Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 55(5) (2023) 127-130
DOI: 10.22060/mej.2023.21382.7440

Experimental investigation on the geometrical characterization of the cone-jet mode of electrospray of ethanol-water mixtures with different concentrations by high-speed imaging

M. Bagherian Dehaghi, M. Shams*, P. Naderi

Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran

ABSTRACT: Due to the vast and diverse applications of electrospray in various aspects of human life, this subject has always been of interest to researchers. This article discusses the experimental investigation of the electrospray process for the ethanol-water mixture with three different concentrations of 70%, 96%, and 99.9%. In this article, different electrospray modes for 70% ethanol, based on high-speed images, are defined and explained. For three concentrations of 70%, 96%, and 99.9% of the ethanol-water mixture, the Taylor cone angle and the jet diameter at the onset and end of the stable electrospray region have been calculated. For this purpose, high-speed imaging and processing of the resulting images have been utilized. The cone angle and the diameter of the jet exiting from the cone for the three fluids have been calculated for all onset and end points of the stable electrospray region for flow rates ranging from 0.1 to 1 mL/h. The average jet diameter for all points of the stable region for 70%, 96%, and 99.9% ethanol fluids is equal to 34.43, 33.78, and 31.70 microns, respectively. Additionally, the average cone angle for all points of the stable region is 87.26°, 85.80°, and 84.13° for ethanol fluids, 70%, 96%, and 99.9%, respectively. Therefore, the highest cone angle and jet diameter values correspond to 70% ethanol, and the lowest values correspond to 99.9% ethanol. When contrasting this article's experimental data with Ganan-Calvo's cone-jet scaling laws, validity is limited to $\varepsilon'\delta_\mu$ values of 0.01 to 100; higher ranges reveal significant deviations.

Review History:

Received: May, 10, 2022
Revised: May, 11, 2022
Accepted: Jun. 18, 2023
Available Online:Jul. 19, 2023

Keywords:

Jet diameter
cone angle
stable region
cone-jet mode
ethanol-water mixture
electrospray

1- Introduction

Electrospray is the process of separating small parts of fluid due to electrical stresses, which is another name for electrohydrodynamic spray [1].

The measurement of the cone angle and the diameter of the electrospray jet are critical geometric parameters that significantly influence the stability of the electrospray. Unfortunately, only a limited number of articles have addressed this subject. In these articles, the main focus is establishing a relationship between the cone angle and the onset voltage [2, 3-5]. However, these equations are not universally applicable to all fluids and operational conditions of electrospray. Instead, they are valid only within specific ranges of physical properties and geometric characteristics of the electrospray setup.

To improve our understanding of electrospray stability, it is essential to conduct further research that encompasses a broader range of fluids and operational parameters. By doing so, we can develop more comprehensive equations that account for the diverse physical properties and geometric characteristics associated with different electrospray setups. This, in turn, will enable more accurate predictions of the onset voltage and ultimately enhance the overall stability of electrospray systems.

The seminal research in the field of cone angle calculation is Taylor's article in 1964, which determined the half-cone angle of the electrospray to be 49.3 degrees [6]. In a more recent article, the half-cone angle of an electrospray with AC current, specifically for fluids with a high dielectric coefficient ratio, was found to be approximately 12.6 degrees [5].

The innovation of the present work is the accurate mensuration of the cone angle and the jet diameter of the DC electrospray stable region for the ethanol-water mixture with three concentrations of 70%, 96%, and 99.9%, using high-speed imaging and image processing in cone-jet mode, which has not been done in previous works.

2- Experimental setup and tests procedure

Figure 1 shows the schematic view of the setup used in this study. For high-speed imaging, a pco.dimax S camera equipped with a 200mm macro lens was utilized. The camera was connected to a laptop for efficient image storage and processing. An appropriate voltmeter was employed to accurately measure the applied voltage.

