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The Effect of Charge Density on Electro-Sprayed Droplets

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Abstract: This paper illustrates the variation in the droplet size with the change in the parameters like voltage, flow rate and electrode spacing when a charged liquid column is made to discharge in ambient conditions. The experimental set up consists of a capillary needle with a ground electrode, which causes the atomization to take place. Image processing techniques were used to determine the droplet size. A series of experiments were conducted with water as the working fluid for flow rates of 3.75 ml/min and 4.6 ml/min. The voltage used for the generation of spray was raised from 2 kV to 4.5 kV. The atomization quality improved with increasing the applied voltage and deteriorated with an increase in the liquid flow rate as well as with the increasing of the distance between the electrodes. The atomization process was also studied by placing a capacitor in the circuit. It was observed that better quality of atomization, without the ground electrode, could be obtained at lower voltage with the introduction of a capacitor in the circuit. This reduces the need of higher working voltage as well as simplifies the overall system by eliminating the requirement of a ground electrode. Furthermore, this study shows that the atomization quality is a function of charge density of the charged liquid column and the droplet size varies as the inverse of the square root of the charge density.

Keywords: Electrostatic atomization, droplet generation, charge density.

INTRODUCTION

Electrostatic atomization is a process in which a liquid jet is dispersed into many droplets due to the action of electrical forces. Applications where electrostatic atomization plays an important role are colloid thrusters, spray painting, ink jet printers, emulsion formation, aerosol generation, thin film coating, etc [1].

Electrostatic sprays are self dispersive and they can be controlled electronically. The mechanism that controls the atomization of charged liquids has not yet been determined conclusively but several have been proposed. No perfect theory has been developed for high-speed jets whereas some theoretical understanding of low speed jets have been developed [1]. In the normal state, the jet coming out of a small diameter needle is disintegrated as droplets and scatter after a small distance from the orifice due to the increased kinetic energy that overwhelms the surface tension forces acting on the jet. When high voltage is applied to the needle, there will be a transformation of the jet. The charge that is transmitted to the jet by a high voltage supply is taken by the liquid and causes a strong repulsive force to act within the liquid column, which cause the jet to scatter after a certain distance from the orifice due to electro-hydrodynamic instability. But if an electrode of opposite polarity is brought near the charged jet, it causes the jet to scatter more because of the concentration of opposite charge which causes the jet to pull apart and cause atomization. The tendency of the electrically atomized droplets is to coalesce after a certain distance when the potential between the droplets gets reduced. The point where the divergence of the jet begins depends on the experimental conditions. The research regarding the understanding of the physics of the electrostatic spray was focused on this aspect of electrostatic atomization [2-6].

The study of electrostatic atomization needs the knowledge of electro hydrodynamic surface stability. The field induced motions lead to deformation of interface and these motions depend on the type and amount of electric field applied and these also lead to several dynamic effects on the liquid interface which affect the jet behavior and drop formation. The droplet formation from capillary tube is generally achieved due to Rayleigh instability [7]. There is equilibrium between surface tension, hydrostatic and electrostatic forces at the surface of the film. The interaction between the electric field and the liquid jet coming out of the capillary tube causes an unstable wave to grow and eventually leads into formation of small drops. In the case of electrostatic atomization, the break up of jet takes place when the electrostatic force generated is higher than the surface tension force of the jet. Depending on the flow rate and the strength of electric field, different spraying modes can occur such as dripping, spindling, simple jet, multi jets, and ramified jets. These modes of electrostatic atomization also depend on the liquid being atomized, the capillary tube diameter, the distance between the capillary tube tip and the ground electrode and the liquid properties like the surface tension, electrical conductivity, density, and viscosity [3]. The dripping mode is obtained when the electric field and the liquid flow rate are too low. The transition from dripping mode to spindle mode takes place when the liquid flow rate is increased and the droplet size is reduced. With further increase in flow rate, fully developed jet is obtained [4]. The tendency of the surface tension forces is to restore the jet in to spherical drops.

