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Interaction of sequential pulsed electrohydrodynamic jets in drop-on-demand printing

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Abstract

A method is demonstrated for studying hydrodynamic effects in pulsed electrohydrodynamic (EHD) jetting, for the drop-on-demand printing of small droplets. The transient behaviour of pulsed EHD jets and the deposition of liquid on to a substrate were investigated by using an ultra-high speed camera (Shimadzu HPV-1) with a Newtonian aqueous liquid (water-glycerol). Time-resolved images of jets induced by two consecutive voltage pulses, with different time delays, were captured. Image analysis was used to determine the jet length, meniscus radius at the nozzle, and deposit volume in each case and revealed that the behaviour of an EHD jet depends strongly on the delay time after a previous ejection event. The effect originates in the time taken for the meniscus shape and position to recover to their equilibrium values and plays a critical role in the design of printing strategies for EHD drop-on-demand applications. It is possible that the maximum printing frequency achievable by pulsed EHD jetting can be increased by optimizing the drive waveform in order to accelerate recovery of the meniscus position.

Introduction

Electrohydrodynamic (EHD) jetting provides a method to generate ultrafine liquid jets and deposit small drops (sub-picoliter) through electrostatic forces. A potential is applied between the liquid in a narrow capillary tube and a grounded plane. When the pressure due to the electric force at the surface of the liquid exceeds that due to the surface tension, a charged liquid column is emitted from the apex of the distorted liquid meniscus[1, 2]. The behaviour of this EHD jet is influenced by the electric field, the static pressure in the liquid, and the physical properties of the liquid. This technique has many practical applications including sample injection for mass spectrometry[3], nano-encapsulation of drugs[4], and high-resolution printing[5].

EHD printing mainly utilises a transient cone-jet modulated by a pulsed voltage to achieve drop-on-demand ejection[5-8]. The effects of constant and pulsed bias voltages on Taylor cone formation have been studied[9]. The current waveform following potential switching has been studied to understand the dynamic response of the jet[10]. Fluid ejection and deposition following a single voltage pulse have been investigated together with the hydrodynamic and electrical phenomena inside the capillary[11-13]. Based on a scaling law[14] and the pulsating currents detected from the EHD jets, the use of a short voltage pulse superimposed on a constant lower bias voltage has been proposed to achieve high speed, high resolution printing[15].

Despite much research, the mechanism of EHD jetting is still not well understood. In pulsed EHD jetting in drop-on-demand mode, where a voltage pulse is applied to generate a single EHD jet, a discrepancy is found between the number of voltage pulses and the number of drops deposited[16-18], which limits its practical use for manufacturing applications. Moreover, these studies showed that only low frequency (O(10Hz)) repetitive jetting can be achieved. Here, we use an ultra-high speed camera to study the processes of pulsed EHD jetting in drop-on-demand mode and liquid deposition on to the substrate. Although time-resolved imaging of EHD jetting has been accomplished by others[19-22], most of these investigations relied on single-frame cameras and the sequence of EHD jetting events was deduced from separate images captured at different time delays from numerous different events. With this technique the volume deposited during each event must be estimated from the average droplet size from many events. In our study, the dynamics of transient EHD jets induced by two identical, consecutive voltage pulses triggered at different time delays were investigated with a high speed camera. In this way the drop volumes associated with individual EHD jetting events can be tracked and directly measured, and the interaction between successive events can be studied.

Experimental apparatus and procedures

The experimental setup is sketched in Fig. 1. A thin wall glass capillary (WPI US Micro-Tip, 30 μm internal tip diameter with a tolerance of $\pm 20\%$) is connected to an electrode holder with a wire emitter electrode inserted inside the capillary. The capillary is held perpendicularly with its end about 185 μm above a conductive grounded substrate. The other end of the capillary is directly connected to a hypodermic syringe barrel acting as liquid reservoir, attached with an inline membrane filter. The air pressure above the liquid is controlled by a pneumatic pressure controller. A three-axis motorized stage (Thorlab UK MAX313D) is controlled by a LABVIEW program.

