Droplet charging in electro-atomization study

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Abstract. There is a big difference between electrostatic atomization and other conventional atomization such as mechanical and air flow atomization. The mechanisms underlying the rupture and atomization of Newtonian fluid jets in the electric field have not been well understood. In this study, we experimentally evaluated the diameter of the droplet produced by charged jet breaking up in electric field, and obtained an empirical relationship between the flow rate and droplet diameter. These results may provide theoretical guidance to further understand the mechanism of liquid atomization in the electric field, and be of great significance to promote the application of electrostatic atomization in the field of atomization.

1. Introduction
The thrust chamber of Liquid Rocket Engine (LRE) consists of injector, combustor and spray tube. In the thrust chamber, the propellant is converted into gaseous reaction product with high temperature by spraying up, atomizing, mixing and combusting, which then speeds up and blows out at high velocity, resulting in the formation of propulsive force [1]. Atomization plays a critical role in the propellant combustion process, as the specific impulse, propulsive force, and combustion stability of engine depend greatly on the propellant atomization. Propellant atomization of LRE is orchestrated by the spray nozzle. Spray nozzles with different structures blow out free jets with different cross section shapes, which then rupture under the disturbance or external force and further break up into thinner droplets to accomplish atomization.

Charged atomization is a new type of atomization technology. This method does not require any special nozzle structure and is able to achieve very good performance of atomization. What it needs is just small input of additional electric power. The size of droplets formed by charged atomization is small. It can reach the nanometer level under certain conditions [2]. The charged atomization technology has a wide range of applications in the spray, inkjet printing and other fields.

When the liquid jet flows out of the nozzle, the initial section will be liquid column shape. The effect of charging on the initial column jet of spray has been investigated both theoretically and experimentally in references [3-12]. When the jet is charged, as the charge increases, the length of the intact jet decreases, the jet breaks up earlier. Reference [6] presents the theoretical formula describing the variance of jet diameter against liquid viscosity.

As we can see from the relevant research, with the increase in voltage applied to the jet, the capillary jet takes on the following flow patterns successively: the drop pattern, the pulsation mode, the spindle mode, the cone jet mode, and the multi-jet mode. The background of the present work is to provide a technical support for the study of the interaction between droplets and flames, hence the drop pattern with a low voltage is studied in this article. Since the relationship among the droplet diameter, the charged quantity and applied voltage, the distance between the nozzle and ring electrode,
the nozzle diameter, and the liquid flow rate have not been well recognized yet, it is very difficult to precisely control the charge and droplet diameter in the experiment. We mainly experimentally investigated the rupture of charged jet in this study.

2. Experiment

The charged jet generation system consists of high-voltage power supply unit, fluid supply system, jet nozzle, attached experiment bench and so on. In order to conveniently control liquid flow rate to form stable jet and droplet, and simultaneously to protect the instrument from high voltage power supply, the system needs to have superior insulation performance.

2.1 High-voltage power supply unit

We employed the high-voltage power generator (Model No. LPZ-20-Ia) produced by Nanjing Xinxing electrostatic spraying company. Technical parameters are shown in Table 1.

Table 1. Technical parameters of high-voltage power generator

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Input voltage AC                 | 220 V±10%              |
| Maximum output voltage DC        | 110 kV                 |
| Adjustable range                 | 0–100 kV               |
| Resolution regulation           | < 2 V                  |
| Regulation mode                  | Potentiometer          |
| Output voltage regulation        | < 0.1%                 |
| Output load regulation           | < 0.5%                 |

The high-voltage power generator adapts 3U standard chassis, the front panel of which has power switch, out switch, reset button, and two groups of output sockets that show output voltage and current value respectively, while the back panel has fuse block, AC220V input electric outlet, earth clip and so on. Additionally, the generator is equipped with over current and short circuit protections.

2.2 Flow supply system

In order to better control liquid flow rate to form stable jet and droplet, we employed miniature syringe pump to supply refrigerant solution and measure flow rate, which could achieve high control accuracy. Technical parameters of miniature syringe pump (Model No. LSP01-1A, Baoding Lange constant flow pump Co. Ltd.) are shown in Table 2.

Table 2. Technical parameters of miniature syringe pump

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Precision accuracy               | ±0.5%                  |
| Repetitiveness                   | ±0.2%                  |
| Maximum stroke                   | 140 mm                 |
| Line speed range                 | 5 μm/min–65 mm/min     |
| Current source                   | AC 90 V–260 V          |
| Size                             | 280×210×140 (mm)       |
| Weight                           | 3.6 kg                 |
| Ambient temperature              | 0℃–40℃                 |
| Relative humidity                | <80%                   |

2.3 Electrostatic voltmeter

The voltage was measured using electrostatic voltmeter (Model No. Q3-V, Beijing Yuandong Instrument Co., Ltd.). Technical parameters are shown in Table 3.

