

Article

Dynamic characteristics of charged droplets in an electrostatic spraying process with twin capillaries[☆]Jun Zhang^{1,*}, Hongzhou He¹, Guanxing Huang²¹ Cleaning Combustion and Energy Utilization Research Center of Fujian Province, School of Mechanical Engineering, Jimei University, Xiamen 361021, China² Engineering training Centre, Jimei University, Xiamen 361021, China

ARTICLE INFO

Article history:

Received 24 October 2017

Received in revised form 22 March 2018

Accepted 25 March 2018

Available online 5 April 2018

Keywords:

Electrostatic spray

Twin capillaries

Simulation

Interaction

ABSTRACT

The experimental and simulated investigations on electrostatic spraying with twin capillaries are carried out. The starting electric voltage required for the cone-jet and the deposition characteristics of the droplets are measured. The whole spraying process, which includes jet and droplet motions, is simulated and the simulated results on the motions of jet and droplet are basically consistent with the experiments. According to the simulated results, the contributions of various electric forces to droplet movement are quantitatively analyzed and the droplet dynamic characteristics, especially the interaction mechanism between two sprays, are revealed. The test results on the droplet deposition characteristics partially support the simulated results on the droplet motion. The present work is useful for a better understanding on the interaction between sprays in double or multi-capillary system. © 2017 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

1. Introduction

The electrostatic spray can effectively atomize bulk fluid into nearly monosized droplets at very low flow rates. This advantage makes it useful for many industrial applications, such as surface coating, nanoparticle preparation [1–3]. In some applications, the higher flow rates are needed for electrospray processing. In this case, in order to obtain very small monodisperse droplets, the multi-capillary or multi-nozzle system may be used [4]. In multi-capillary spraying process, there is an interaction between different sprays. In addition, the changes in nozzles' spacing and configuration also result in a change in field strength distribution. These features on multi-nozzle spraying will affect the characteristics of jet and droplet motion. Therefore, in order to improve the atomization device design and obtain the required atomization characteristics, it is necessary to have a better understanding on the characteristics of multi-capillary atomization. In the last 20 years, a few studies on this subject have been reported. Snarski [5] and Dunn [6] experimentally investigated on the interaction between two sprays of electrically charged liquid droplets and analyzed the effects of applied voltage and needle spacing on the droplet velocities and the droplet mixing between the two needles' sprays. Rulison and Flagan [7] studied

a linear array of capillary jets and found that the closer the capillary electrodes were to each other, the higher was the potential required for cone jet formation. Regele [4] and Si [8] proposed models to predict the onset voltage for the center nozzle of electrospray array. Hubacz [9] studied the spraying in a linear array of four nozzles and found that the shape of the plumes at the periphery of the array was skewed. Lhernould [10] proposed a new design of a multiple electrospray system involving an innovative nozzle shape and flow restrictor system. It is undeniable that these studies provide important help in understanding the mechanism of multi-nozzle atomization and improving the design of atomization device. However, the electrostatic spraying with multi-nozzle is an extremely complex physical process, there are still some problems that need to be understood more deeply. Such as how to quantitatively describe the contributions of various electrostatic forces to droplet movement, how the interaction between the sprays affects the movement of the droplet group, how to simulate the entire spray process. The understanding on these issues helps to gain a better understanding on the atomization mechanism for multi-spray and to better improve the atomization system. Therefore, the purpose of this paper is to reveal the atomization mechanism in twin capillary system more deeply by simulating the whole spraying process and combining with experimental research.

2. Theory

Existing studies [11,12] have shown that when a threshold voltage applied in capillary is reached, the droplet at the capillary exit will

[☆] Supported by the Science and Technology Project of Fujian Province (2017H0024) and the Fujian Provincial Department of Education research project (JK2012027), China.

* Corresponding author.

E-mail address: junzhang@jmu.edu.cn (J. Zhang).

deformed into a liquid cone and a very fine jet will be formed at the tip of the cone. The jet is broken downstream into a spray of fine charged droplets. For the above electrostatic spraying process, we can divide it into two stages to describe separately: jet and spray stages, namely. In jet stage, the liquid presents a very fine charged jet. With the extension of the jet, at a location downstream of the jet, the jet will break into scattered droplets due to the instability on surface between liquid and gas. The stage after the jet is broken can be regarded as the spray stage. The theoretical models in the two stages can be described separately.

2.1. Jet stage

The electrostatic jet motion can be described using the Lagrangian control volume element integration method, which was early proposed in studying on buoyancy jet by Lee [13] and used in simulating flume dynamics in underwater oil spill by some researchers [14,15]. According to this method, as shown in Fig. 1, each jet trajectory is divided into a sequential series of control volume elements (CV) that are characterized by their location, average velocity.

In jet stage, it is not necessary to consider the entrainment effect. So that the following conservation equations for each control volume element (CV) in each jet can be established.

Mass conservation in CV :

$$\frac{dQ}{dt} = \frac{d\left(\frac{\pi}{4}d_j^2 V_j\right)}{dt} = 0 \quad (1)$$

where the subscript j indicates the jet parameters. d_j and V_j are diameter and velocity of CV in jet, respectively.

Momentum conservation in CV can be given as

$$\frac{d(m_j V_j)}{dt} = \frac{d\left(\rho \frac{\pi}{4} d_j^2 h_j V_j\right)}{dt} = F_{jg} + F_{je} + F_{jk} + F_{jd} \quad (2)$$

where m and h are mass and thickness of CV in jessst, respectively. F_{jg} and F_{jd} are gravity and drag forces on CV, respectively. Unlike buoyancy plume [14,15], the buoyancy force on CV can be ignored, and electrostatic force must be considered in charged jet. F_{je} and F_{jk} are the electric field force due to applied electrical field strength and the interaction force due to the electric interaction between charges on different CVs, respectively. The gravity force on CV can be estimated as

$$F_{jg} = \frac{1}{4}\pi d_j^2 h \rho_l g \quad (3)$$

where ρ_l is liquid density.

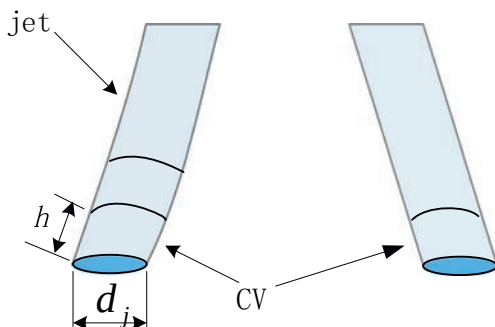


Fig. 1. Double jet and CV schematic.

Since the CV is very small, it can be approximated as a point charge with electric charge. q In this way, the electric field force on CV can be expressed as

$$F_{je} = qE \quad (4)$$

where E is electrical field strength, and q is charge on CV.