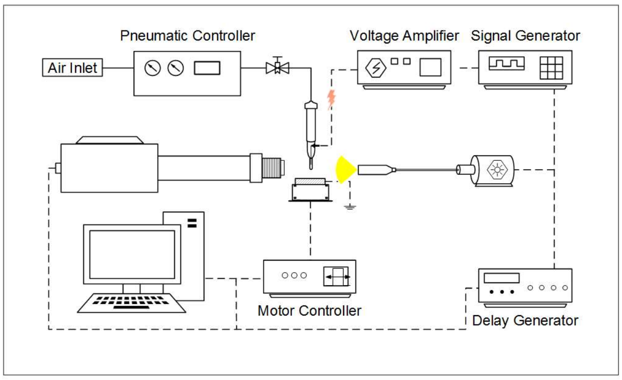

***Figure 1** Experimental setup for high-speed imaging of pulsed electrohydrodynamic jetting*

A high positive potential from a voltage amplifier (Matsusada, Japan, AMJ-2B10) modulated by a function generator (TTI, USA, TG2511A) is applied between the emitter and ground electrodes to generate the electric field. An ultra-high speed camera (Shimadzu, Japan, HPV-1), capable of recording 100 images at up to 1 million fps, was used to capture images of the jetting process via a long working-distance microscope (Navitar, USA, MVL12X12Z) with an extension tube (Navitar, USA, MVL20FA) and a 10× infinity-corrected objective lens (Mitutoyo, Japan, M Plan Apo). The backlit illumination was provided by a flashlamp with a duration of about 1 ms. The camera, the flash, and the function generator were synchronized through a delay generator (Stanford Research, USA, DG535). The liquid used in this study was a 40 wt% glycerol- 60 wt% deionized water mixture with viscosity and surface tension of 3.7 mPa·s and 68.0 $mN \cdot m^{-1}$ at 20 °C, respectively. The electrical conductivity and the dielectric constant were 12.6 $\mu S \cdot cm^{-1}$ and 68.8[23]. The pressure applied to the liquid reservoir was adjusted to 10 kPa to maintain a steady convex meniscus at the capillary nozzle. EHD jetting takes place when the electrostatic force outbalances the surface tension. Based on published guidelines[15], a short duration pulsed voltage superimposed on a constant bias voltage was used in this study. The bias potential V_b of +400 V was chosen to be small enough not to induce dripping, but large enough to maintain the Taylor cone. Furthermore, when applying a bias voltage, the effective surface tension[11] can be reduced to facilitate ejection at lower pulsed voltage. EHD jetting was then induced by the application of additional square pulses of +1280 V (i.e. V_p = +1680 V) with a duration of 100 µs. The value of the pulse voltage was chosen to generate a single EHD jet for drop-on-demand operation but was not so large as to induce multiple ejections[8, 15]. By setting a time delay between the consecutive voltage pulses, the interaction of sequential pulsed EHD jets can be studied.

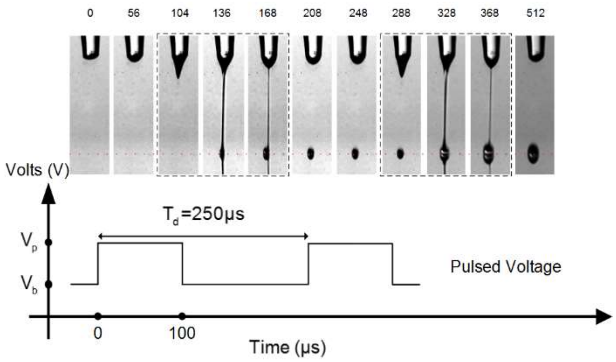

***Figure 2** Sequence of images (at times indicated in µs) showing jetting events resulting from the application of two voltage pulses with a time delay of 250 µs. V_p and V_b denote the pulse and bias voltage, respectively.*

Fig. 2 shows the effects of applying two identical pulses with a time delay T_d of 250 µs. The history of two consecutive EHD jets and their dynamics was captured with an 8 µs frame interval. The two jets shown in the sequence of frames at the top were generated by these two voltage pulses. The first pulse initiates the first sequence of meniscus distortion, Taylor cone formation, liquid ejection and meniscus relaxation. We can estimate the maximum current through the liquid jet from its diameter and the conductivity of the liquid to be 27 µA. This is very much less than the rated output current of the high voltage amplifier (10 mA) and the potential applied to the system did not change. The temperature rise in the liquid ligament due to Joule heating can be estimated as ca. 10 ℃ over the ejection time of 100 µs, too small to cause any significant effects. Similarly, there was insufficient electrical energy to cause significant electrolysis of the water or other electrochemical reaction. At a time of 250 µs after the start of the first pulse, the second pulse starts, generating another complete jetting cycle. In this case the time delay was not sufficient to allow the meniscus to recover its equilibrium shape before the start of the second pulse, resulting in a significantly greater volume in the second droplet than in the first.