In this study, the stable region or cone-jet mode has been investigated with regards to the cone angle and the diameter of the emerging jet from the cone. Within this region, high-

*Corresponding author's email: shams@kntu.ac.ir

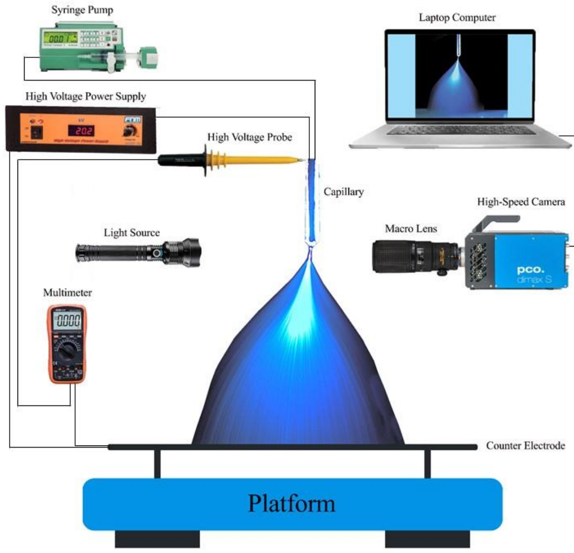

Fig. 1. Schematic view of the laboratory setup and the experiment tests process

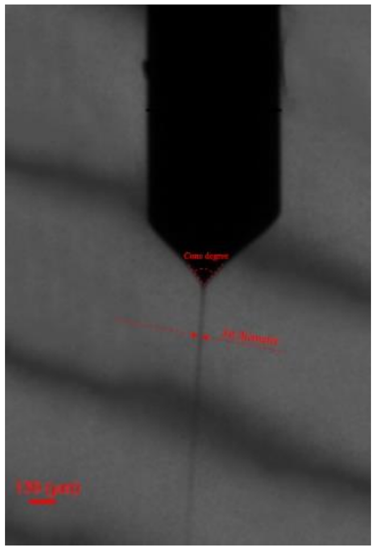

Fig. 2. A frame of high-speed imaging for electrospray of 96% ethanol in cone-jet mode.

speed images were captured for the onset and end voltages, encompassing a range of 0.1 to 1 mL/h flow rates. The process of high-speed imaging was repeated five times for each onset and end point to ensure the reliability and consistency of the experimental findings.

3- Results and Discussion

The cone angle and jet diameter play crucial roles in electrospray stability and droplet size. In this study, the high-speed images of the Taylor cone-jet mode were processed using ImageJ software. Figure 2 presents one frame from these images, providing a visual representation.

Figure 3 presents a comparative analysis of cone angles at onset points across a flow rate range of 0.1 to 1 mL/h for ethanol-water mixtures with concentrations of 70%, 96%, and 99.9%. The article also includes a similar comparison of cone angles at endpoint points within the same flow rate range. Additionally, the full text article provides a comprehensive examination of the jet diameter at these flow rates for both the onset and endpoint of the cone-jet mode.

Table 1 presents the average angle of the Taylor cone at the onset, end, and all points within the stable region in the cone-jet mode for the three aforementioned fluids.

Table 2 displays the average diameter of the Taylor cone jet at the onset, end, and all points within the stable region for the three fluids: 70%, 96%, and 99.9% ethanol.

4- Scaling Laws

It is crucial to acknowledge that achieving a steady cone-jet mode requires a flow rate that is not lower than the natural rate. The natural flow rate plays a critical role in determining both the minimum flow rate and the minimum droplet size achievable through electrospraying [7].

In a seminal paper by A. M. Ganan-Calvo in 2013, they proposed the minimum flow rate required for the Taylor cone-jet mode and its corresponding diameter [7]. While the paper did not explicitly specify the validity range for the proposed equations, they were rigorously validated using a total of 15 distinct cases, with a limited range of $\varepsilon'\delta_\mu$ values spanning from 0.01 to 100.

According to their equations, for ethanol 99.9%, the minimum flow rate is determined to be 568.97 mL/h, which is significantly higher than the minimum flow rate employed in the experiments. Additionally, the corresponding jet diameter is calculated to be 377.66 microns, which is much smaller than the average experimental value (32.98 microns). This discrepancy can be attributed to the fact that the range of $\varepsilon'\delta_\mu$ for ethanol 99.9% is 1369.93, which exceeds the validated range of 0.01 to 100 specified by the scaling laws proposed by A. M. Ganan-Calvo. While the values of $\varepsilon'\delta_\mu$ for ethanol 70% and 96% were 117.41 and 115.39, respectively, they were still in close proximity to the upper limit of the validated range. Consequently, it can be concluded that the scaling laws developed by A. M. Ganan-Calvo may not be applicable for $\varepsilon'\delta_\mu$ values that significantly deviate from 100.