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The electric field introduces a force in opposite direction leading to electro-hydrodynamic instability of the jet [5]. The frequency of fluid instability is a function of the change of electricity in the electric field and the droplet size produced due to the dispersion of the jet depends on the wavelength of the unstable waves [6].

The current carried by the electro spray is a function of liquid properties and flow rate as well as the dielectric constant of the medium [8 -16]. Ganan Calvo *et al.* [14] have studied the electrostatic atomization of a very low flow rate (order of 0.1 ml/min) charged liquid column subjected to fairly high voltage (4.5 kV) and have proposed some scaling laws relating the droplet diameter with the flow rate and the electrical properties and fluid properties. Gomez and Tang [9] have studied the electrostatic sprays for a fluid flow range of 0.25 ml/h to 28 ml/h for applied voltage ranging from 3.0 to 5.4 kV and have reported the mean droplet size as high as 100 μm for 28 ml/h flow rate subjected to 3.6 kV. Balachandran *et al.* [12] have studied the atomization of a fully developed liquid jet (flow rate 3.7 ml/min) subjected to 7 kV dc voltage and have reported a poly-dispersed spray with droplet size ranging from 50 μm to 650 μm. The present study focuses on the initiation of atomization process in an electrically charged simple water jet [4] and its dependence on the liquid flow rate and inter-electrode gap as well as tries to elucidate the effect of charge concentration due to the presence of a capacitor in the circuit.

EXPERIMENTAL PROCEDURE

The schematic of the experimental set up used in this study is shown in Fig. (**1**). The set up mainly consists of a liquid feed system, a metallic needle, high voltage power supply, ground electrode, a CCD (Charged Coupled Device) camera and a diode laser source with collimating optics. Water was used as the atomizing liquid for this study. The flow rates of water used for the characterization were 3.75 ml/min and 4.6 ml/min.

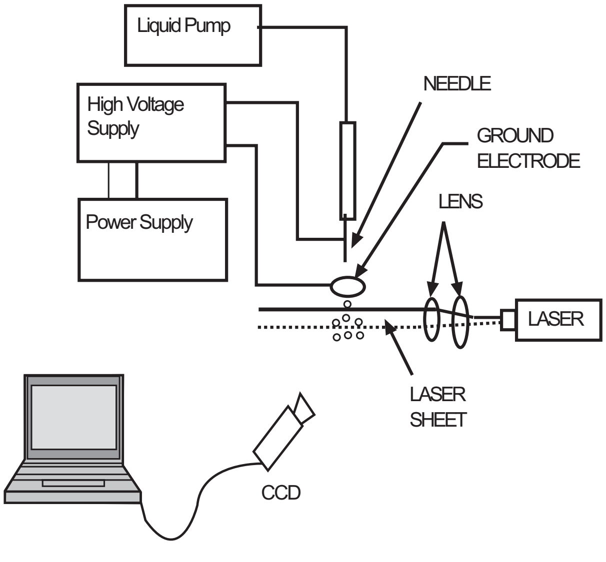


Fig. (1). Schematic of the experimental setup.

A high voltage output DC-DC converter was used as the main voltage supply that converts an input voltage between 4 V to 30 V (supplied from a APLAB® DC power supply) to a very high voltage output in the order of kV DC. A schematic of the power supply circuit is shown in Fig. (**2**). The average output voltages from the power supply were measured to be equal to 0.88 kV and 3 kV for input voltages of 4V and 12 V respectively. The device essentially works by chopping the input DC voltage at the designed frequency, and applying this to the transformer to step it up to some intermediary high voltage. Then, there is a voltage multiplier portion of the circuit, which further multiplies as well as rectifies the transformer output to give the desired high DC voltage output. The circuit is wired on a specially designed printed circuit board. The whole device is quite rugged and has been tested extensively. This high voltage is applied between the needle tip and the ground electrode. The current output from the power supply and the average voltage across the terminals were measured using a Protek® 506 digital multimeter. A 1000:1 voltage reduction probe was used to measure the average voltage at the capillary end.

