Experimental Study on Repetition Frequency of Drop/Jet Movement in Electro-Spraying of Deionized Water

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ABSTRACT

The electro-spraying process can be regular and periodic, consisting of cyclical phases of initiation (meniscus, drop, and/or jet), pulsation, deformation and separation. This paper presents an experimental study on the repetition frequency of drop and/or jet ejection from the capillary end with various spraying modes during an electro-spraying process of deionized (DI) water. The influence of operating parameters such as applied voltage, liquid flow rate, electrical conductivity (DI) and the number of emitters is considered. The time evolution of drop and/or jet initiation, pulsation, deformation and separation from the capillary tip or meniscus was captured and analyzed in detail in different spraying modes. The repetition frequency was calculated offline based on the time-resolved images captured by a high-speed camera and was found to be highly affected by the electrical strength and dependent on the spraying mode. This frequency firstly increased and then decreased with an increase in applied voltage. Peak frequency and the applied voltage were related and both correlated to the liquid flow rate. The repetition frequency was very sensitive to the applied voltage at a low volume flow rate. Particular attention was given to the electro-spraying characteristics of single, double and triple emitters. The similarities and differences are discussed.

Keywords: Electro-spraying; Repetition frequency; High-speed camera; Evolution; Spraying mode; Multiple emitters.

INTRODUCTION

Electro-spraying is a well-established technique that, by applying high voltage on the liquid surface at a nozzle (capillary) outlet, a drop or jet is formed, which further disintegrates into fine drops due to electric stresses. It offers several benefits compared to other atomization methods where trajectory and size of the fine drops could be controlled by varying the applied voltage and adjusting the liquid flow rate (Chen et al., 1999; Wilhelm et al., 2003; Mei and Chen, 2008). As a result, electro-spraying has been widely used in medical protein production (Gomez et al., 1998), painting and printing (Lee et al., 2013), film coating (Miao et al., 2002), fuel injection (Waits et al., 2010; Gan et al., 2015, 2016), micro- and nano-particles generation (Jaworek and Sobczyk, 2008; Gañán-Calvo et al., 2013), and particle collection (Kim et al., 2010; Jaworek et al., 2013; Chen et al., 2017).

Following the pioneering work of Zeleny (1917) on mechanism of electro-spraying, significant efforts have been made to better understand the electro-spraying mechanisms and modes (Hayati et al., 1987a, b; Chen et al., 2003). Taylor (1964) was the first to relate the conical shape of the electro-spraying to the hydrostatic balance between electrical force and the surface tension. Cloupeau and Prunet-Foch (1994) introduced the electro-spraying modes classification based on experimental observations. Based on their work, dripping, micro-dripping, spindle, multi-spindle, oscillating-jet, precession, cone-jet and multi-jet modes were defined (Jaworek and Krupa, 1999). During past two decades, substantial works have been reported to study the effect of various parameters on the formation, characterization and control of the spraying modes. Among such parameters are the liquid type (Delamora and Loscertales, 1994; Lopez-Herrera et al., 2003), surface tension (Sato et al., 1998; Samalikova and Grandori, 2005), liquid conductivity (Tang and Kebarle, 1991; Modesto-Lopez and Biswas, 2010), nozzle diameter (Kim et al., 2011; Zhang et al., 2012), applied voltage (Marginean et al., 2009), power supply (Sung et al., 2004, Higashiyama and Saito, 2013) and the liquid volume flow rate (Lopez-Herrera et al., 2003).