The electrostatic field strength can also be described as the gradient of electrical potential as

$$E = -\nabla U \quad (5)$$

where U is electric potential. The charge q on CV, which depends on the charge density and the volume of CV, can be calculated by

$$q = \rho_q \pi \left(\frac{d_j}{2}\right)^2 h \quad (6)$$

where ρ_q is charge density.

For two capillary spraying system, the electric interaction force on CV can be divided into the interaction force between internal CVs of a jet and the interaction force between CVs in different jets. So it can be expressed as

$$F_{jk} = F_{jk_1} + F_{jk_2} = \sum_{i \neq j}^N \frac{q_i q_j}{4\pi\epsilon_0 r_{ij}^2} \vec{r}_{ij} + \sum_{i,k}^N \frac{q_i q_k}{4\pi\epsilon_0 r_{ik}^2} \vec{r}_{ik} \quad (7)$$

where F_{jk_1} is interaction force between internal CVs of a jet, and F_{jk_2} is interaction force between CVs in different jets. ϵ_0 is the vacuum dielectric constant. q_i and q_j are charges on the i -th and j -th CVs of a jet, respectively. q_k is charge on the k -th CV in another jet. $r_{i,j}$ and $r_{i,k}$ are the distance between i -th and j -th CVs and the distance between i -th and k -th CVs, respectively. $\vec{r}_{ij}$ and $\vec{r}_{ik}$ are unit vector along the line joining the centres between i -th and j -th CVs and the line joining the centres between i -th and k -th CVs, respectively.

The drag force on CV, which depends on the interface shear stress between jet and surrounding gas, can be expressed as

$$F_{jd} = \pi d_j h \tau_0 \quad (8)$$

where τ_0 is interface shear stress between jet and surrounding gas and can be approximately estimated using the wall shear stress in tube flow.

For the given initial values, spray conditions and fluid physical properties, the above equations can be used to solve the jet motion and obtain jet parameters along the time series (such as jet trajectory, velocity, diameter, and so on).

2.2. Spray stage

From the point where the jet is broken, the liquid appears as discrete droplets. The movement of these droplets can be described by the Lagrangian method. Assuming buoyancy is ignored, the droplet motion equation can be described by

$$m_d \frac{dV_d}{dt} = F_{dg} + F_{dd} + F_{de} + F_{dk} \quad (9)$$

where the subscript d indicates the droplet parameters. m_d is the mass of the droplet. F_{dg} and F_{dd} are the gravity force and the drag force on droplet, respectively. F_{de} and F_{dk} the electric field force due to applying external electric field and the interaction force between droplets due to Coulomb repulsion, respectively.

The mass of a spherical droplet with diameter D_d can be calculated by

$$m_d = \rho_l \frac{\pi}{6} D_d^3 \quad (10)$$

where ρ_l is the density of liquid. The gravity force can be expressed

$$F_{dg} = \rho_l \frac{\pi}{6} D_d^3 g \quad (11)$$

Ignoring air flow, the drag force acting on a droplet can be described by the equation

$$F_{dd} = \frac{1}{2} C_d \rho_g A_d V_d^2 \quad (12)$$

where ρ_g is the air density and A_d is the projected area of the droplet. C_d is drag factor, which is related with the droplet Reynolds number Re_d . The drag factor is determined using Klyachko's correlation [11].

$$C_d = \frac{24}{Re_d} \left(1 + \frac{Re_d^{2/3}}{6} \right), 2 < Re_d < 800 \quad (13)$$

The droplet Reynolds number can be expressed as

$$Re_d = \frac{\rho_g V_d D_d}{\mu_g} \quad (14)$$

where μ_g is the air viscosity. The electric field force on droplet can also be calculated using Eq. (4) in jet stage, but the charge on droplet, which is associated with the droplet volume, should be expressed as

$$q = \rho_q \frac{\pi}{6} D_d^3 \quad (15)$$

Similar to handling jet, the interaction force F_{dk} is also divided into the interaction force between internal droplets of a spray and the interaction force between two sprays.

$$F_{dk} = F_{dk_1} + F_{dk_2} \quad (16)$$

where F_{dk_1} and F_{dk_2} are the interaction force between internal droplets of a spray and interaction force between two sprays, respectively, and they can also be calculated using Eq. (7).

In order to obtain charge q in Eqs. (6) and (15), the charge density needs to be determined. In present work the charge density is approximately estimated from Rayleigh limit and it is simply described below.

When the liquid flows out of the capillary at very small flow rate, a droplet will form under the capillary due to surface tension. By simply considering the balance between electric force, gravity and surface tension forces, the following equation can be obtained.

$$\frac{1}{6} \pi D^3 \rho g + q E_0 = \pi D_0 \sigma \quad (17)$$

where D is droplet diameter, E_0 is the electrical field strength at the capillary exit. D_0 and σ are the inner diameter of capillary and the surface tension factor of liquid. When the applied voltage reaches a threshold value, the droplet under the capillary will be deformed into a conical shape and a very fine jet will appear at the tip of the cone [16,17]. At this point, the maximum charge on droplet can be estimated by the Rayleigh limit

$$q_{cr} = 2\pi \sqrt{2\epsilon_0 \sigma D^3} \quad (18)$$

From Eqs. (17) and (18), we can get the charge density approximately.

For the given initial values, spray conditions and fluid physical properties, the Eqs. (9)–(18) can be used to solve the motion of charged droplets and obtain droplet position, velocity and others parameters.

2.3. Determination of jet breakup position

In order to link jet and spray stages, the position of jet breakup or the jet length needs to be determined. There are some experimental or semi-theoretical expressions to be used [18–20]. According to the literature [18], for a laminar jet, the jet length L can be estimated

$$L = 19.5 d_j We^{0.5} (1 + 3Oh)^{0.85} \quad (19)$$

For a turbulent jet, the jet length can be estimated by a Grant and Middleman relationship [20]

$$L = 8.51 d_j We^{0.32} \quad (20)$$

where Oh is the Ohnesorge number and can be defined as

$$Oh = We^{0.5} Re_j^{-1} = \frac{\mu_l}{(\rho_l \sigma d_j)^{0.5}}$$

where We and Re_j are the jet Weber number and Reynolds number, respectively, defined as

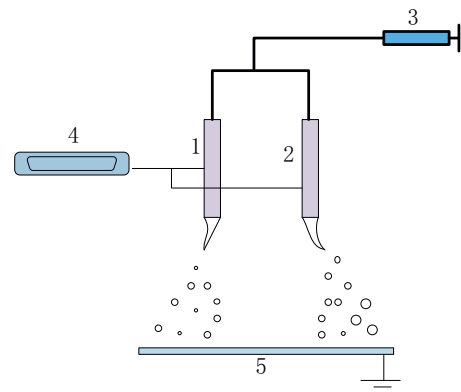
$$We = \frac{V_j \rho_l d_j}{\sigma}, \quad Re_j = \frac{\rho_l V_j d_j}{\mu_l} \quad (21)$$

