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The atomization current and droplet size of ethanol in two different small-scale electro-spraying systems

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ABSTRACT

An experimental study on electro-spraying from small-scale combustors is carried out using liquid ethanol as fuel. Two systems of electro-spraying are employed in the present study; one is a nozzle system (without a ring electrode) and the other is a nozzle-ring system (with a ring electrode). The photos of electro-spraying at the cone-jet mode are taken by a digital camera. The voltage drop across the resistance in the loop is measured by a data acquisition instrument, and the atomization current is calculated according to Ohm's Law. The size and velocity of electro-spraying droplets are measured by a Phase Doppler Anemometer. A non-dimensional analysis on atomization current is completed to explain the electro-spraying phenomena of liquid at the stable cone-jet mode. The results show that, the lower atomization current and droplet velocity corresponds to smaller size of droplet. Based on the results of non-dimensional analysis, it is found that the dimensionless atomization current in both the nozzle system and nozzle-ring system obeys the scaling law as square root of the dimensionless flow rate. The charge density is of a -1.5 power dependence on droplet diameter. Both of the nozzle and the nozzle-ring systems show a good agreement with Rayleigh instability.

1. Introduction

With the progress in micro-fabrication techniques, there is an increasing demanding for the miniaturization of mechanical and electro-mechanical engineering devices. The miniaturized power generating devices using liquid hydrocarbon as fuel with high specific energy may have more competitive advantages than those using batteries [1–2]. Zeleny photographed drops held at the end of capillary tubes and raised to a high potential, forming a jet of glycerine from an electrified drop [3]. Since then, many experiments and simulations have been carried to study this phenomenon [4–9]. A conical meniscus is formed at the tip of the nozzle, and followed by a ligament, the narrow jet broken into monodisperse droplets due to Rayleigh instability. No droplets coalescence will take place due to the coulombic forces generated by the electric field; this mode of electrospray is known as "cone-jet" mode [10]. Thong and Weinberg [11] used the electric fields for dispersing solid and liquid fuels, and this made it possible that the droplet size and the charge in terms of the parameters of applied electrical, geometrical and flow can be predicted.

The cone-jet is a stable atomization mode. Many researchers have carried out experimental investigations on the stability of the cone-jet mode and the dependence on the liquid properties, flow rate and the electrostatic conditions of the current and droplet size [12–15]. Fernandez and Loscertales [13] found that the scaling law of the spray current emits from an electrified meniscus and fits an equation based on the square root of flow rate of the highly conducting liquid. Gañan-Calvo et al. [14] found another different dependence between the current and flow rate for the liquid of low polarity. In fact, an atomization process is affected by many parameters. In order to propose a general dimensional description of the entire range of working parameter for cone-jet electrospraying, a two-dimensional parametrical 'chart' with four distinct regions and corresponding scaling laws for droplet size and current was established by Gañan-Calvo [15].

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According to the scaling laws, very low flow rate is needed to produce small droplets. A low flow-induction charger was used to improve aerosol delivery efficiency [16]. The formation of a stable Taylor cone was very important for electrospray operation. A ball-point pen electrospray emitter greatly expands the operation range in the flow rate-voltage space [17]. A ring electrode was used to prevent the Taylor cone frequently change its shape under various external disturbance [18–19]. There were many extraordinary properties of the cone-jet mode, such as monodispersity of the primary droplets; high charge on the surface of the generated droplets; controllable droplet size by varying the flow rate [12]. It remained necessary to identify whether the cone-jet spraying mode was obtained or not. The classifications are mainly based on visual observations of the liquid meniscus, but it is very hard to observe the morphology of the spraying in the practical application. Some experiments were done to research the relationship between the current and the behavior of the liquid meniscus [20–21]. Verdoold et al. [22] found a general mapping between the properties of the current through the system and the spraying mode that was independent of the material properties of the liquid, the electrode geometry and other experimental conditions.

In our previous study [19], two different electro-spraying systems were compared to investigate the effect of the ring electrode on the cone-jet characteristics. Numerical calculation was performed to investigate the effect of ring electrode on the electric field. The same electro-spraying systems are employed in the present study. The combustor in nozzle-ring system is consisted of three pieces of quartz glass tube connected by a ring electrode and a stainless steel grid electrode. Because of the reflections on the quartz tubes, the spray modes are difficult to be observed clearly, and the photos of electro-spraying can only be obtained after removing the outer surface of the combustors [19]. Although the size and velocity distributions of electro-spraying droplets could not be measured by a Phase Doppler Anemometer through the quartz tubes, the atomization current could be measured. Therefore, to obtain the relationship between the atomization current and droplet size is very important. In the present study, the photos of electro-spraying at the cone-jet mode are obtained by a digital camera. The voltage drop across the resistance between the grid and the ground is measured by a data acquisition instrument, and the atomization current is calculated according to Ohm's law. The size and velocity distributions of electro-spraying droplets are measured by a Phase Doppler Anemometer both for the nozzle system (without a ring electrode) and the nozzle-ring system (with a ring electrode). A non-dimensional analysis on atomization current is proposed to explain the electro-spraying phenomena of liquid at the stable cone-jet mode.