There is a large body of literature on the electro-spraying of liquids from capillaries. In most of the studies, electro-spraying is described as random and irregular; however, a
A few qualitative studies have indicated the spraying process could be somewhat regular and periodic (Sample and Bollini, 1972; Bailey and Borzabadi, 1978; Wang et al., 2017). A complete electro-spraying cycle usually occurs in a very short time consisting of meniscus deformation, pulsation and drop or jet separation from the capillary. The jet is then dispersed into fine drops. In most spraying modes, drops are usually ejected from the nozzle outlet randomly, and meniscus fluctuation could occur even with a constant applied voltage (Nguyen et al., 2014). The stability is a function of several parameters including nozzle geometry, electric field strength, and the flow rate (Lopez-Herrera et al., 2003; Inthavong et al., 2006). The drop or jet pulsation was also investigated in prior works (Alexandar et al., 2006; Higuera et al., 2014; Hijano et al., 2015). In the reported literature, the spraying modes were visualized by snapshot photos, handwritten sketches and stroboscopic technology, providing only snapshots for random events. With the development of laser measuring technology, time-resolved information on how electro-spraying initiates, develops and produces drops and/or jet from single capillary were able to be visualized (Kim et al., 2011, 2014). Although much work have been done, the evolution of the drop or jet and their relationship to the applied voltage and flow rate are still not clear. In a recent study of Kim et al. (2014), the effects of polarity, applied voltage and the gas environment on the stability of water electro-spraying were investigated. However, a complete periodic electro-spraying cycle where the meniscus, drop, or/and jet initiation, pulsation, deformation and separation from capillary occurs periodically is not fully understood.

In this study, time-resolved evolution of the deionized (DI) water electro-spraying was captured by a high speed camera under various operating conditions. The experiments were designed to allow detailed analysis on effects of the applied voltage and volume flow rate on the drop and/or jet separation frequency. Instability was also analyzed. In addition, the spraying pattern of a dual and triple electro-spraying heads configuration was investigated which has never been performed in the past. The study on evolution and cycle of electro-spraying modes could further our understanding on electro-spraying process.

**EXPERIMENTAL SETUP**

The experimental setup includes a liquid supply device, a high voltage power supply, a dispersion system and a high speed camera (Fig. 1). A glass syringe of 5.0 mL volume was used to feed the DI water to the nozzle. Both nozzles of Model 24G and 22G are used for single-nozzle electro-spraying, and Model 24G issued for multi-capillary electro-spraying. The capillaries were installed at the end of the glass syringe (Fig. 1). Table 1 summarized the parameters of two capillaries. The three capillary-plate configurations are: (1) one capillary, (2) double-capillary and (3) triple in a row. The capillary protruded 10 mm from a stainless-steel guard plate of diameter 100 mm bearing the same potential as that of the capillary. Liquid volume flow rate was moderated by an injection pump (Jiashan Ruichuang Electrical Inc., Model RSP01-B, maximum speed of 65 mm min⁻¹, and minimum speed of 1.0 µm min⁻¹) via a silicone tube. High DC voltage potential was applied to the stainless steel nozzle by a negative high voltage power supply (Tianjin Dongwen Inc., voltage 0–30 kV and current 0–2.0 mA). The ground electrode was connected to a collection plate of diameter 150 mm, 50 mm below the nozzle outlet. A high speed camera (MotionPro™ X4 puls) with microscopic zoom lens (Model NAVITAR12X, 12 times magnified) capable of 105 frames per second (fps), was used to capture time-resolved electro-spraying images. Captured images were analyzed off-line. The DI water properties were summarized were summarized in Table 2. The electrical conductivity was measured with a conductivity meter (Mettler Toledo), the surface tension

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**Fig. 1.** Experimental setup of electro-spraying.
Table 1. Parameters of capillary used in this study.