Table 3. Technical parameters of electrostatic voltmeter

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Range                            | (0-7.5) KV, (0-15) KV, (0-30) KV |
| Ambient temperature              | 0℃–40℃                 |
| Relative humidity                | <85%                   |
| Exchange frequency scope         | 20 HZ-5 MHZ            |
2.4 Experiment device

The charged jet generation system mainly consists of electrostatic voltmeter, high-voltage generator, injection pump, pipeline, experiment platform, spray nozzle, computer and ring electrode. The pipeline material quality is PVC, while the experiment platform is made of PTFE. The material quality of the spray nozzle is 1Cr18Ni9Ti, with a internal diameter 0.37mm. The output terminal of the high-voltage generator connects with the exterior tip of the spray nozzle. The computer, high-speed photography and optical source comprise the image acquisition system. Charged modes of jet mainly include Contact, Sensitive and Corona charge. For Contact charge, the medium is polarized in the interior of the spray nozzle, and atomized in both the mechanical and Coulomb forces. The atomization induces medium polarization and then separation of the electrical double layer, while the atomized droplet is static charged. This charging effect is quite preferable, as the droplets produced by jet breakup carry the same charge with the electrode. Therefore, the Contact charge was employed in our experiment: positive electrode of the high-voltage generator connects with the tip of the capillary tube, while negative electrode of the generator, electrostatic torus and other nearby precision instruments connect to the ground. All connection sites are insulated. The flow rate is controllably stable by adjusting the injection pump, then the liquid effuse from the spray nozzle. Adjust the voltage on the generator, precisely measure and control the voltage using the electrostatic voltmeter.

2.5 Image processing

We can just obtain qualitative but not quantitative results using initial images of the jet and droplet from high-speed camera in the experiment. In order to better analyze the experimental data, we aim to establish an image processing method. Take the shooting of the jet image for example: adjust high-precision using digital control interface, define appropriate exposure rate, simultaneously measure and record the jet flow rate. Then, the optical signals from camera lens are converted to digit signals that could be recognized by the computer using high-speed photography, as a consequence, the jet image can be obtained in the computer (Fig. 1). The shooting of the droplet image is similar to that of the jet image.

2.6 Experiment program

In this study, we selected alcohol, ultra-pure water, 5% or 10% NaCl as experimental medium, the parameters of which are shown in Table 4. The capillary diameter is 0.37 mm, the flow is 4 ml/min. To ensure that the jet burst in the drop mode, the supply voltage is set as 0 ~ 5.5 KV. The distance
between the nozzle tip and the ring electrode is 2.5 cm to make sure that the droplet falls at the center of the ring electrode. Detailed experimental device settings are provided in reference [13]. The images are shot with a shooting speed of 1971 frames/sec. A representative image of the obtained droplets produced by jet breakup is shown in Fig. 2. The droplet diameters were obtained using image analysis.

Table 4. Parameters of experimental mediums

| Medium       | Density (kg/m³) | Coefficient of Dynamic Viscosity (kg/ms×10⁻³) | Relative Permittivity |
|--------------|-----------------|-----------------------------------------------|-----------------------|
| Alcohol      | 788             | 1.06                                          | 25.7                  |
| Ultra-pure water | 998         | 0.89                                          | 78.5                  |
| 5% NaCl      | 1035            | 1.0097                                        | 78.94                 |
| 10% NaCl     | 1070            | 1.0132                                        | 79.76                 |

Figure 2. A representative image of the droplets produced by jet breakup

As shown in Fig. 2, the droplet size is not uniform. In order to ensure the consistency of each continuous droplet, we selected the process of continuous drops of droplets in the drop mode for further experiments. The droplet diameter is quite uniform under the precise control of the flow system.

2.7 Droplet size distribution

We measured the sizes of droplets produced by liquid jet breakup, including the initial droplets. As shown in Fig. 3, in which percentage of diameter A/% versus diameter d, the diameter of most droplets was approximately 0.3 mm.
To better understand the mechanisms underlying jet breakup, we investigated the breaking up of jet into droplet in three different kinds of fluids (alcohol, water, NaCl). As shown in Fig. 4, the charged-droplet diameter increases with mounting flow rate in alcohol, ultra-pure water, 5% NaCl or 10% NaCl. Under the same flow rate, the droplet diameter in alcohol was obviously smaller than that in the other three liquids, maybe due to the smallest relative permittivity and consequent poorest electrical conductivity in alcohol.

We further processed the data in Fig. 4, and defined the dimensionless droplet diameter and jet flow. The dimensionless droplet diameter is defined as:

$$D = d / (\beta - 1)^{1/3} d_0$$  \hspace{1cm} (1)

the dimensionless jet flow $\dot{M}$ is defined as:

$$\dot{M} = \left[ \dot{m} / (\beta - 1)^{1/2} \dot{m}_b \right]^{1/3}$$  \hspace{1cm} (2)

The droplet diameter and jet flow are converted to dimensionless parameter according to equations (1) and (2). As shown in Fig. 5, the relationship curve between the dimensionless droplet diameter and liquid flow is obtained. Using least square method, the curve is further fitted to the following equation:

$$d / (\beta - 1)^{1/3} d_0 = 0.8 \left[ \dot{m} / (\beta - 1)^{1/2} \dot{m}_b \right]^{1/3} + 0.1$$  \hspace{1cm} (3)
where \( d \) is the droplet diameter, \( \dot{m} \) is the liquid flow,

\[
d_o = \left[ \frac{\sigma \varepsilon}{\rho K} \right]^{1/3}, \quad \dot{m}_o = \frac{\sigma \varepsilon}{\rho K}.
\]

Comparison between the equation fitted from Fig. 6 and previous studies, suggests the equation (3) is superior to previous equation\(^{[6]}\) in evaluating the droplet precision.

![Graph showing the relationship between dimensionless droplet diameter and flow rate](image)

**Figure 5.** Dimensionless droplet diameter \( D \) versus \( Q \)

### 3. Conclusion

In this study, we experimentally investigated the droplet electrification, and obtained computational formula of the dimensionless droplet diameter and flow rate through investigating charged breakup of different fluids (alcohol, water, NaCl), which may provide an experimental foundation for further understanding of the electro-atomization theory.

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