The critical Reynolds number for transition between the laminar jet and turbulent jet can be estimated by Grant and Middleman [20]

$$Re_{cri} = 3.25 Oh^{-0.28} \quad (22)$$

3. Experimental Configuration

The experimental system configuration is shown in Fig. 2. Two parallel vertically placed metal capillaries are applied a negative high voltage by a EST801A type electrostatic voltage generator. A plate electrode, which is grounded, is placed at a distance of 25 mm from the capillary outlet. The inner and the outer diameters of two capillaries are 0.25 mm and 0.45 mm, respectively. The center spacing between two capillaries is 5 mm. A LSP02-1B type injection pump provides liquid to two capillaries. A fluid distributor and the required connection line can ensure that the flow rates through two capillaries are equal. The water is chosen as spraying liquid. By adjusting the applied voltage on capillaries, we can obtain the required electric field strength. During



1,2-metal capillaries 3-injection pump 4-high voltage generator 5-plate electrode

Fig. 2. Experimental configuration.

the experiment, the jet trajectories under different conditions are recorded by a MZ81 type digital camera and the droplet sizes under various spraying conditions are measured using a Phase Doppler Anemometer (PDA).

4. Numerical Simulation Process

The numerical techniques are used to solve the above models in jet and spray stages. For computational efficiency, we only calculate two-dimensional motion on jet and droplet. The whole calculation process can be divided into two steps as follows.

Step 1 to solve jet model in jet stage

During this step, the jet motion is solved and the jet trajectory and other relevant parameters (jet velocity, diameter and so on) are obtained. For solving the required initial values: The initial position for each jet is at the capillary exit and the initial velocity is selected as the exit velocity, which can be determined by flow rate and inner diameter of capillary. The initial diameter is selected as the inner diameter of capillary. The choice of time step should ensure that the sizes of length and diameter are consistent for CV, so that the CV with charge can be closer to a point charge ($\Delta t = d_j/V_j$). Once the jet length reaches the breakup position of jet, the calculation in this step will end.

Step 2 to solve droplet motion model in spray stage

During this step, the droplet motion equations are solved and the positions, the concentration distribution as well as various electrostatic forces on droplets can be obtained. The measured droplet size is used to calculate. For solving the required initial values: The initial positions of all droplets are assumed to be distributed uniformly in the terminal section of the jet and the initial velocities of droplets are jet velocity at breakup position. The time step in this stage is determined by using authors' previous approach, which had been used in simulation on single spray [21]. The processing method is briefly described as follows.

Assuming an initial time, the first droplet is generated at jet breakup position. After a time step Δt , the second droplet is generated, with the first droplet moved to a new position. Passing a time step again, the third droplet is generated, with the previous two droplets moved to their new positions, respectively. In this way, the number of the droplet in spray increases one by one with time passing. Assuming that N droplets with average diameter D_{av} are generated at a jet breakup spot in unit time, the time step Δt can be determined from the flow rate:

$$\Delta t = \frac{1}{N} = \frac{1}{6} \frac{\pi D_{av}^3}{Q} \quad (23)$$

Obviously, the length of time simulated is related to the droplet number. In the present work, For each spray, the motion of droplet group with 2000 droplets generated one by one is simulated. The droplet number is large enough to allow an understanding of an actual electrostatic spray process. The simulation on droplet movement also requires given droplet size, which can be measured by PDA. For simplicity, we only tested the total average droplet diameter. The average droplet is obtained by averaging droplet sizes at several positions in a section 10mm away from capillary outlet. The droplet size distribution is considered in the simulation and the distribution is assumed to be a normal distribution with average D_{av} diameter, so that the diameters of all droplets by using a random number method. More details can be found in reference [21].

During solving jet and droplet motion models, the applying external electric field strength or potential distribution needs to be also known (see Eqs. (4) and (5)). In present work, the Ansys is used for numerical

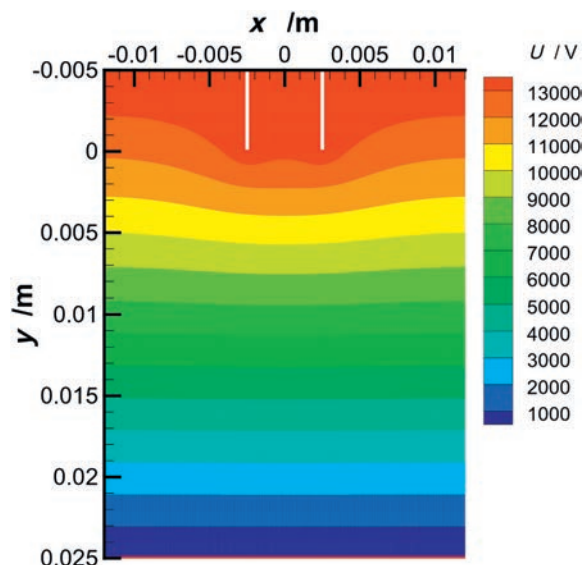


Fig. 3. Electric potential distribution when two capillaries is applied with a voltage of 14000V.

solution to obtain electric field strength and potential and the Fig. 3 shows an electric potential distribution when two capillaries is applied with a voltage of 14000V. The obtained data on field strength or potential from Ansys can be imported into the programmed code on model. The coordinate configuration in Fig. 3 is also used in subsequent simulation. According to data from Ansys, we can also determine the field strength at the capillary outlet, so that we can obtain the charge density under different conditions (see Eqs. (17) and (18)).

5. Results and Discussion

When the applied voltage reaches a certain value, the cone-jet, which is the beginning of electrostatic atomization, will appear. There are many reports on the starting voltage of the stabilized cone jet in various spraying configurations. In present work, the starting voltage of cone-jet is also measured and the Fig. 4 shows the starting voltage required for the cone-jet as a function of flow rate (in the full text, Q is the flow rate for each capillary). Obviously, for larger flow, the starting

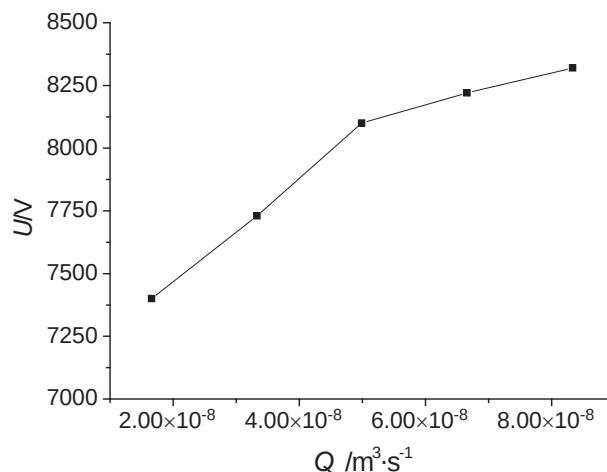


Fig. 4. Starting voltage required for cone-jet as a function of flow rate.

voltage required for the cone jet is higher. In addition, the starting voltage in twin capillary spray is slightly higher than that in single-capillary spray, and this is consistent with the existing researches on double (or multi)-capillary spray [4,5,7,22]. The subsequent simulation and experiment are limited to the condition of cone-jet.