<table>
<thead>
<tr>
<th>Model of capillary</th>
<th>Inner diameter id (mm)</th>
<th>Outer diameter od (mm)</th>
<th>Length l (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24G</td>
<td>0.30</td>
<td>0.55</td>
<td>13.00</td>
</tr>
<tr>
<td>22G</td>
<td>0.40</td>
<td>0.70</td>
<td>13.00</td>
</tr>
</tbody>
</table>

Table 2. Properties of DI water samples used in this paper.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Density $\rho$ (kg m$^{-3}$)</th>
<th>Surface tension $\sigma$ (N m$^{-1}$)</th>
<th>Permittivity $\varepsilon$</th>
<th>Conductivity $K$ (S m$^{-1}$)</th>
<th>Viscosity $\nu$ (pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI water</td>
<td>999.0</td>
<td>0.072</td>
<td>81</td>
<td>$3.30 \times 10^{-4}$</td>
<td>0.00107</td>
</tr>
</tbody>
</table>

was measured by a surface tensiometer (Model JK99C, made in Shanghai), and viscosity was measured with a viscosimeter (Model NDJ-1, made in Shanghai). All experiments were carried out in atmosphere at room temperature of 15°C.

RESULTS

Time Resolved Spraying Mode

Based on meniscus, drop and/or jet formation pattern, the electro-spraying could be classified into dripping, spindle, pulsating, cone-jet and multi-jets modes, under combined effects of liquid property, applied voltage, volume flow rate and background gas property. The electro-spraying mode shape and behavior could shed light to better understand underlying physical mechanisms, and lead to more accurate controls. Figs. 2 to 5 displayed the time-resolved evolution of electro-spraying modes with single capillary. Detailed physical conditions to achieve each mode were given respectively.

Dripping Mode with Sibling

As shown in Fig. 2, following the drop detachment, nozzle meniscus contracted back to form a hemisphere. New spherical drop was slowly formed at the nozzle as a result of liquid accumulation. Time scale of nozzle drop formation is significantly larger than that of the falling. A complete cycle of the dripping mode is about 0.80 s or longer. The liquid thread could be formed between main drop and the meniscus at end of the nozzle. It broke off quickly under the effect of gravity and electrical forces, and frequently a sibling or satellite drop was observed accompanying the main drop in this mode. At a lower voltage, sibling drop may bounce up and down in space between the droplet and meniscus. At a higher voltage, the sibling drop first bounced up and down, and then ejected perpendicular to the capillary axis due to a repulsive force between the electrical field of the capillary potential and charge of the main drop (Fig. 2). The main drop fell down with a continuous deformation.

Micro-Dripping Mode

In micro-dripping mode (Fig. 3(a)), a fine drop (smaller than nozzle diameter) was ejected from a stable hemispherical ellipsoidal meniscus with delayed contraction following detachment. One or several satellite drops could appear. No further breakup of the fine drop was observed in the electrical field. Evolution of a complete micro-dripping mode cycle required considerably less time and the separation was significantly faster. In this mode, diameter of the drop was clearly smaller than that in the dripping mode due to an increased applied electrical forces. Varying the operating conditions, the micro-dripping mode with swing (Fig. 3(b)) was observed. The meniscus swings from one side to the other, and likely occurred in high electrical field. The swing motion was associated with corona wind (a few meters per second) caused by the momentum exchange due to collision between positive ions and the surrounding gas molecules.

Spindle Mode

For spindle mode I (Fig. 4(a)), an elongated fragmental meniscus, slightly narrower than the nozzle diameter, was slowly formed. Usually the spindle drop was tip at top and blunt at the bottom. The top was connected to the meniscus with a thin thread. When the thin thread broke off and was ejected into one or two satellite drops, the spindle drop could be crushed into an oblate shape (due to the repulsive forces generated by capillary potential) with a quick recovery. Agreed with Rayleigh instability (Wang et al., 2012), the elongated fragment was observed to further break up into finer drops of varying sizes during detachment from nozzle outlet. Occasional, elongation of the meniscus or the jet (before the detachment) was significantly longer, and broke into two parts, with distinctive spindle mode II as shown in Fig. 4(b).