Results and Discussions

From individual images of the EHD jets, the length of the jet and the volume of liquid deposited on the substrate can be measured. The length, measured from the nozzle tip to the distal end of the meniscus or liquid column and normalized by the gap between nozzle and substrate, is shown in Fig 3 where the normalized values 1 and 0 represent the positions of substrate surface and nozzle tip respectively.

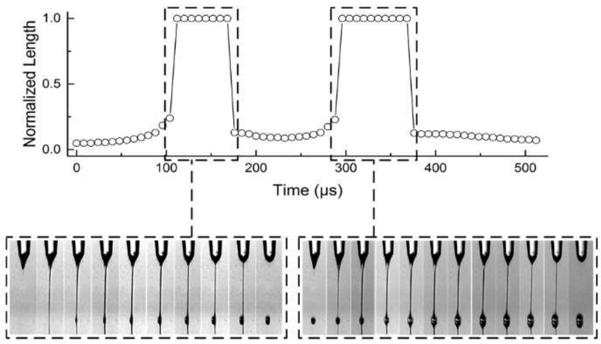

***Figure 3** Length of jet normalized by the nozzle-substrate distance plotted against time, for two voltage pulses with a delay of 250 µs.*

The tip of the meniscus extends relatively slowly at first, accelerating over a period of about 100 µs, and then as the jet forms the normalized length increases rapidly to 1 and the jet impinges on to the substrate. This occurs over a time period of one or two frame intervals, from which we can estimate the maximum speed of the jets to be of the order of 20 m/s. Using this method a series of jets was measured, created by pairs of consecutive pulses with delays (T_d) of 333, 250, 200, 167, and 143 µs. The results are compared in Fig 4. In these experiments only the time delay was varied and all other parameters were held constant. For all time delays, the first jets were very similar and occurred at a constant time of about 120 µs after the initiation of the first pulse. The formation of the second jet moves closer in time to the start of the second pulse as the time interval between the two pulses reduces. While there is little effect for T_d = 333 µs, the effect increases with reduced pulse gap so that there is only a small interval between the two jets for T_d = 167 µs. Only a single jet with a longer ejection time is formed for T_d = 133 µs. Moreover, the total ejection time (duration) of the second jet increases as T_d decreases. The explanation for this behaviour is that for short intervals the recovery time for the liquid meniscus from the first jet overlaps with the process of meniscus distortion and Taylor cone formation for the second jet. The second jet starts from a non-equilibrium meniscus position. The time and the electric force needed to initiate EHD jetting are thus reduced, and hence as the time delay is decreased a wider jet is produced, with longer ejection time.

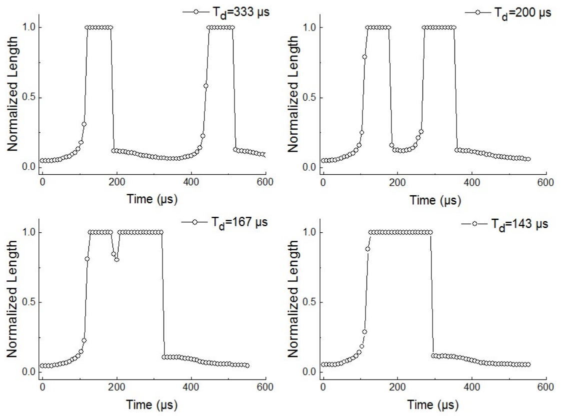

Figure 4 Normalized jet length resulting from pairs of voltage pulses with time delays of 333, 200, 167 and 143 μs.

The equilibrium shape of the meniscus can be approximated as a spherical cap attached to the nozzle, and the meniscus continues to have a near-spherical surface until just before the jet forms. The radius of curvature of the meniscus R was calculated from measurements of the width W and height H of the spherical cap, from the equation[24]

$$R = \frac{H}{2} + \frac{W^2}{8H} \qquad (1)$$

which is valid for $H \leq 0.5W$. Fig 5. shows how R changes as the meniscus distorts prior to jetting, and during its subsequent relaxation, for jetting with time delays T_d of 200, 250, and 333 μs.