2. Experimental setup

2.1. The test rig

The test rig is shown in Fig. 1, which consists of a liquid fuel feeding system, a test section, a high voltage supply system. A capillary is used as a nozzle, which is supported by the substrate (a ceramic package). The fuel is supplied though a plastic tube to the nozzle by a syringe pump (KDS100, KD SCIENTIFIC, USA) with ±1.0% accuracy. The test section consists of a fuel-supply nozzle, a ring electrode (only for the nozzle-ring system) and a ground electrode (a stainless steel grid).

Three types' diagnostic techniques are employed to monitor the electro-spraying modes. They are (1) the observations, in which the photographs of different electro-spraying modes are taken by a digital single-lens reflex camera (Cannon EOS 5D Mark III) with a green laser light as an illuminating light source; (2) the size and velocity distributions measurements, of which the size and velocity distributions of electro-spraying droplets are measured by a Phase Doppler Anemometer (Particle Dynamics Analysis, Dantec, Denmark); (3) the current measurements, in which the voltage drop across the resistance between the grid and the ground is measured by a data acquisition instrument, and the atomization current is calculated according to Ohm's law.

The liquid fuel used is pure ethanol (CH_3CH_2OH, molecular weight of 46.07, purity >99.5%). A conductivity meter with ±1.0% accuracy (Rex; DDS-307A; Shanghai, China) is applied for measuring the conductivity of ethanol.

2.2. Test section

The two electro-spraying systems are employed in the present experiment, namely, the nozzle system in which the nozzle is maintained at high potential by connecting it to a direct-current (DC) power source (71030P, GENVOLT, UK), and a stainless steel grid is grounded; and the nozzle-ring system in which the nozzle and the ring electrode are connected to two DC power source (71030P, GENVOLT, UK) separately, and the stainless steel grid is also grounded. The distance between the nozzle and the stainless steel grid is the same for both the nozzle system and nozzle-ring system. Fig. 2 shows the test section and the distribution of measuring cross-sections (z = 5.0 mm, 10.0 mm) and points (No. 0-No. 16).

The inner diameter of the stainless steel nozzle is 0.90 mm ($d_n = 0.90$ mm); the outer diameter, 1.20 mm ($D_n = 1.20$ mm); the inner diameter of the ring electrode, 12.40 mm ($d_r = 12.40$ mm); the outer diameter, 16.00 mm ($D_r = 16.00$ mm); and the thickness, 5.00 mm ($\delta = 5.00$ mm). The stainless steel grid has a diameter of 16.00 mm, and each hole in it has a diameter of 1.00 mm. A high DC power source (71030P, GENVOLT, UK) is used to supply high voltage on the nozzle (V_n). For the nozzle system, the stainless steel grid is arranged above the tip of the nozzle with a vertical distance of 26.10 mm ($L = 26.10$ mm). For the nozzle-ring system, the ring electrode is arranged above the tip of the nozzle with a distance of 1.10 mm ($L_1 = 1.10$ mm), and the grid is arranged above the tip of the ring electrode with a vertical distance of 20.00 mm ($L_2 = 20.00$ mm). Another DC power source (71030P, GENVOLT, UK) is employed to supply high voltage on the ring electrode (V_r).

2.3. Measuring system

The spray current was so small that it is difficult to be measured directly by the electrometer. A standard 1 MΩ resistance is connected between the grid and the ground electrode. The electric potential difference across the resistance is measured, and the spray current is calculated by the measured potential. The signals are transferred to a computer though the data acquisition instrument (34790A, Agilent USA). The equivalent electrical circuit with spray is shown in Fig. 3, which consists of DC power sources, electro-spray, electrodes, and the standard resistance. V_n is the voltage on nozzle; V_r is the voltage on ring electrode; R_1 is the total spray resistance in the nozzle system, U_1 is the voltage of R_1; R_2 is the liquid cone-jet resistance, U_2 is the voltage of R_2; R_3 is the spray resistance in the nozzle-ring system, U_3 is the voltage of R_3; R_s is the standard resistance connected, U_s is the voltage of R_s; I is the effective value of the spray current. According to Ohm's law, the electric current can be calculated.

$$I = U_s/R_s \tag{1}$$

The electric potential difference across the resistance is 0.00–0.08 V, the power source voltage is 0.00–7.00 kV. Compared