![Fig. 2. The evolution of dripping mode.](image-url)
Jet Mode

With the increase of applied voltage, liquid ejected from capillary formed a jet, either in the oscillating-jet mode, precession mode or cone-jet mode (Jaworek and Sobczyk, 2008). In the present paper, due to larger surface tension, the jet was issued from the capillary end with intermittency.
(Fig. 5) and precession mode was not observed. In an oscillating-jet mode, a rotating oscillating jet was released and further disintegrated into varying sizes due to kink instability. In other cases, a thin and stable axisymmetric jet was ejected, and further dispersed into finer drops due to varicose and kink instability.

Of the common DI water spraying modes, precession and multi-jet modes were not distinctively observed in the current experiment. The present study was focused on the repetition frequency of a complete cycle consisting of the meniscus, drop or jet deformation, separation from capillary end in an electro-spraying process. A comparison between the single, dual and three emitter setups, which has never been studied in the past, was performed. The repetition frequency was calculated offline from the time-resolved images containing a minimum of 30–50 cycles (Kim et al., 2014).

Drops Size of Different Modes

The mean diameter of drops could be measured using electro-spraying images by software i-speed viewer. Each drop of mean values of long axis and short axis could be considered drop diameter due to drop deformation when falling down. The arithmetic mean diameter could be described as:

$$D_{\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} D_i$$  \hspace{1cm} (1)

where, $N$ is the total number of drops, $D_i$ is the diameter of the individual drops.

Different drop size distribution was observed in different electro-spraying modes, and the drop diameters decrease with an increase of applied voltage, (Fig. 6). A flow rate of 10.0 µL s$^{-1}$ was analyzed in present study. When the applied voltage is less than 6.0 kV, the spraying mode was dripping and the diameter of drops is larger than 1.0 mm. At applied voltage of 5.5 kV, a main drop with a significantly smaller satellite drop could be ejected from the capillary end. When the applied voltage increased to 6.0 kV, a sharp decrease in drop diameter was observed due to spraying mode transition from dripping to micro-dripping or spindle mode. As applied voltage continue to increase, the drops diameter further decreased at a milder rate. One or several satellite drops formed at the liquid thread could be observed. They usually have smaller diameters than main drops. With an increase in applied voltage, liquid ejected from capillary formed a jet. The diameter of the jet was between 30 µm to 70 µm, and the diameter of the drops at the end of the jet was only a dozen microns. The jet could further disintegrated into varying sized drops due to kink instability. The main drop at the end of jet could be formed at about 100 µm to 150 µm due to larger surface tension force of DI water. The satellite drops had similar diameter with the jet. The flow rate also affected the diameter of drops and lower flow rate could generate smaller drops.

Voltage on Repetition Frequency

Repetition frequency versus the applied voltage at two liquid volume flow rates (1.0 and 10.0 µL s$^{-1}$) in the nozzle (Model 24G, $odi/d=0.55/0.30$ mm, $l=13.00$ mm) was examined (Fig. 7). The measurement of Kim et al. (2014) was plotted for comparison. Though with a lower volume flow rate and a narrower bandwidth (of the applied voltages), the variation trend agreed with the current measurement. The present study provided additional detail on the repetition frequency at higher applied voltages (> 6.0 kV) which were distinctive from the pattern observed under low electrical strengths ($\leq$ 6.0 kV). In absence of an applied electrical potential, only one singly drop of diameter 2675 and 3630 µm

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**Fig. 6.** The drops diameter distribution versus applied voltage.
Fig. 7. Repetition frequency for single nozzle.

were emitted from the capillary end with a repetition frequency of 0.10 and 0.40 Hz at a volume flow rate of 1.0 and 10.0 µL s⁻¹ respectively. Under low electrical strength (< 5.0 kV), the repetition frequency slightly increased with an increase in the applied voltage, however, the size of the drop was decreased. At an applied voltage of 5.0 kV, the repetition frequency was 1.1 and 3.1 Hz, and the diameter of the singly drop was 1350 and 1834 µm, respectively. At low electrical strength (< 5.0 kV), the repetition frequency of the electro-spraying was sensitive to the volume flow rate. An extremely low repetition frequency (frequency < 1.0 Hz) was observed for the electro-spraying at a volume flow rate of 1.0 µL s⁻¹. At a volume flow rate of 10 µL s⁻¹, the observed repetition frequency was slightly higher, however, still below 5.0 Hz. Contribution of the current study was the information on repetition frequency versus the applied voltage higher than 5.0 kV, which has not been fully studied in the past. Therefore following discussion was focused on the measurement with the electrical voltage higher than 5.0 kV.