The Fig. 5(a)–(c) are a few pieces of photos on spray at different flow rates and applying voltages. As we expected, the jets and droplets of two sprays have a significant tendency to migrate to the left and right sides due to the interaction between two sprays. In addition, the applying voltage and flow rate have a significant effect on the atomization

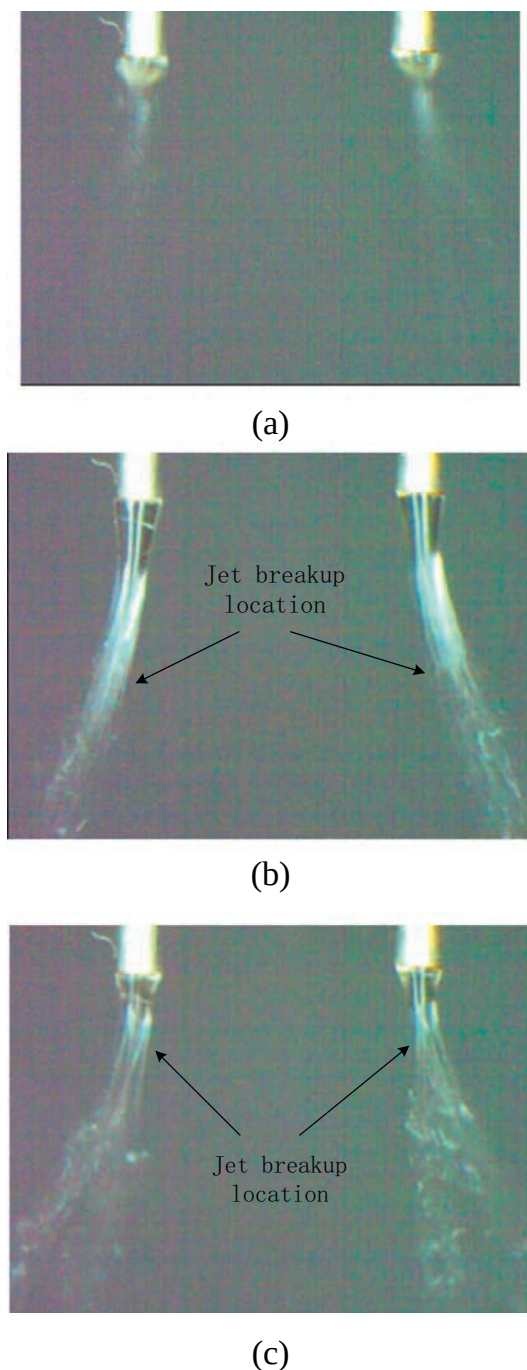
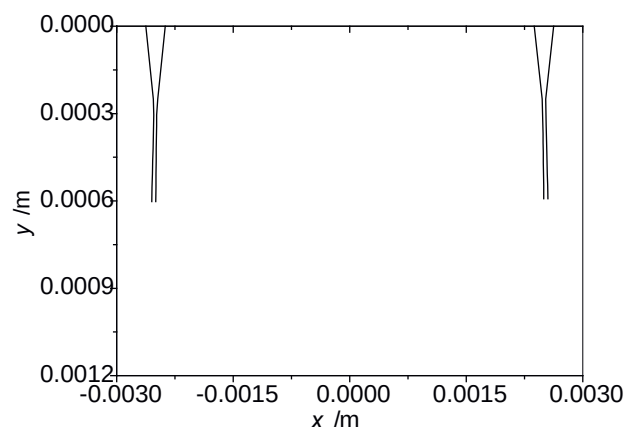


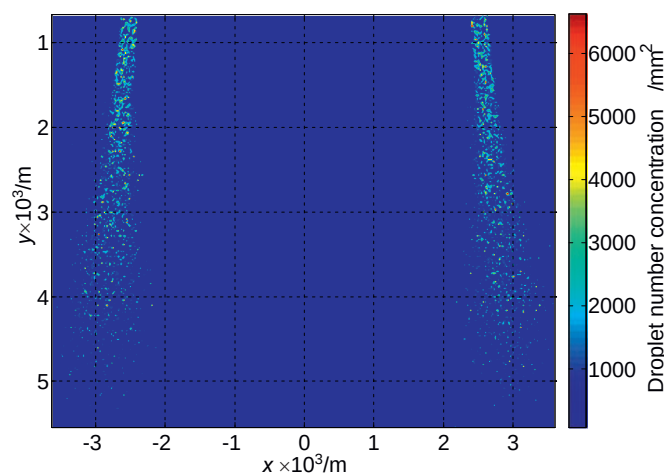
Fig. 5. Spraying photos at different flow rates and applying voltages: (a) $Q = 8.33 \times 10^{-9} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 14000 \text{ V}$, (b) $Q = 5.8 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 11000 \text{ V}$, and (c) $Q = 5.8 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 14000 \text{ V}$.

morphology. In the case of higher voltage and lower flow rate, the formed jet, which is very fine, is broken into droplets at a position very close to the capillary outlet, while at higher flow rate and lower voltage, the jet in diameter and length is larger.

Using above models, we simulate the whole spray process at several condition and the Figs. 6 and 7 show the simulated jet and droplet distributions in two cases. The calculation of the location of jet breakup must be mentioned. When the jet length is calculated using Eqs. (19) and (20), the jet diameter and jet velocity must be given. In the present calculation, the velocity and diameter of jet at top of the cone are used to determine the jet length due to weak changes in diameter and velocity in jet downstream along jet axis (See Figs. 5(a) and 6(a)). By comparing Figs. 6 and 7 with Fig. 5, it can be found that the simulated and experimental results on two sprays are basically consistent, and the simulated motions in jet and droplet better demonstrate the interaction between two sprays. The simulated jet positions are at 0.59 mm and 3.7 mm from the capillary outlet respectively for Figs. 6(a) and 7(a), and the corresponding experimental values (see Fig. 5(a) and (b)) are approximately in the range of 0.5–0.7 mm and 3.5–5 mm from capillary exit, respectively. So it indicates that the simulated jet length is basically consistent with the experiment. The color bar in Figs. 6(b) and 7 represents droplet number concentration distribution. We can find that the droplet spread range is very small and the local concentration

