Experimental Thermal and Fluid Science 100 (2019) 328–336

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Investigating the effect of electrical conductivity on electrospray modes

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ARTICLE INFO

Keywords:
Electrospray
Electrical conductivity
Droplet diameter
Electro-hydrodynamic mode

ABSTRACT

This study investigated experimentally the effect of electrical conductivity on electro-hydrodynamic (EHD) modes in the electrospray process. The geometric shape of the micro-droplets having different electrical conductivity was studied. For this purpose, three fluids, including acetic acid, ethanol, and toluene, were selected as the representation of three different fluid classifications in terms of electrical conductivity. The difference in conductivity of these fluids can be characterized by **α** denoting the ratio of electrical relaxation time to the characteristic hydrodynamic time. The experiments showed that the increase in **α** did not significantly affect the transfer of the EHD modes. In addition, analytical and graphical investigations showed why ethanol as a leaky dielectric fluid produced lower droplet diameters in comparison with acetic acid as a conductive fluid at highest electrical capillary numbers. Also, a pulsation mode was monitored in the experiments related to toluene as a dielectric fluid. Finally, an equation was presented for calculating the dimensionless diameters of ethanol droplets and acetic acid using non-dimensional numbers derived from the experimental data.

1. Introduction

Electrospray is a physical process producing fine liquid droplets on a fluid surface by induced charges due to applied electric field. The liquid is elongated downward under the influence of electrical and inertial forces as well as gravity. Liquid jet disrupts into droplets when these forces overcome the surface tension. Michelson [1] stated that the formation of the fine droplets in the electrospray was usually a result of hydrostatic equilibrium between electrostatic and surface tension forces. He showed that the surface tension was suppressed by the electrical potential. Rayleigh [2] oversimplified the electrospray process in his analysis, considering only the electric stresses and surface tension, while other factors such as fluid conductivity, nozzle diameter, applied voltage and flow rate should also be considered. Therefore, it is expected that various fluid behaviors or electro-hydrodynamic (EHD) modes occur by changing the effective parameters involved in the electrospray process. EHD modes can be divided into two main groups, including dripping and jetting. In the first case, only a liquid fragment is separately issued from nozzle, but in the second form, a long continuous jet emitted from the capillary tube tip is disintegrated into fine droplets in certain distances from the capillary tube. In fact, electric charges existing on the liquid jet surface cause the electrostatic repulsive forces to result in kink or whipping instabilities, tending to break up the jet into a spray of small droplets. Considering the electrospray potential for producing uniformly sized droplets, it can be an adequate substitute for conventional methods of fabricating droplets. Recently, electrospray has been widely used as a new method for the fabrication of micro- and nano-scale particles, including disintegration, combination, and mixture of powder, surface coating and encapsulation.

So far, several experimental studies have been done on the classification of EHD modes in the electrospray phenomenon. Hayati [3], Cloupeau and Prunet-Foch [4] and Jaworek [5] tried to present a comprehensive classification of EHD modes. Recently, many details of this classification have been revealed by Hung Ha Kim [6] using a high-speed camera. In 2018, Wang et al. did experimental studies on ethanol using a double capillary system to monitor electro-hydrodynamic (EHD) spraying of this fluid. They observed different types of electrospray modes, including dripping, spindle, pulsed, tiled straight, and multi jet modes and their transformations [7]. Also, there have been a number of experimental studies into the impact of effective parameters on EHD modes and droplet diameter in the electrospray process [8–11]. Recently, Verdoold et al. have proposed that the electric current can effectively control the electrospray process and droplet diameter [12].

The effects of electrical conductivity, viscosity, liquid density and flow rate were studied in the electrospray process in the cone-jet regime [13]. In order to study the electrical properties of the fluid, Pui and Chen [14] investigated the effect of dielectric constant on the cone-jet mode, ultimately resulting in the introduction of scale rules between

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https://doi.org/10.1016/j.expthermflusci.2018.09.012
Received 18 May 2018; Received in revised form 6 September 2018; Accepted 14 September 2018
Available online 22 September 2018
0894-1777/