It was shown in Fig. 6 that the repetition frequency of then drop and/or jet separation from capillary in the electro-spraying experienced a steep rise in the vicinity of an applied voltage around 5.0 kV, reaching a peak and then declined as the electrical strength increased further. At a volume flow rate of 1.0 µL s⁻¹, sharp rise of the mode frequency occurred from 5.5 to 7.0 kV, followed by a steady decline from 7.0 to 17 kV at a relatively slower rate. Inversely related to the sharp rise of the repetition frequency, size of the electro-spraying drop was reduced with an increase of the applied voltage from 5.5 to 7.0 kV. The phenomenon could be attributed to a combined effect of the enhanced electrical attraction between the collection plate and the liquid drop at the nozzle outlet, and the reduction in liquid surface tension due to an opposite electrostatic pressure to the capillary (Cloupeau and Prunet-Foch, 1994). When applied voltage is higher than 7.0 kV, it takes much more time to finish a complete cycle which consisting of a longer meniscus and/or jet accompanying with deformation, oscillation and rotation. The repetition frequency started to decline. At a feeding rate of 1.0 µL s⁻¹, for an applied voltage of 5.5 kV, the electrified meniscus was in dripping mode. The frequency was very low due to larger volume of drop. When the applied voltage increased from 5.5 to 6.0 kV, the repetition frequency increased from 1.0 to 455 Hz, and the electro-spraying mode changed from dripping to micro-dripping. The maximum repetition frequency of 555.8 Hz was achieved at 7.0 kV, and a complete electro-spraying cycle including liquid accumulation, cone formation, drop ejection, and relaxation was observed. With an applied voltage increase from 8.0 to 10.0 kV, the electrical force applied to the meniscus was also increased, leading to a larger mass content but a lower repetition frequency due to longer time to replace the displaced liquid. As the applied voltage was increased to the range 10.0 to 13.0 kV, the cone exhibited oscillating motion around the capillary axis, and liquid drops were ejected from both sides of the capillary. Stability of the meniscus was further reduced with the increased electrical strength. An up and down oscillating of the cone was also observed. It took longer to complete a full electro-spraying cycle. With a further increase in applied voltage, the repetition frequency decreased. As the applied voltage reached to the range between 14.0 and 16.0 kV, a regular axisymmetric liquid cone was ejected from the nozzle either as linear sides, convex or concave due to negative corona discharge. In this case, the thin jet could not be observed clearly due to insufficient feeding of liquid at 1.0 µL s⁻¹. Waverly jet surface was observed under the effect of corona wind (Jurashcek and Röllgen, 1998).
At a feeding rate of 10.0 µL s⁻¹ (Fig. 7), repetition frequency was increased in the voltage range from 5.5 to 9.5 kV. The repetition frequency started the decline at 9.5 kV. In general, the repetition frequency at 10.0 µL s⁻¹ was lower than that of 1.0 µL s⁻¹ when the applied voltage was lower than 8.5 kV. Beyond 8.5 kV, repetition frequency was higher at larger volume flow rate. This might imply a transition from the feeding time dominating to an electro-hydrodynamic equilibration dominated process. From 5.5 to 6.5 kV, dripping mode was displayed. Between 6.0 to 6.5 kV, the repetition frequency had a sharp increase from 26 to 227 Hz. At a higher flow rate of 10.0 µL s⁻¹, meniscus volume and surface area were clearly larger to increase the compensation for lost fluid. Different from the low volume flow rate of 1.0 µL s⁻¹, peak repetition frequency of 10.0 µL s⁻¹ lasted longer in the range from 6.5 kV to 12.0 kV. Maximum repetition frequency of 332.5 Hz was observed around 9.5 kV. When the applied voltage was further increased from 10.5 to 13.0 kV, oscillating and cone modes were observed. A complete cycle from meniscus pulsation, growing up, and ejecting from the capillary would spend longer time than spindle drop separating from the nozzle.