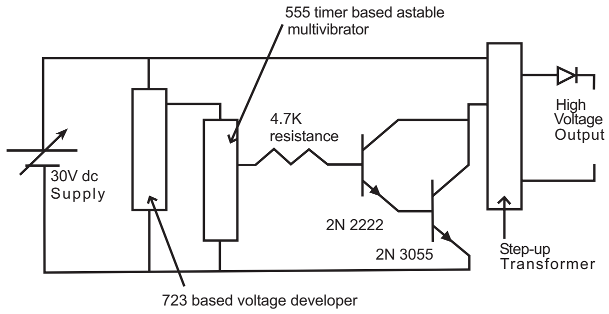
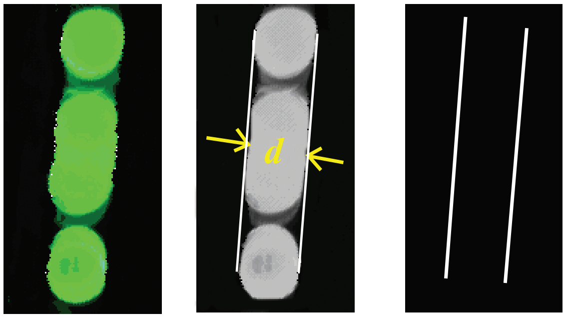


Fig. (2). Circuit diagram of the High Voltage DC/ DC converter.

The gap between the needle tip and the ground electrode is varied from 10 mm to 15 mm for a particular configuration. The internal diameter of the needle tip is 0.5 mm. The ground electrode used in this study is in the shape of a ring with internal diameter of 3 mm and external diameter of 10 mm. The fluid is allowed to pass from the needle into the ring at a constant flow rate. The atomization starts when the fluid enters the ring. The process was characterized using image-processing technique. The spray images were grabbed by a CCD camera along a plane illuminated by a laser sheet at the centerline of the spray. The laser sheet was created by passing the laser beam through a cylindrical lens and a concave lens.

A PIXLEFLY® digital CCD camera (resolution 1360 X 1024 pixels) interfaced to a PC is used to obtain the images of the droplet break down and these images were processed using an image processing code developed in MATLAB®. Fig. (**3**) demonstrates the various steps involved in the droplet envelope extraction process. An original image captured using the CCD camera is shown in Fig. (**3i**). This image is then converted into the corresponding gray scale form, filtering out the background from the image. Through analysis it was found that the pixel intensity greater than 50 for a digitized gray scale image can efficiently separate the spray droplets from its background. Thus, this intensity value of 50 was used as the critical value for filtration of the image. Once the droplet band was identified and separated from its background, it was enveloped and demarcated using tangent lines by fitting the coordinates of the periphery of the droplet to the best fit straight line equation, as seen in Fig. (**3ii**) and Fig. (**3iii**). The perpendicular distance between the tangent lines was termed as ‘d’. The distance ‘d’ was measured at different locations between the tangent lines enveloping the droplet band. The maximum value of ‘d’ among these was taken as the droplet diameter value for the image. The droplet diameter obtained from 10 such images was averaged to obtain the Average Droplet Size corresponding to a particular operating condition. In the analysis for the Average Droplet Size at different operating conditions using sample images, the maximum error was estimated to be 2.2% and the maximum standard deviation was estimated to be 1.35% of the mean value.



(i) (ii) (iii)

Fig. (3). Illustration of the steps involved in the image analysis process; (**i**) Actual image, (**ii**) Gray-scale image after background elimination, (**iii**) Tangents representing the droplet diameter.

One set of test was carried out without a capacitor and the other one was carried out incorporating a commercial oil filled capacitor having a capacitance of 20μF (open circuit resistance of 32 MΩ) in parallel with the output of high voltage power supply. It should be pointed out that in the absence of the capacitor there was no atomization until the jet passes through the ring of ground electrode, but when the capacitor was introduced in the circuit the atomization occurred without the ground electrode after a break down length of 25 mm. Hence, the tests were carried out without the ground electrode when the capacitor was used.