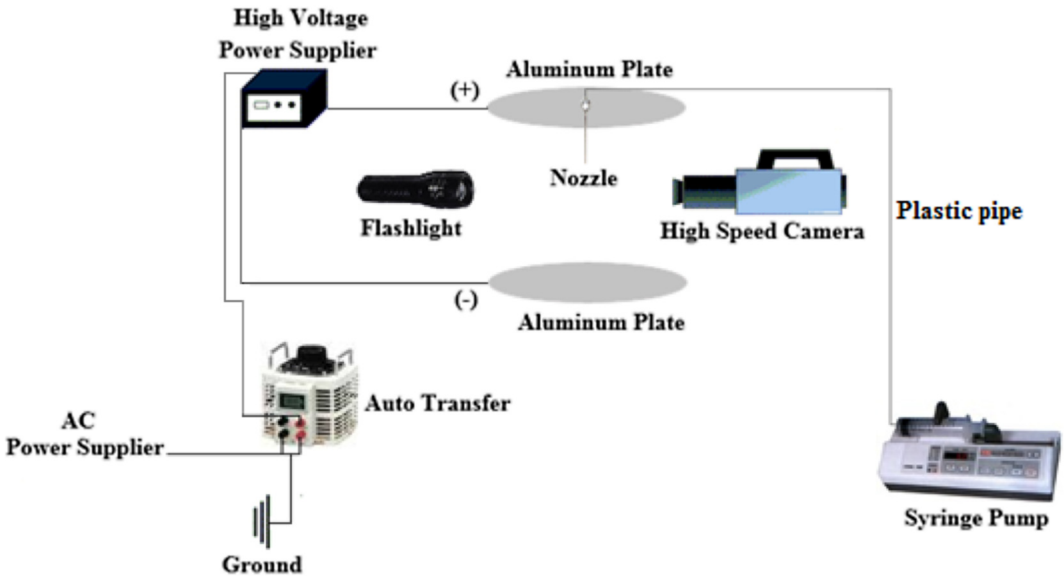

Fig. 1. Schematic of electrospray system.

droplet production and dielectric constants.

It has been found that the difference between the electrical properties of the liquid jet and the surrounding air under the external electric field creates the driving force at the interface of two fluids. Hence, it seems that electrical properties play a dominant role in the size of droplets and EHD modes generated via the electrospray process. Despite the importance of fluid conductivity and electrical properties, few papers have considered this parameter. Smith [15] found that increasing the electrical conductivity of a leaky dielectric fluid by adding ionic solution had no effect on the onset voltage of the process, but decreased the formed droplet diameter.

Using suitable additives, Barraro et al. also concluded that the electric field mainly influenced the formation of Taylor cone. They also found that electrical conductivity played an essential role in the formation of tangential electrical tensions on the cone surface [16]. Carol and Joo found that increasing the electrical conductivity of leaky dielectric liquid through adding salt tended to delay jet thinning [17]. Recently, by adding KCl, Faraji et al. studied the role of electrical conductivity in distilled water [18].

Regarding the studies done on the electrospray and its influential parameters, it seems that the effect of electrical properties of fluids is poorly understood. Therefore, further exploration is needed to determine the role of electric conductivity in the electrospray process.

The present study was an attempt to investigate the effect of electrical conductivity of liquid on the droplet diameter and EHD modes generated by the electrospray process. For this purpose, instead of using additives, three types of liquid were used to enhance the electrical conductivity: conductive, dielectric, and leaky dielectric. It is worth mentioning that these three types had different electrical properties, while other properties were kept constant. Parametric analysis was carried out using dimensionless numbers. Moreover, a statistical model was derived to estimate the diameter of droplets which may help the production of nano-powders for surface coating and encapsulation.

2. Dimensionless numbers

The effect of physical properties involved in the current research was studied in terms of related dimensionless numbers to provide an accurate interpretation and achieve better understanding of the droplet formation. In this study, the electric field was characterized by electric capillary number Ca_e:

$$Ca_e = \frac{\varepsilon_0 E_\infty^2 D}{\gamma} = \frac{\varepsilon_o(\psi^2)}{\gamma D} \tag{1}$$

where ε_0 is the permittivity of free space; ψ is the applied electric field between two electrodes; γ is the surface tension and D is the outer diameter of nozzle. Indeed, electric capillary number represents the relative effect of electrostatic forces versus surface tension. Volumetric flow rate of the fluid exited from the nozzle is specified by Weber number written as:

$$We = \frac{\rho(U^2)D}{\gamma} \tag{2}$$

where ρ the solution density, D as a characteristic length is the outer diameter of nozzle, and U is the velocity of fluid emitted from the nozzle outlet calculated by the applied flow rate of syringe pump:

$$U = \frac{Q}{\pi r^2} \tag{3}$$

where Q is volumetric flow rate and r is the inner radius of nozzle. The Weber number shows the ratio of the inertial force to the surface tension. It is worth mentioning that the volumetric flow rate of each fluid exited from the nozzle was kept constant within experiments, here. Hence, Weber number is constant in all experiment analyses.

Physical properties, including permittivity and electrical conductivity of solution are characterized by a dimensionless parameter measured by the ratio of electrical relaxation time to characteristic hydrodynamic time:

$$\alpha = \frac{\tau_e}{\tau_H} \tag{4}$$

where τ_e is the electrical relaxation time, $\tau_e = \frac{\varepsilon\varepsilon_o}{\sigma}$, measuring the speed of charge relaxation, ε is the permittivity of the solution; σ is the electrical conductivity and τ_H is the hydrodynamic characteristic time defined as below:

$$\tau_H = \sqrt{\frac{\rho D^3}{\gamma}} \tag{5}$$

The values of physical properties involved in the study were measured and used to calculate the dimensionless numbers.