**Effect of Volume Flow Rate on Repetition Frequency**

To investigate effect of flow rate on repetition frequency, several volume flow rates and applied voltages were included in the study. The electro-spraying processes were captured and analyzed, and the repetition frequencies were presented in Fig. 8. Fig. 8 clearly showed that, at low volume flow rate, observed repetition frequencies was more sensitive to applied voltage. On the other hand, negligible variation in repetition frequency was observed at higher flow rate. Fig. 8 indicated that the applied potential dominated the repetition frequency at smaller volume flow rate, while the volume flow rate dominated the repetition frequency at larger volume flow rate.

Effect of the volume flow rate on electro-spraying pattern was illustrated in Fig. 9 under four different voltages. Meniscus or jet deformation, pulsation, and separation were observed in all cases in a full cycle. At 7.0 kV, a drop with diameter about 60 to 190 µm was ejected with pulsation at a volume flow rate of 1.0 µL s⁻¹. As the volume flow rate was increased to 5.0 µL s⁻¹, meniscus was elongated to an inverted cone (Fig. 9(a)). After detachment, a main and two satellite drops were further developed. Similar process was observed at a flow rate of 10.0 µL s⁻¹. At a flow rate of 15.0 µL s⁻¹, a longer meniscus or jet was formed. The number of satellite and main drops were increased with an increase in flow rate. Sample images of meniscus or jet separations and pulsation for applied voltage of 9.0 kV were shown in Fig. 9(b). Length of the thread and main drop diameter steadily increased with an increase in volume flow rate. The micro-dripping mode and spindle mode were observed in Fig. 9(b). As the applied voltage increased to 11.0 and 13.0 kV, drop separation process (Figs. 9(c) and 9(d)) were very similar to that of the 9.0 kV, in which micro-dripping, spindle, oscillating-jet, precession and cone-jet mode might occur and entangle with each other not easily distinguishable. The elongated thread was off capillary axis, swinging, vibrating, and rotating due to the electrical forces and surface waves. The varicose or kink instabilities were enhanced, leading to disintegration in both sides of the capillary axis. Similarly, larger volume flow rate implied longer time to complete the full electro-spraying cycle.

**Effect of Conductivity on Repetition Frequency**

NaCl solution with different concentration was also studied in present work. The properties of the NaCl solutions were listed in Table 3. Fixed flow rate of 5.0 µL s⁻¹ was enforced in the experiment. Repetition frequencies for
NaCl solutions with different concentration were shown in Fig. 10. It is observed in Fig. 10 that the repetition frequencies at all concentrations were similar. In the dripping mode, the frequency was usually lower than a few Hz. A sharp increase was observed due to transition from dripping to micro-dripping mode. The frequency appeared to reach a peak and then declined as the electrical strength increased further. It is clearly shown that the conductivity had negligible effect on jet and/or drop formation, separation processes from the capillary. It might be interpreted by the time of constant of the jet formation together with the electrical relaxation time constant (Jaworek and Krupa, 1999). The time of constant of the jet formation is describe as,

\[ \tau_j = \frac{\mu D_0}{\sigma} \]  

(2)

where \( \mu \) is the viscosity of liquid, \( \sigma \) is the surface tension, and \( D_0 \) is the characteristic distance defined as the internal diameter of the nozzle.

The electrical relaxation time constant, characteristic time of charge transport in the liquid, is defined as,

\[ \tau_e = \frac{\varepsilon}{K} \]  

(3)

where \( \varepsilon \) is permittivity of liquid, and \( K \) is the conductivity.