RESULTS AND DISCUSSION

Study without Capacitor

Fig. (**4**) shows the variation in the average droplet diameter with the applied voltage for the flow rates of 3.75 ml/min and 4.6 ml/min. It can be seen in Fig. (**4**) that the average droplet size decreases with increase in the applied voltage for a constant flow rate. Also, the droplet size increased with an increase in the flow rate for a given applied voltage. In order to understand the mechanism responsible for this phenomenon, the charge density of the liquid column was estimated by dividing the measured current (C/s) by the liquid flow rate (m^3/s).

The variation of charge density for the two flow rates at different voltages are shown in Fig. (**5**). Correlating the data presented in Figs. (**4** and **5**), it can be seen that the droplet size decreases as the charge density increases. The variation of the droplet size with the charge density (combining the results for both the flow rates) is shown in Fig. (**6**) and the data shows that the droplet diameter is inversely proportional to the square root of the charge density. Therefore, the decrease in droplet diameter with the decrease in flow rate as well as with the increase in applied voltage can be attributed to the increase in charge density resulting in higher repulsive force developing inside the charged liquid column.

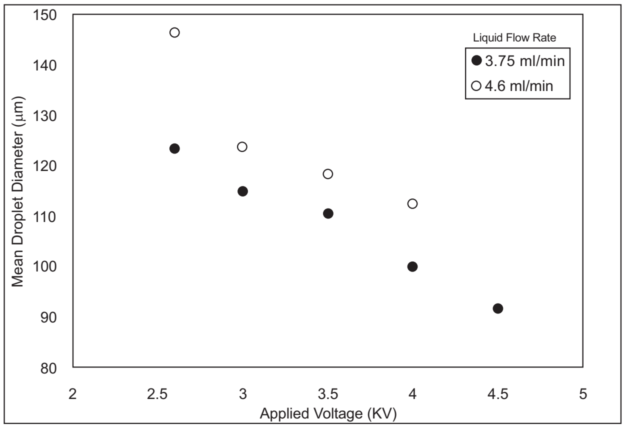


Fig. (4). Variation of droplet size with applied voltage (without the capacitor) for different water flow rates.

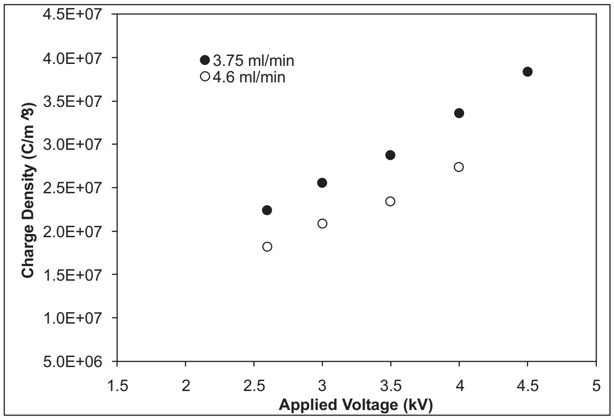


Fig. (5). Variation of charge density with applied voltage for different water flow rates.

Fig. (**7**) shows the change in the average droplet size with the variation in the gap between the electrodes for a constant flow rate of 4.6 ml/min. It was observed that the droplet size increases with the increase in the electrode gap. The increase in the distance between the electrodes for a constant applied voltage results in the reduction in the electrostatic force acting on the fluid surface resulting in poorer atomization.

Study with Capacitor

Fig. (**8i**) shows the shape of the spray in the absence of the capacitor. It appears homogeneous all along the distance covered. However, when the capacitor is applied, a tendency to break up after a certain distance from the needle is observed (Fig. (**8ii**)). This behavior can be explained by considering that in the absence of the capacitor, the flow charge density (for the given flow rate of 4.6 ml/min and applied voltage of 1.27 kV) is not sufficient to overcome the surface tension forces of the fluid and hence it requires additional help from the attractive forces generated by oppositely polarized ground electrode to rapture the liquid column. However, increased charge density in the fluid in the presence of the capacitor, as seen in Fig. (**9**), makes the requirement of the jet scatter by the opposite polarity ground electrode redundant and the atomization process is primarily governed by the increased repulsive forces acting on the fluid column between the similarly charged molecules [1-6].

