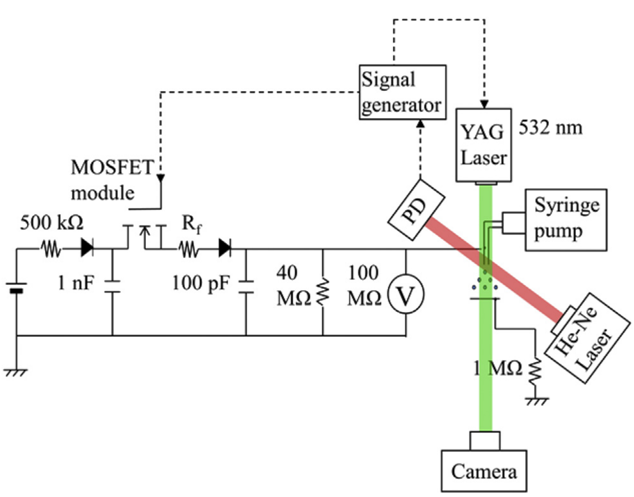

Fig. 1. Schematic of the experimental setup. R_f is inserted to get longer voltage rise time and it has three variations: 0 Ω, 10 kΩ and 1 MΩ. MOSFET module for the pulse generation circuit and YAG laser for optical observation are triggered by signal generator. Base time of the triggering is determined by monitoring system of meniscus condition.

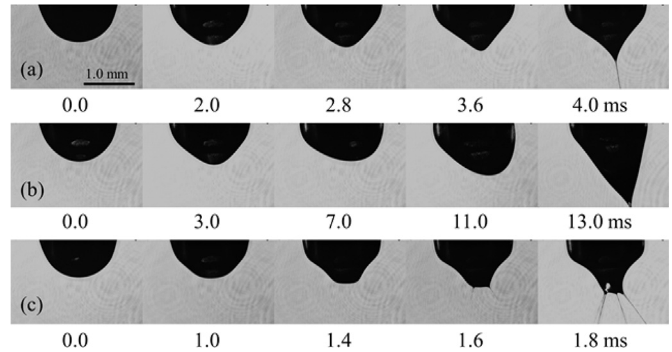

Fig. 2. Sequential images of the meniscus deformation for the different applied voltages of (a) 4.86 kV, (b) 4.75 kV, and (c) 6.84 kV. The voltage with a 50 ns rise time begins to be applied to a 1.2 mm-diameter nozzle at 0.0 ms.

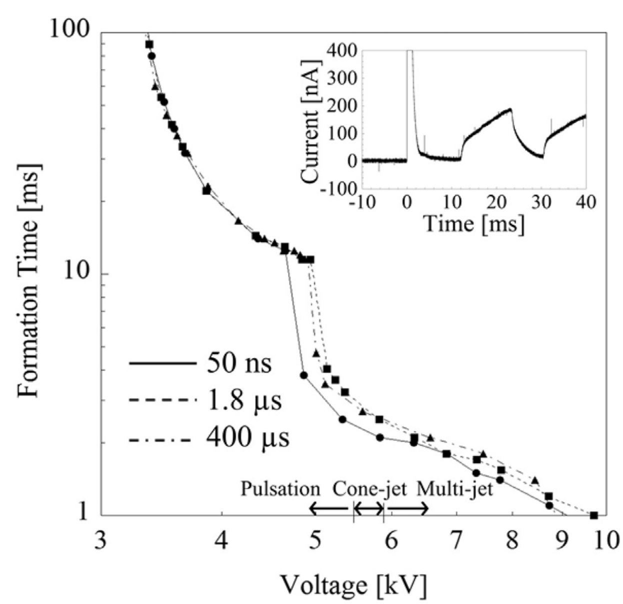

Fig. 3. Taylor-cone formation time as a function of applied voltage for different rise times of 50 ns, 1.8 μs, and 400 μs with typical current waveform. All data points express the mean value of ten independent measurements. Each rise time is subtracted from these formation time values. Data standard deviations are negligent within the symbols. The each range of voltage for spraying modes in DC driven is indicated above the horizontal axis. The current waveform shows the charging current immediately after voltage application and current pulses associated with jet ejection. The inset current waveform monitored under the conditions that the applied voltage was 4.66 kV and the rise time was 50 ns.