The Results for Two Capillaries

The repetition frequency versus applied voltage for the dual capillaries was showed in Fig. 11. Trend of the variation agreed with Fig. 7 for the single head setting. It was clearly shown that the repetition frequency firstly increased and then decreased for both side of nozzles with increasing of volume flow rate. For both flow rates, there was a peak frequency corresponding to the same voltage for both left and right nozzles. The peak frequency at 10.0 µL s⁻¹ volume flow rate was reached with applied voltage being 7.0 kV. The corresponding spraying mode was dripping with sibling. At 20.0 µL s⁻¹ flow rate, peak repetition frequency occurred when the applied voltage was 11 kV. The corresponding spraying mode was spindle mode. Fig. 12 showed a complete cycle of meniscus or jet deformation, pulsation and separation...
Fig. 10. The repetition frequency for NaCl solution with different conductivity.

Fig. 11. Repetition frequency with applied voltages for double capillaries (volume flow rate for each nozzle).

for double capillaries at a volume flow rate of 5.0 µL s⁻¹ in the left nozzle. Four typical spraying modes were observed, which are tilted dripping, spindle, and jet mode, respectively. In order to observe and analyze the electro-spraying mode, the left capillary was chosen for analyzing the evolution of the different modes in electro-spraying. It is clearly observed that drop ejecting direction was not perpendicular to the nozzle axis. The smallest angle between the two directions was observed in dripping mode, while the largest was in cone-jet mode. This is associated with the repulsive forces between the two-capillary and the drops or jets respectively.

1) Dripping Mode

In a tilted dripping mode, the main drop was gradually formed with liquid accumulation at the capillary end. A thin thread was connected to the main drop and meniscus was formed and broke off due to electrical and gravitational forces. In the cycle, drop separated from the left nozzle caused the meniscus vibrate, swing, and affected the right drop in a similar manner (Fig. 12(a)). Similar to single capillary, time scale of drop formation was significantly longer than that of the falling. During drop formation, an angle between the direction of ejection and the capillary axis
II) Spindle Mode

At an applied voltage of 6.5 kV (Fig. 12(b)), the spindle mode might occur similarly to the single capillary. A spindle drop with tip on top and blunt at the bottom was ejected from the capillary at a certain angle relative to the nozzle axis. A thin thread between meniscus and the drop was elongated and broke off over time. A main and satellite drop could be formed. The main drop and satellite drop bounced off from each other like two colliding billiard balls due to repulsive forces during the course of falling. The angle between the direction of drop movement and the nozzle axis was in the range from $16.7^\circ$ to $28.2^\circ$.

III) Jet Mode

With the applied voltage continue increasing, the liquid ejected from the capillary were elongated into a jet, forming the pulsating or oscillating-jet, and the cone-jet as shown in Figs. 12(c) and 12(d). The ejected direction of the jet always formed an angle with respect to the nozzle axis. The pulsed, oscillating-jet, and cone-jet mode could be observed under certain operating conditions (usually in range of high applied voltage). At the same time, irregular jets could form. The irregularities usually appear with an unpredictable geometry, disintegration, and dispersion.

The Results for Three Capillaries

The repetition frequency for three capillaries in a row was showed in Fig. 13. Similar trend of variation (between the repetition frequency and applied voltage) to the single and the double emitters was shown. The repetition frequency firstly increased, and then decreased with an increase of the applied voltage. The repetition frequency of the middle nozzle was significantly lower at an applied voltage smaller than 13.5 kV. Beyond 13.5 kV, all three nozzles displayed similar repetition frequency.