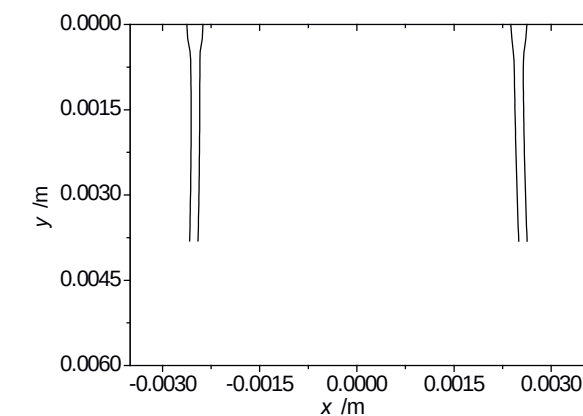


(a) Jet stage

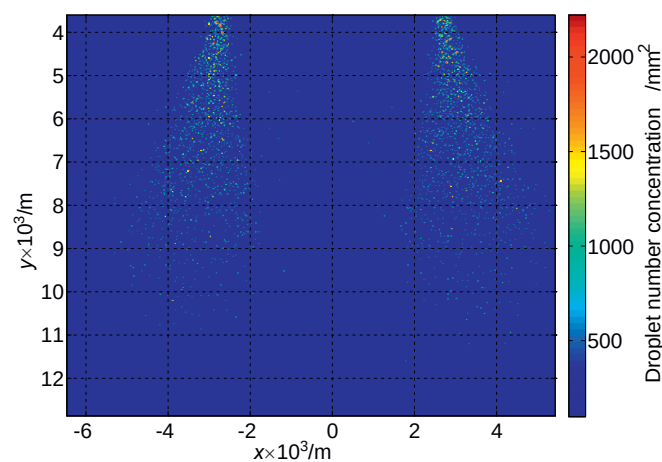


(b) Spray stage

Fig. 6. Simulated jet and droplet at flow rate of $8.3 \times 10^{-9} \text{ m}^3 \cdot \text{s}^{-1}$ and voltage of 14000 V: (a) Jet stage, (b) spray stage.



(a)

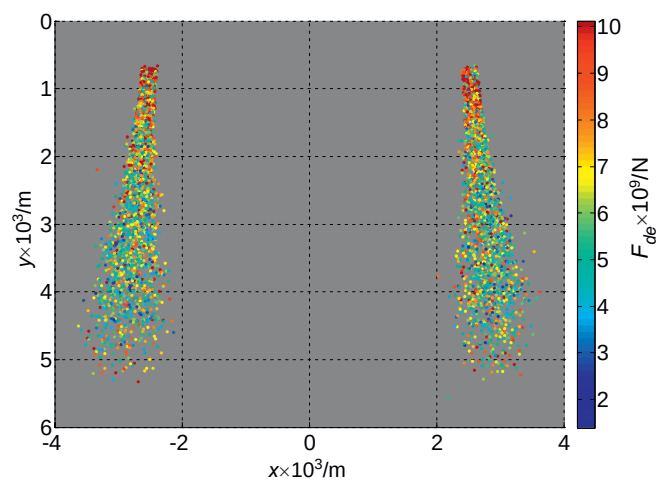


(b)

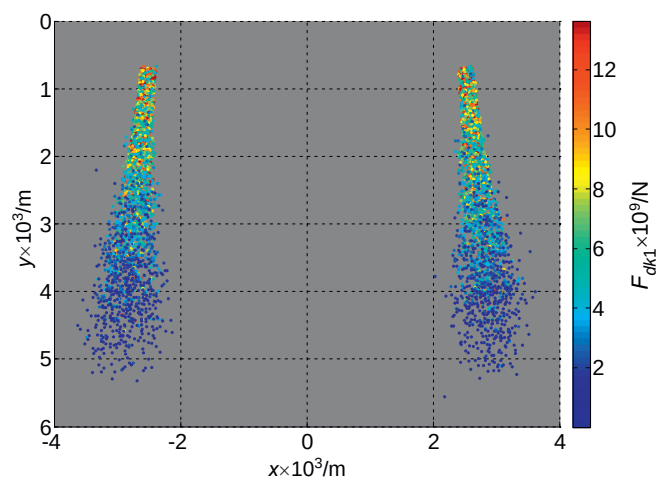
Fig. 7. Simulated jet and droplet at flow rate of $5.83 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$ and voltage of 11000 V: (a) Jet stage, (b) spray stage.

is very high when the voltage is higher and the flow rate is lower. For the spread of droplets, the motion of droplets to inside (area between two capillaries) is limited to a certain extent and the droplets have a clear tendency to spread to the outside, due to the interaction between two sprays.

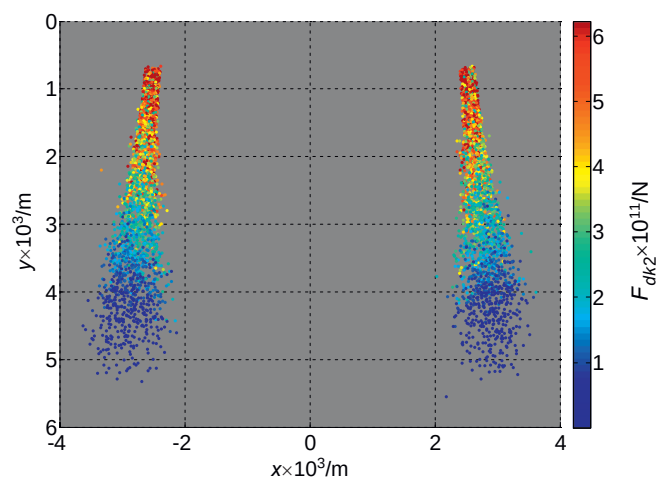
The motion characteristics of the droplets as well as the interaction between the two sprays depend on the electrostatic forces on droplet, so we need to explore the contributions of various electrostatic forces to motion. Figs. 8–10 show distributions of various electrostatic forces at different spraying conditions. The symbols F_{de} , F_{dk1} and F_{dk2} represent the electric field force, the interaction force between internal droplets of a spray and the interaction force between two sprays, respectively. From these figures we can get some features on the electrostatic force. First of all, the various electric forces on the droplet vary greatly with the position of the droplet. Relatively, the electric field force distribution is slightly uniform since the electric field strength change along the spatial position is not too large, while the interaction between internal droplets of a spray and the interaction force between two sprays vary dramatically with spatial location. In a region closer to the capillary exit, where the local concentration of the droplets is very high, the interaction between internal droplets of a spray is extremely large, even more than electric field force due to very small distance between



(a)



(b)



(c)

