Journal of Aerosol Science 101 (2016) 196–206

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Technical note

Effects of corona space charge polarity and liquid phase ion mobility on the shape and velocities of water jets in the spindle jet and precession modes of water electro-spray

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ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form
1 August 2016
Accepted 18 August 2016
Available online 26 August 2016

Keywords:
Electrospray
Corona discharge
Polarity effect
Ion mobility
High-speed camera

ABSTRACT

The paper presents the experimental study of the effect of ions of different mobilities (H^+, Cl^-, Li^+ and OH^-) in electrosprayed water solutions under atmospheric pressure conditions in air and in SF_6 background gas. Generally, at the atmospheric air conditions, the main difference between water electrospray (ES) in positive and in negative polarities is the shape and elongation direction of the water jets propagating from the charged nozzle. These phenomena can be associated with the movement of ions in water (i.e. the mobility of ions) or with the influence of the corona discharge and its ionic space charge. A comparison of HCl and LiOH water solutions with inversed mobility ratios of cations and anions showed that the mobility of ions inside the liquid is not an important parameter determining this difference between two ES polarities. The combined measurements in atmospheric air and SF_6 gas clearly showed that the only important factor determining the different shapes and propagations of the water jets for both polarities is the corona discharge and its ionic space charge.

1. Introduction

Electrospray (ES) of liquids occurs when an electric field of sufficient strength acts on the liquid surface that flows through a capillary. The electric field induces the surface charge density, which leads to a radial electrostatic pressure on the surface equilibrated by the capillary pressure. Subsequently, the critical volume of a liquid droplet before tearing off from the capillary decreases and the droplet is eventually deformed into a conical shape called Taylor cone. Critical voltage for the

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http://dx.doi.org/10.1016/j.jaerosci.2016.08.008
0021-8502/

formation of ES from the Taylor cone scales with the liquid surface tension as $\gamma^{1/2}$ and there must be a balance between the capillary pressure and the normal electrostatic pressure at the conical liquid surface (De La Mora, 2007; Higuera, 2003);

$$\frac{\gamma}{r} = \varepsilon_0 \frac{E^2}{2} \tag{1}$$

where r is the local Taylor cone radius, E is the normal electric field in the gas and ε_0 is the permittivity of vacuum. The pioneering experimental works in this field were conducted by (Zeleny, 1914, 1917). Later, another important theoretical study was conducted by Taylor (1964).

Regarding the various ES modes, they have been thoroughly evidenced and discussed in many papers (Borra, Ehouarn, & Boulaud, 2004; Borra, Tombette, & Ehouarn, 1999; Cloupeau & Prunet-Foch, 1990, 1994; Grace & Marijnissen, 1994; Jaworek & Krupa, 1999). The most studied mode is the cone–jet mode for the constant drop size distribution. In case of liquids with high surface tension (e.g. water) the necessary voltage for cone–jet mode generation can be higher than the electrical breakdown threshold of the surrounding gas. In this situation, a disruptive electric discharge can ensue and prevent or destabilize this mode. Many authors recommended stabilizing ES in gases such as CO_2, O_2, SF_6 or Freon rather than noble gases at both high and low pressures (Cloupeau & Prunet-Foch, 1990; Smith, 1986; Straub & Voyksner, 1993; Tang & Gomez, 1995; Wampler, Blades, & Kebarle, 1993).

In the last decades, the ES phenomenon became the subject of extensive studies and found important applications in many diverse fields, such as nanotechnology, thin film deposition, drug inhalation, spray painting and surface coating, ink-jet printing, and as a source of ions of macromolecules for mass spectrometry (Bailey, 1988; Fenn, Mann, Meng, Wong, & Whitehouse, 1989; Jaworek, 2007). All the above mentioned applications of ES are typical for cone–jet mode at low flow rates and without electrical discharge. High flow rate modes with or without electrical discharge typically generate large droplets irregular in size, which renders them of lower practical importance. One example of the high flow rate ES mode applications is electro-filtration (Ehouarn, Unger, & Borra, 2001; Unger, Ehouarn, & Borra, 2003). Recently, novel bio-medical applications of relatively high flow rate water electrospray in combination with plasma discharges have been introduced (Kovaľová, Zahoran, Zahoranová, & Machala, 2014; Machala et al., 2013).

There are not many works dealing with the polarity effect on the electrosprayed water jets which is the main topic of this paper. Kuroda and Horiuchi (1984) attributed different looking phenomena of the negative and positive ES to the difference between positive and negative corona discharge. They claimed the corona ionic space charge field reduces the surface electric field of the droplet. Cloupeau and Prunet-Foch (1994) observed that spraying is less easily disturbed by positive corona discharges rather than negative corona. They also stated that the spraying phenomena should remain the same whatever the polarity, as long as there is no corona discharge. Their explanation was also based on the regulating effect of the corona discharge on the electric field, as confirmed e.g. by Borra, Hartmann, Marijnissen, and Scarlett (1996), Borra et al. (1999, 2004, 2001). According to Jaworek and Krupa (1996a, 1997), Jaworek, Sobczyk, Czech, and Krupa (2014) the differences between positive and negative ES are caused by the corona space charge, which locally reduces the electric field at the liquid meniscus. They supposed that for the positive polarity the space charge formed by the positive ions in the drift region is more stable than in the negative polarity, where the current is mainly conducted by electrons. They also stated that the length of the jet from the apex of the Taylor cone to the point of its breakdown is shorter for negative polarity than for positive one, but this difference decreases with the increasing jet velocity. Borra et al. (1996, 1999, 2004, 2001) studied the effect of positive corona discharge development on water ES for impulse transient discharges destabilizing the ES in the unstable electric dripping and micro-dripping modes including the below discussed spindle mode. They also investigated the ES of water stabilized by continuous atmospheric glow corona discharge in the corona assisted cone–jet mode. The space charge field induced by gaseous ions created by these discharges temporarily decreased the field in the gas around the liquid. In the paper Borra et al. (2004) dealing with the ES of water stabilized by glow discharge they postulated that all their results presented and obtained under the positive polarity were similar under the negative polarity. However, their postulate was not supported by experimental results in the negative polarity and is not consistent with the results of other authors mentioned in this paper. De La Mora (2007) in his comprehensive paper also noted that negative ES of high surface tension liquids are harder to stabilize than positive ones because of the increased presence of electrical discharges.

To our best knowledge, the most of the above mentioned papers showed no direct experimental results dealing with the polarity effect on the jet behavior; except some statements and hypotheses. Recently, Kim et al. (2014) observed the effect of polarity on water ES with the presence of corona discharge. The essential differences particularly in the spindle ES mode were the shape and elongation direction of the water jets according to the polarity. In positive polarity, the water jet propagated straight toward the counter-electrode with a forward-tapered shape. On the contrary, a negative water jet elongated with a round-shaped front, and the inverse-tapered shape appeared toward the nozzle tip. They introduced a new hypothesis that different spray patterns can be associated with the movement direction of the ionic species in water. If the mobility of positive ions is higher than the mobility of negative ions, the positive ions accelerate faster than negative ions due to the presence of the electric field.

In this paper, we investigated the nozzle polarity effect on the electrosprayed water jets in the spindle and precession modes at high flow rate water, producing a very large size distribution of droplets from a few to tens of micrometers. We experimentally verified the effect of different ion mobility ratios by using various water solutions. We also showed the experimental results demonstrating the effect of corona discharge on the water jets observed by high-speed camera imaging