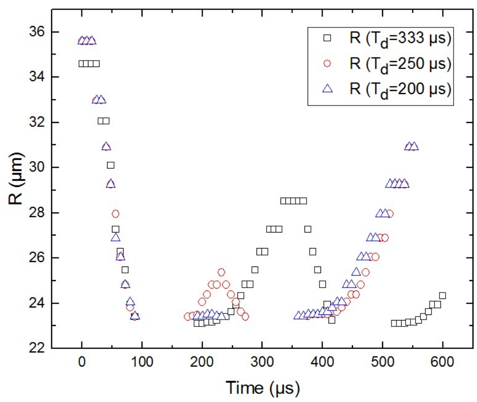

Figure 5 Radius of curvature of the liquid meniscus plotted against time, for the delay times indicated.

For the longest interval (T_d = 333 μs) the meniscus has not fully relaxed before the second pulse is applied, while for T_d = 200 μs the meniscus does not have time to flatten at all. These observations show how initiating a second pulse during the time taken for the meniscus recovery will change the timing and duration of the second ejection event. The interactions between the formation of EHD jets and the relaxation of the liquid meniscus after each jetting event, as shown in Figs. 4 and 5, imply a limit to the maximum frequency with which EHD jetting can be repeated. This may explain the discrepancy reported between the number of driving pulses and the number of EHD jets generated[16-18].

A direct consequence of reducing the time delay between pulses is an increase in the deposited volume. By measuring the height h and width w of the deposited droplets, the volume of deposited liquid V can be estimated from[25]

$$V = \frac{\pi h}{2}\left(\frac{h^2}{3} + \frac{w^2}{4}\right) \qquad (2)$$

Fig. 6 shows the volumes of liquid deposited on the substrate, plotted against the time interval (i.e. the time T_d – 100 μs). The measured outer diameter of the nozzle, 47.2 μm, was used to calibrate the magnification of the images. The nozzle was fully wetted, which avoided any variation in the base diameter of the EHD cone[13]. The droplet volumes from the first jet are effectively constant for all cases except for the shortest interval, when only one large drop was formed. For the longest time interval, the volume deposited from the second jet was almost the same as that from the first. As the time delay is decreased, there is a very significant increase in the liquid volume deposited from the second jet.

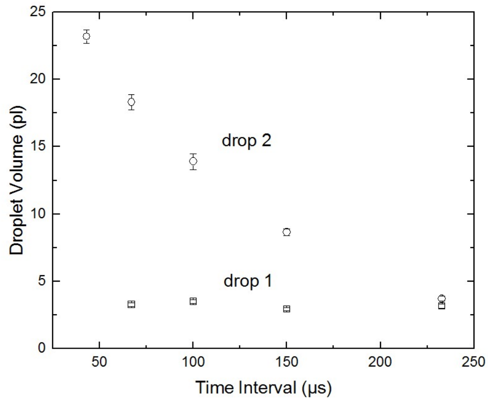

Figure 6 Volumes of the first and second drops generated by pairs of voltage pulses, plotted against the time interval between the pulses

Conclusion

We demonstrate here that pulsed EHD jetting in drop-on-demand mode can be achieved with voltage pulses of 100 μs duration and that repeated deposition of the liquid can be achieved at about 3 kHz. Also, the relaxation of the meniscus position after the formation of a jet plays a critical role in determining the ejected volume of a subsequent jet. The time needed to restore the meniscus can potentially limit how quickly the next jet can be ejected; the influence of these hydrodynamic effects must be accounted for in high-throughput drop-on-demand EHD printing. The results provide an explanation for the discrepancy between the number of driving pulses and the number of jets generated in pulsed EHD jetting in drop-on-demand mode previously reported [16-18]. Although we have studied only two drops in succession we can estimate the maximum frequency achievable in repeated jetting. If after some delay the first drop has no influence on the second, then we can argue that this will continue for further drops and hence a continuous stream of drops can be controllably produced. The smallest delay at which this occurred in our experiments was around 300 μs. Hence, the maximum stable frequency would be approximately 3 kHz. A significant change in ejected volume would be expected between 3 and 7 kHz. The replenishment of liquid to the nozzle may in principle further limit the maximum frequency, but did not play a role in these experiments. While recovery of the meniscus shape will depend on the liquid properties, our results suggest that it may also be possible to accelerate the process, and thus attain a higher maximum printing frequency, by designing the drive waveform to force the meniscus to regain its original shape more quickly. These experimental methods will facilitate fundamental understanding of the dynamics of pulsed EHD jetting as well as the development of drop-on-demand EHD jet printing. In further work this study will be extended to examine the effects of the shape of the drive waveform and of liquid replenishment on continuous pulsed jetting.

Acknowledgements

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