Fig. 8. Distributions of various electric forces to droplet motion ($Q = 8.33 \times 10^{-9} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 14000 \text{ V}$): (a) F_{de} , (b) F_{dk1} , (c) F_{dk2} .

droplets. As the distance from capillary exit increases, the droplets gradually spread and the interaction between internal droplets of a spray is correspondingly weakened. The interaction force between two sprays depends on the distance between droplets from two sprays. In the

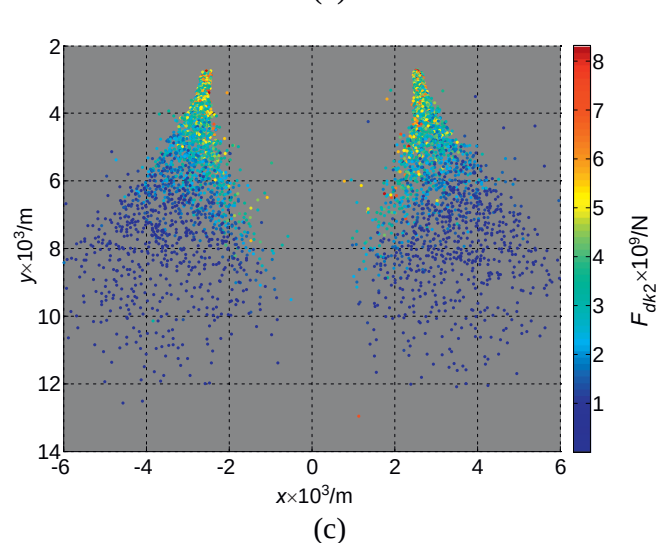
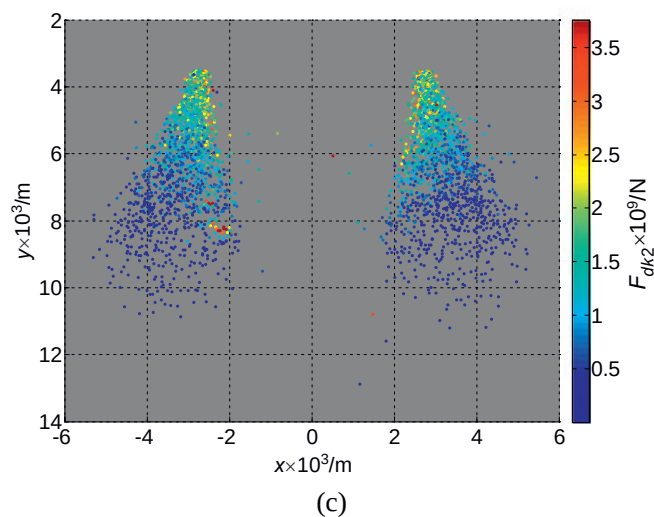
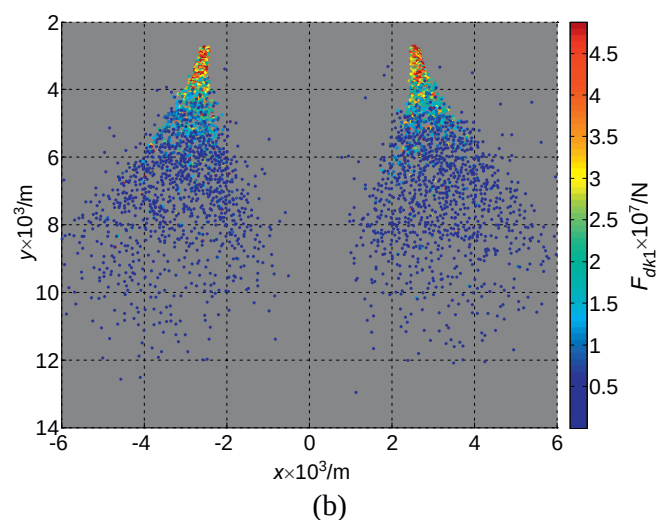
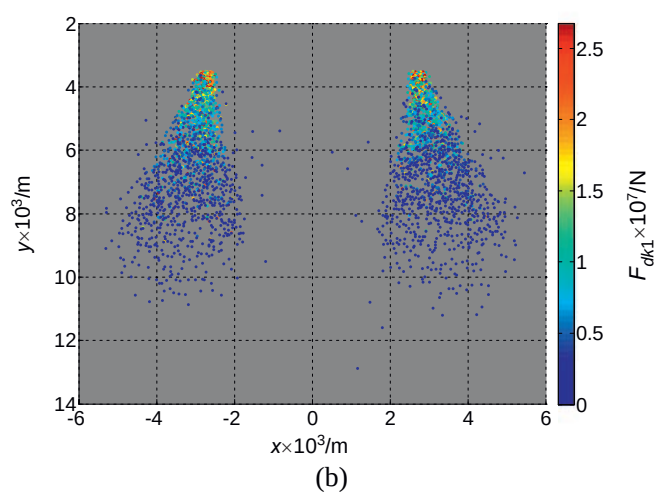
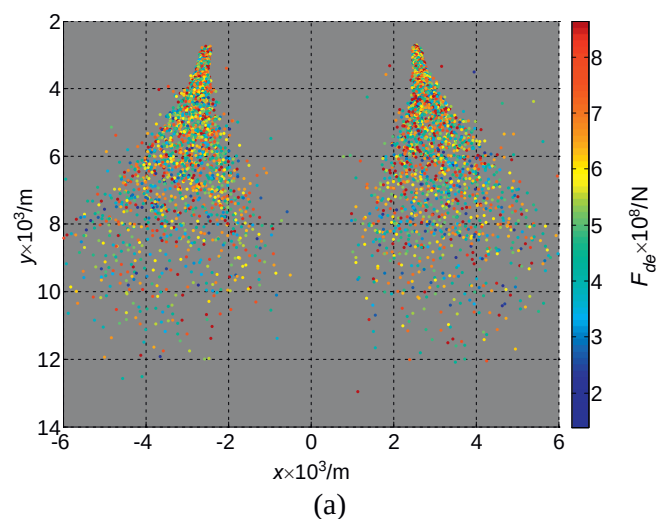
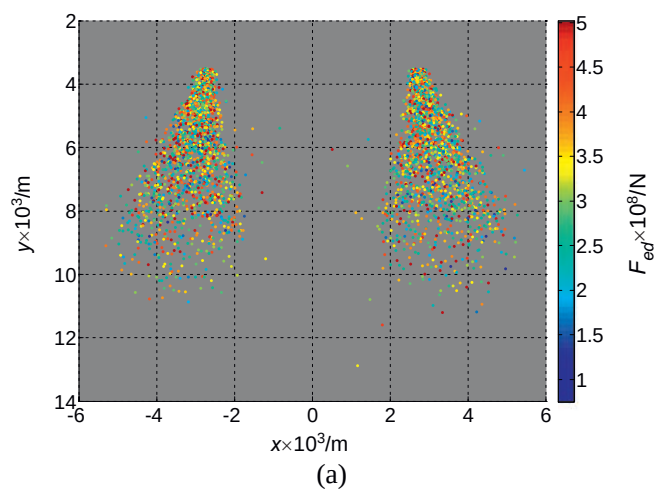


Fig. 9. Distributions of various electric forces to droplet motion ($Q = 5.83 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 11000 \text{ V}$): (a) F_{de} , (b) F_{dk1} , (c) F_{dk2} .