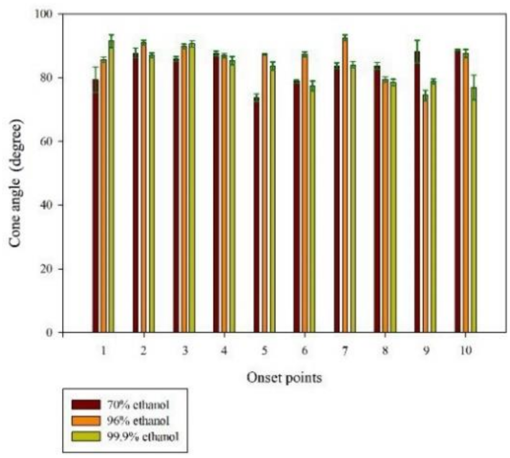

Fig. 3. Taylor cone angle for three ethanol liquids: 70%, 96% and 99.9%; Points 1 to 10 respectively correspond to the onset points of the electrospray stable area for flow rates of 0.1 to 1 ml/h.

Table 1. Average Taylor cone angle for the onset, end and all points of the electrospray stable region

Fluids	Average cone angle for all points	Average cone angle for endpoints	Average cone angle for onset points
Ethanol 70%	87.26°±1.17°	90.73°±0.92°	83.18°±1.44°
Ethanol 96%	85.80°±1.11°	85.36°±1.36°	86.23°±0.86°
Ethanol 99.9%	84.13°±1.37°	84.84°±1.30°	83.42°±1.44°

Table 2. The average diameter of the jet emerging from the Taylor cone at the onset, end and all points of the electrospray stable region

Fluids	For all points [µm]	For end points [µm]	For onset points [µm]
Ethanol 70%	34.43±1.60	33.78±1.79	35.08±1.41
Ethanol 96%	33.78±1.26	34.22±1.19	33.80±1.33
Ethanol 99.9%	31.70±1.21	30.43±1.53	32.98±0.88

5- Conclusion

This article delineates and elucidates various electrospray modes for 70% ethanol, employing high-speed imaging as the primary methodology.

Furthermore, the investigation encompasses the calculation of cone angles and jet diameters of the Taylor cone jet in the ethanol-water mixture, specifically at concentrations of 70%, 96%, and 99.9%. To accomplish this, high-speed imaging and image processing techniques are utilized within the cone-jet mode, employing flow rates spanning from 0.1 to 1 mL/h.

An additional objective of this study is to validate the scaling laws proposed by A.M. Ganan-Calvo in 2013. Through meticulous analysis of our experimental data, we discerned that these scaling laws may exhibit limited applicability for values that markedly deviate from 100. Consequently, our findings serve to identify a constraint in the practical applicability of the scaling laws devised by A.M. Ganan-Calvo.

References

[1] J. Rosell-Llompart, J. Grifoll, I.G. Loscertales, Electrosprays in the cone-jet mode: from Taylor cone formation to spray development, Journal of Aerosol Science, 125 (2018) 2-31. https://doi.org/10.1016/j.jaerosci.2018.04.008

[2] D.P. Smith, The electrohydrodynamic atomization of liquids, IEEE transactions on industry applications, (3) (1986) 527-535.

[3] A. Jones, K. Thong, The production of charged monodisperse fuel droplets by electrical dispersion, Journal of Physics D: Applied Physics, 4(8) (1971) 1159.

[4] R. Krpoun, H.R. Shea, A method to determine the onset voltage of single and arrays of electrospray emitters, Journal of Applied Physics, 104(6) (2008) 064511.

[5] R. Krpoun, Micromachined electrospray thrusters for spacecraft propulsion, EPFL, 2009.

[6] G.I. Taylor, Disintegration of water drops in an electric field, Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 280(1382) (1964) 383-397.

[7] A.M. Gañán-Calvo, N. Rebollo-Muñoz, J. Montanero, The minimum or natural rate of flow and droplet size ejected by Taylor cone–jets: physical symmetries and scaling laws, New Journal of Physics, 15(3) (2013) 033035.

HOW TO CITE THIS ARTICLE

M. Bagherian Dehaghi, M. Shams , P. Naderi, Experimental investigation on the geometrical characterization of the cone-jet mode of electrospray of ethanol-water mixtures with different concentrations by high-speed imaging , Amirkabir J. Mech Eng., 55(5) (2023) 127-130.

DOI: 10.22060/mej.2023.21382.7440