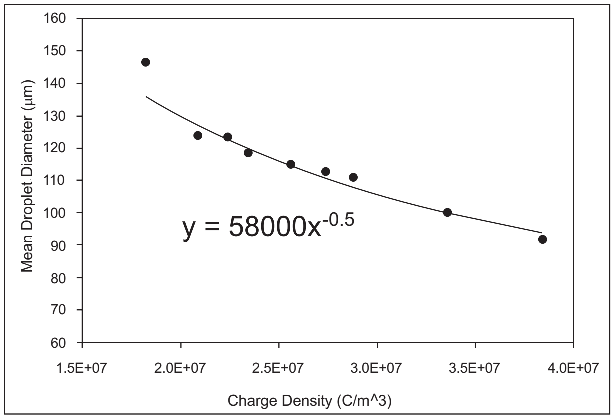


Fig. (6). Dependence of droplet diameter on charge density (without the capacitor).

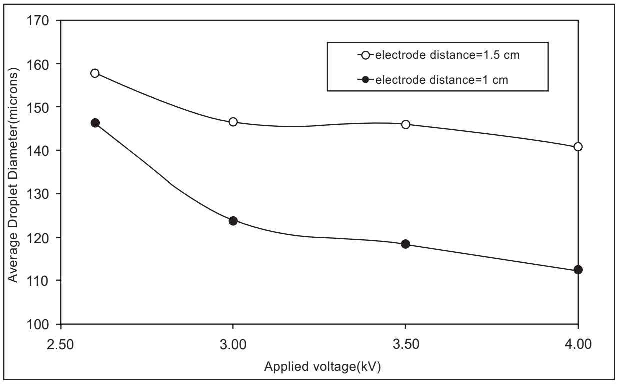
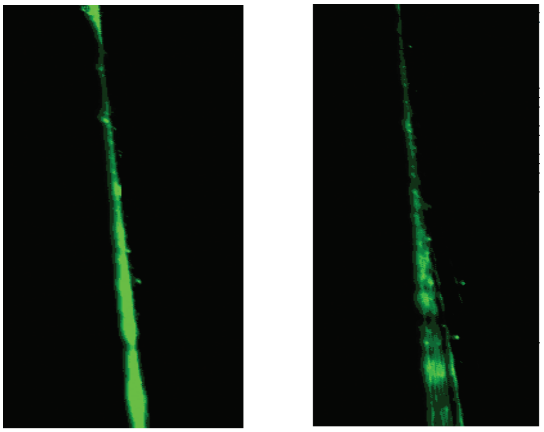


Fig. (7). Variation of droplet size with applied voltage for different inter-electrode gaps at constant water flow rate of 4.6 ml/min.

One can argue that the production of finer droplets when the capacitor was used in the circuit can be due to the oscillations in the applied voltage, which may be resonating with the instability modes of the liquid column. In order to check this argument, the voltage outputs at the capillary end with and without the capacitor were measured and the corresponding voltage traces are shown in Fig. (**10**). The data in Fig. (**10**) show that there is a significant drop in the average output voltage from the power supply in the presence of capacitor. However, the frequency content of the signal remains invariant. Therefore, the frequency of voltage oscillations seems to have no effect on the atomization quality. If the oscillations in the supplied voltage were responsible for atomization, one should expect better atomization without the capacitor as the magnitude of voltage oscillations are higher for that case.



(i) (ii)

Fig. (8). Spray pattern (**i**) Without and (**ii**) With a capacitor (in the absence of the ground electrode) at a voltage of 1.27 kV.