Fig. 10. Distributions of various electric forces to droplet motion ($Q = 5.83 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 14000 \text{ V}$): (a) F_{de} , (b) F_{dk1} , (c) F_{dk2} .

area where the two sprays are close, the interaction force between sprays is more intense and this allows the droplet motion to the area between two sprays to be constrained to a certain extent. Due to the combined effect of the interaction between internal droplets of a spray and

the interaction between two sprays, the two droplet groups from two sprays are skewed to the outside, respectively. In addition, the flow rate and applying voltage have a significant effect on the electric force. When the applying voltage increases, whether the interaction between

internal droplets of a spray or the interaction between sprays will become strong due to increased charge density. In this case, the strong interaction between internal droplets of a spray causes the droplets to spread farther around and so that the droplets from two sprays to gradually approach in the area between the two sprays. The reduction in the distance between the droplets from two sprays leads to an increase in the interaction between different sprays, which limits the further proximity and mergence of the two sprays. As a result, a higher voltage causes the droplets to spread over a wider range. The droplets tend to spread to the outside, while spreading to the area between two sprays is limited. When increasing the flow rate and keeping the voltage constant, the sizes of the droplets formed in spray increase. These larger droplets will carry more charge and this also results in strong interaction between internal droplets of a spray and the interaction between sprays. In this case, the droplet spreading trend is similar to the above case.

In order to understand the difference in moving trend among different size droplets, Fig. 11 demonstrates simulated spatial distributions of droplets in two size ranges. We can find that larger droplets due to large inertia mainly appear in the respective central region of two spray, while the smaller ones have a trend moving toward the edge of two spray. The movement characteristics of droplets with different sizes will eventually have an impact on droplet deposition.

A simple test on the deposition characteristics of droplets is also conducted in present work. In the experiment, the spray liquid is injected with a little pigment and then the liquid is sprayed on a small piece of

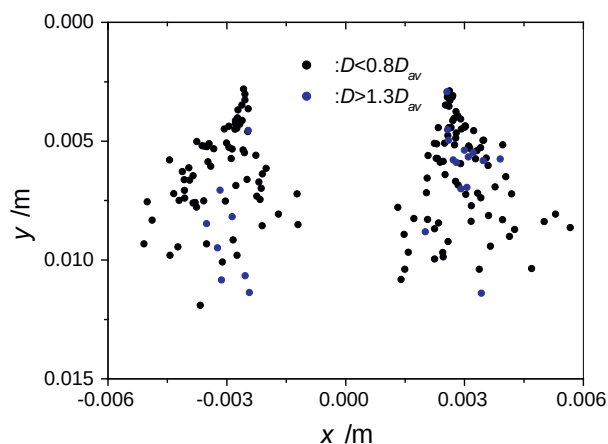
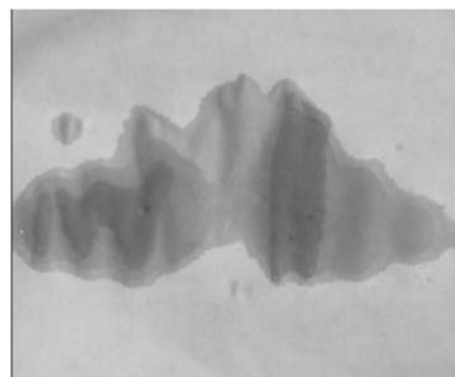
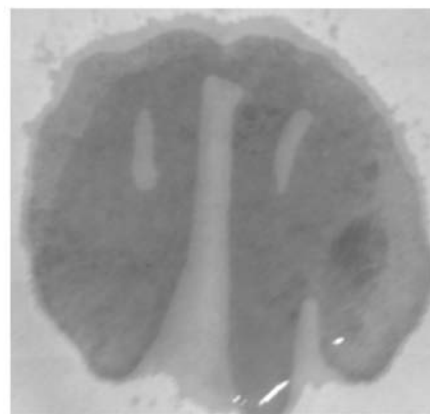


Fig. 11. Simulated spatial distributions of droplets in two size ranges ($Q = 5.83 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$, $U = 14000 \text{ V}$).

paper placed on the plate electrode. By using this method, we can more clearly observe the deposition of droplets on paper and the Fig. 12 show the depositions of droplets at different conditions. We can find that the droplets from two sprays are deposited respectively in two areas that are almost unconnected, due to the interaction between two sprays. When the applied voltage increases, the deposition area of droplets is expanded and the two regions have a near trend. The droplet deposition characteristics are consistent with the motion behaviors of the droplets analyzed above and it also partially support the simulation results on droplet motion. In addition, from the deposition morphology in Fig. 12 it can be also found that the color in the center deposition areas from two sprays is darker than that in the edge areas, which indicates that more liquid is deposited in the central areas. The reason for this phenomenon is that more large droplets move in the respective central areas of two sprays and they result in higher deposition in the central areas, and this is also consistent with the simulated result from Fig. 11.



(a)



(b)

Fig. 12. Deposition of droplets: (a) $U = 11000 \text{ V}$, $Q = 5.83 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$, (b) $U = 14000 \text{ V}$, $Q = 5.83 \times 10^{-8} \text{ m}^3 \cdot \text{s}^{-1}$.

Existing studies [5,6,22] on twin or multi-capillary spraying rarely involve the quantitative analysis of the effect of electric interaction forces on the droplets motion, which does not allow one to gain a deeper understanding of the interference between the twin sprays. Although the above simulation work is only carried out under limited conditions, it still revealed some details of the twin-capillary spraying, especially the quantitative analysis on the influence of the electric interaction force on the interference between two sprays is conducted. Obviously, the present simulated work is helpful for the design of multi-nozzle atomizer.

6. Conclusions

The experimental and simulated investigations on electrostatic spraying with twin capillaries are carried out and the following basic conclusions are obtained.

The starting voltage required for the cone jet is measured. The experimental result shows that the starting voltage increases with increasing flow. The starting voltage in twin capillary system is slightly higher than that in single-capillary.

Using the Lagrangian control volume element integration method as well as droplet motion equation, the whole electrostatic spraying process in twin capillaries system is simulated and the simulation in the motions of jet and droplet are basically consistent with the experiment.