The electro-spraying modes of three capillary were dripping, spindle, and irregular jet. At low voltage of 5.0 and 6.0 kV, the dripping mode was observed in all emitters. A drop was slowly emitted with an average diameter in the range from 1820 to 1380 µm. The repetition frequency for middle nozzle was slightly lower than the other two nozzles.
So did the drop size. This could be attributed to the space distribution of the electrical strength. The meniscus, thread, or drops hanging on the left and right nozzles always skewed away from the middle due to repulsive forces. For the same reason, the middle nozzle drop was directed along the nozzle axis. As the applied voltage exceeded 20.0 kV, angles between the left and right thread was increased to 90° (at 15.0 kV) to 100° (at 20.0 kV). For the voltage from 15.0 to 20.0 kV, elongated thread from the left and right nozzle was always separated from edge of the capillary and appeared to be varicose and linear. Thread from the middle nozzle was always a straight line, and broke into a main drop with several satellite drops, which might merge into the main drop at a later time.

CONCLUSIONS

The full cycle of meniscus or jet initiation, deformation, pulsation and ejection of DI water electro-spraying were observed and discussed in this study. The typical modes such as dripping, spindle and jet mode were observed in order with applied voltage increased for a fixed flow rate. These electro-spraying modes were classified for the single and multiple emitters based on meniscus and jet configurations or dispersed forms. Irregularities of mixed modes with random shape, disrupted jet process and intermittencies were also observed however not focused in the current study. Irregularities were observed more in the multiple emitter settings. Each nozzle may appear differently or have the same modes simultaneously or alternatively.

The repetition frequency of meniscus or jet deformation, pulsation and ejection of electro-spraying was calculated based on time-resolved images. The repetition frequency was closely related to the applied electrical strength that, it firstly increased and then decreased with an increase in applied voltage. A consistent trend was observed in single, double and three nozzle setups. Peak frequency varied under different conditions and was found to be related to a combined effect of applied voltage, nozzle feeding rate, nozzle numbers. The repetition frequency was mainly determined by applied voltage, flow rate, and not affected by conductivity. For single nozzle, the repetition frequency was dominated by the applied potential at low flow rate (< 15 µL s⁻¹), while the repetition frequency was dominated by volume flow rate at larger ones. For double-capillary, the repetition frequency of right and left nozzle appears the same variation due to symmetrical electrical strength distribution. For three nozzles, the repetition frequency for middle nozzle was slightly lower than the other two nozzles. It is concluded that the repetition frequency of drop or jet separating from the capillary could be controlled by varying applied voltage and flow rate.

The full cycle of meniscus or jet initiation, deformation, pulsation and ejection of DI water electro-spraying was observed and discussed in this study. Typical modes such as dripping, spindle and jet mode were observed while increasing applied voltage for a fixed flow rate. These electro-spraying modes were classified for single and multiple emitters based on meniscus and jet configurations or dispersed forms. Irregularities in mixed modes with random shapes, disrupted jet processes and intermittencies were also observed; however, this study does not focus on them. More irregularities were observed with multiple emitter settings, in which individual nozzles may use unique modes or share modes simultaneously or alternately.

The repetition frequency of meniscus or jet deformation, pulsation and ejection of electro-spraying was calculated based on time-resolved images. This frequency was closely related to the applied electrical strength in which it firstly increased and then decreased with an increase in applied voltage. A consistent trend was observed in single, double
and triple nozzle setups. Peak frequency varied under different conditions and was found to be related to the combined effects of applied voltage, nozzle feeding rate and nozzle count. The repetition frequency was mainly determined by applied voltage and flow rate; it was not affected by conductivity. With one nozzle, the repetition frequency was dominated by the applied potential at low flow rates (< 15 µL s⁻¹), while at higher rates, the repetition frequency was dominated by the volume flow rate. With two nozzles, the repetition frequencies of the right and left nozzles appeared comparable due to the symmetrical distribution of electrical strength. With three nozzles, the repetition frequency of the middle nozzle was slightly lower than that of the other two nozzles. We conclude that the repetition frequency of drop or jet separation from the capillary can be controlled by varying the applied voltage and the flow rate.

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