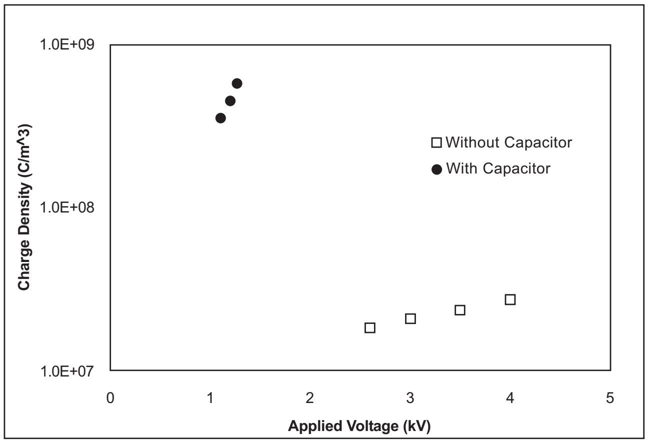


Fig. (9). Charge density variation with applied voltage for a flow rate of 4.6 ml/min with and without the capacitor.

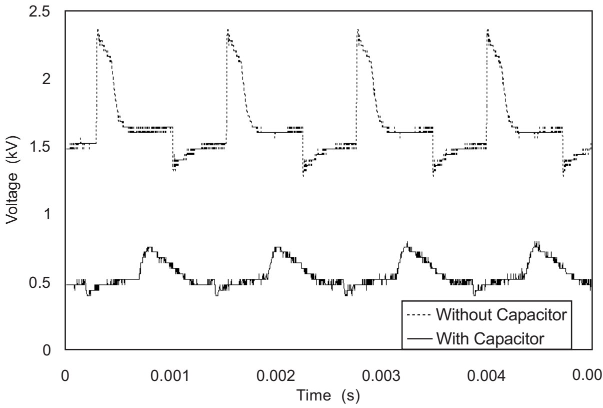


Fig. (10). Voltage at the capillary end with and without the capacitor for 6V input from the power supply.

Fig. (**11**) shows the droplet diameter variation with the applied voltage when the capacitor was used in the circuit for a water flow rate of 4.6 ml/min. It can be seen that with the incorporation of the capacitor in the circuit, the droplet size decreases to a lower value at a lower voltage as compared to the data presented in Fig. (**7**). The presence of the capacitor lowers the average voltage for the same input power, as seen in Fig. (**10**), and hence, increases the circuit current. This results in an increase in the charge concentration, as seen in Fig. (**9**), thereby causing the fluid stream to break into droplets at a lesser voltage due to the enhanced repulsive forces. The droplet size decreased to 92 µm at a supply voltage of 1.27 kV with a capacitor compared to 115 µm at 4 kV without the capacitor, i.e., 20% reduction in droplet size was achieved at a 68.25% lower supply voltage when the capacitor was used in the circuit. It is worthwhile to note that the droplet size achieved in the present study with the capacitor is of the same order to magnitude (100 µm) as that reported by Gomez and Tang [9] and Balachandran *et al.* [12] but at a much lower applied voltage (1.27 kV compared to 7 kV) for similar liquid flow rates and without the ground electrode.

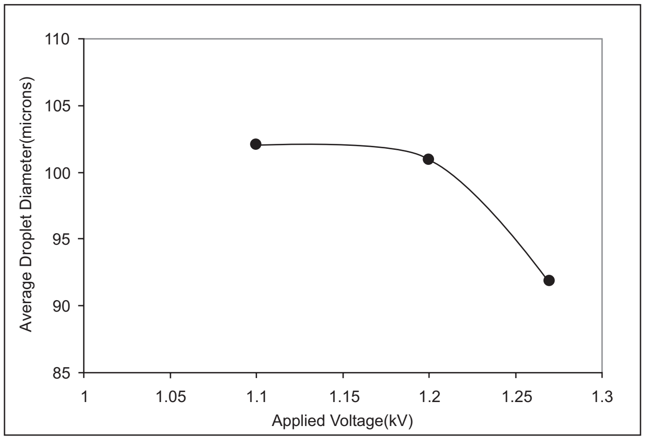


Fig. (11). Variation of droplet diameter with applied voltage when a capacitor was used parallel to voltage supply.