The simulated results show that various electric forces strongly influence the movement of droplets and the contributions of electric forces to the motion of the droplets vary with the location of the droplets. Relatively, the electric field force distribution is slightly uniform since the electric field intensity decreases regularly with the spatial position, while the interaction between internal droplets of a spray and the

interaction force between two sprays vary dramatically with spatial location. In a region closer to the capillary exit, where the local concentration of the droplets is very high, the interaction between internal droplets of a spray is extremely large, even more than electric field force due to very small distance between droplets. As the distance from capillary exit increases, the droplets gradually spread and the interaction between internal droplets of a spray is correspondingly weakened. The interaction force between two sprays depends on the distance between droplets from two sprays. In the edge area between two sprays, the interaction force between sprays is more intense and this allows the droplet motion to the area between two sprays to be constrained to a certain extent. Due to the combined effect of the interaction between internal droplets of a spray and the interaction between two sprays, the two droplet groups from two sprays are skewed to the outside, respectively.

The simulated results also show the flow rate and applying voltage have a significant effect on the interaction forces. When the applying voltage increases, whether the interaction between internal droplets of a spray or the interaction between sprays will become strong due to increased charge density. In this case, the strong interaction between internal droplets of a spray causes the droplets to spread farther around and so that the droplets from two sprays to gradually approach in the area between the two sprays. The reduction in the distance between the droplets from two sprays leads to an increase in the interaction between different sprays, which limits the further proximity and merger of the two sprays. As a result, a higher voltage causes the droplets to spread over a wider range. The droplets tend to spread to the outside, while spreading to the area between two sprays is limited. When increasing the flow rate and keeping the voltage constant, the sizes of the droplets formed in spray increase. These larger droplets will carry more charge and this also results in strong interaction between internal droplets of a spray and the interaction between sprays. In this case, the droplet spreading trend is similar to the above case.

The simulation results will also guide the experiment and it can reveal the approximate area of droplet deposition, which is obviously very important for the experimental configuration. In addition, using simulation methods, we can also understand the effect of capillary spacing on electric field strength and droplet motion, which is also helpful for the design of atomizer.

The droplet deposition characteristics are simply tested and the results partially support the simulation on the droplet motion.

References

- [1] J. Osuntokun, P.A. Ajibade, Structural and thermal studies of ZnS and CdS nanoparticles in polymer matrices, *J. Nanomater.* 2016 (9) (2016) 1–14.
- [2] M.B. Gebeyehu, Y.H. Chang, C.M. Wu, et al., Fabrication and characterization of silver nanofibers using coaxial electrospinning process, *RSC Adv.* 6 (59) (2016) 54162–54168.
- [3] B. Seong, S. Ha, H.U. Kim, et al., Deposition of controllable nanoparticles by hybrid aerodynamic and electrostatic spray, *Nano* 12 (02) (2017) 4343–4349.
- [4] J.D. Regele, M.J. Papac, M.J.A. Rickard, et al., Effects of capillary spacing on EHD spraying from an array of cone jets, *J. Aerosol Sci.* 33 (11) (2002) 1471–1479.
- [5] S.R. Snarski, P.F. Dunn, Experiments characterizing the interaction between two sprays of electrically charged liquid droplets, *Exp. Fluids* 11 (4) (1991) 268–278.
- [6] P.F. Dunn, S.R. Snarski, Velocity component and diameter distribution characteristics of droplets within two interacting electrohydrodynamic sprays, *Phys. Fluids A Fluid Dyn.* 3 (3) (1991) 492–494.
- [7] A.J. Rulison, R.C. Flagan, Scale-up of electro spray atomization using linear arrays of Taylor cones, *Rev. Sci. Instrum.* 64 (3) (1993) 683–686.
- [8] B.Q.T. Si, D. Byun, S. Lee, Experimental and theoretical study of a cone-jet for an electro spray microthruster considering the interference effect in an array of nozzles, *J. Aerosol Sci.* 38 (9) (2007) 924–934.
- [9] A.N. Hubacz, J.C.M. Marjijnissen, The scale-up of electrohydrodynamic atomization, *J. Aerosol Sci.* 34 (Suppl. 1) (2003) S1269–S1270.
- [10] M.S. Lhernould, P. Lambert, Compact polymer multi-nozzles electro spray device with integrated microfluidic feeding system, *J. Electrostat.* 69 (4) (2011) 313–319.
- [11] R.P.A. Hartman, J.P. Borra, D.J. Brunner, J.C.M. Marjijnissen, B. Scarlett, The evolution of electrohydrodynamic sprays produced in the cone-jet mode, a physical model, *J. Electrostat.* 47 (1999) 143–170.
- [12] S. Martin, A. Perea, P.L. Garcia-Ybarra, et al., Effect of the collector voltage on the stability of the cone-jet mode in electrohydrodynamic spraying, *J. Aerosol Sci.* 46 (4) (2012) 53–63.
- [13] J.H.W. Lee, V. Cheung, Generalized Lagrangian model for buoyant jets in current, *J. Environ. Eng.* 116 (6) (1990) 1085–1106.
- [14] P.D. Yapa, L. Zheng, F. Chen, A model for deepwater oil/gas blowouts, *Mar. Pollut. Bull.* 43 (7) (2001) 234–241.
- [15] H. Chen, W. An, Y. You, et al., Numerical study of underwater fate of oil spilled from deepwater blowout, *Ocean Eng.* 110 (2015) 227–243.
- [16] M. Cloupeau, B. Prunet-Foch, Electrostatic spraying of liquids in cone-jet mode, *J. Electrostat.* 22 (2) (1989) 135–159.
- [17] W. Wei, Z. Gu, S. Wang, et al., Numerical simulation of the cone-jet formation and current generation in electrostatic spray—Modeling as regards space charged droplet effect, *J. Micromech. Microeng.* 23 (1) (2013) 15004–15014 (11).
- [18] H. Liu, Science and Engineering of Droplets: Fundamentals and Applications (Materials and Processing Technology), Noyes Publications, Park Ridge, NJ, 2000.
- [19] N. Ashgriz, A.L. Yarin, Capillary Instability of Free Liquid Jets, *Handbook of Atomization and Sprays*, Springer US, (2011) 3–53.
- [20] R.P. Grant, S. Middleman, Newtonian jet stability, *AIChE J.* 12 (4) (1966) 669–678.
- [21] J. Zhang, H. He, Simulation on motion of a group of charged droplets in an electrostatic spray, *Atomization Sprays* 22 (1) (2012) 37–56.
- [22] Z. Wang, L. Xia, S. Zhan, Experimental Study on Electrohydrodynamics (EHD) Spraying of Ethanol with double capillaries, *Appl. Therm. Eng.* 120 (25) (2017) 474–483.