Since the charge density appears to be the prime reason for improved atomization, it should be possible to achieve similar effects if the capacitor is replaced by a high resistance resistor that can hold off high voltage and can handle similar power. One needs to explore this possibility in detail to reduce the system complexity.

CONCLUSIONS

This paper presents an insight into the droplet formation in electrostatic atomization. It was observed that the droplet size decreases with the increase in charge density, i.e., decrease in flow rate and/or increase in applied voltage. Changes in atomization characteristics with fluid flow rate and electrode gap were also observed providing the scope for controlled atomization for low fluid flow rates. Comparing the results of electrostatic atomization with and without the capacitor in the high voltage circuit, it was revealed that better quality of atomization in terms of droplet size could be obtained at a lower voltage with the introduction of a capacitor in the circuit. This reduces the need of higher working voltage. The atomization was achieved without the ground electrode by using the capacitor, which will reduce the system complexity. Furthermore, the droplet size achieved in the present study was comparable to the sizes reported in the literature [9, 12] for similar flow rates but at a much lower supply voltage.

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REFERENCES

[1] Reitz RD, Bracco FV. Mechanism of atomization of a liquid jet. Phys Fluids 1982; 25(10): 1730-42.
[2] Orme M, Courter J, Liu Q, Huang C, Smith R. Electrostatic charging and deflection of nonconventional droplet streams formed from capillary stream breakup. Phys Fluids 2000; 12(9): 2224-35.
[3] Hayati I, Bailey AI, Tadros TF. Investigations into the mechanisms of electrohydrodynamic spraying of liquids. I: effect of electric field and the environment on pendant drops and factors affecting the formation of stable jets and atomization. J Colloid Interface Sci 1987; 117: 205-21.
[4] Horning DW, Hendricks CD. Study of an electrically driven jet. J Appl Phys 1979; 50: 2614-17.
[5] Jaworek A, Krupa A. Classification of the modes of EHD spraying. J Aerosol Sci 1999; 30(7): 873-93.
[6] Okuda H, Kelly AJ. Electrostatic atomization – experiment, theory and industrial applications. Phys Plasmas 1996; 3(5): 2191-6.
[7] Rayleigh JWS. The theory of sound, Vol. II. New York: Dover Publications 1945.
[8] Sung K, Lee CS. Factors influencing liquid breakup in electrohydrodynamic atomization. J Appl Phys 2004; 96(7): 3956.
[9] Gomez A, Tang K. Charge and fission of droplets in electrostatic sprays. Phys Fluids 1994; 6(1): 404.
[10] Higuera FJ. Flow rate and electric current emitted by a Taylor cone. J Fluid Mech 2003; 484: 303-27.
[11] Ganam-Calvo AM. On the general scaling theory for electrospraying. J Fluid Mech 2004; 507: 203.
[12] Balachandran W, Machowski W, Ahmed CN. Electrostatic atomization of conducting liquids using AC superimposed on DC fields. IEEE Trans Ind Appl 1994; 30(4): 850-5.
[13] Fernandez de la Mora J, Loscertales IG. The current emitted by highly conducting Taylor cones. J Fluid Mech 1994; 260: 155-84.
[14] Ganan Calvo AM, Davila J, Barrero A. Current and droplet size in the electrospraying of liquidsscaling laws. J Aerosol Sci 1997; 28: 249-75.
[15] Ganan-Calvo AM. The surface charge in electrospraying: its nature and its universal scaling laws. J Aerosol Sci 1999; 30: 863-72.
[16] Joshi RP, Qian J, Schoenbach KH, Scamiloglu E. Microscopic analysis for water stressed by high electric fields in the prebreakdown regime. J Appl Phys 2004; 96(7): 361725.

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