Experimental Investigation of Flow Field Inside a Taylor Cone

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Abstract
Electrohydrodynamic atomization is a technique to produce small size (diameter in the range of μm–nm), mono-disperse particles of liquid by the application of a strong electric field. Under the action of electrical force, the meniscus of fluid at the nozzle exit is elongated and a Taylor cone jet is formed. The present work investigates the flow field induced inside the Taylor cone. The induced flow field has been studied experimentally by using flow visualization and particle image velocimetry techniques. The presence of toroidal vortex has been observed and it is found that the velocity inside the Taylor cone is of the order of mm/s.

Keywords: *Electrohydrodynamic atomization; Taylor cone; Toroidal vortex*

I. Introduction

Electrohydrodynamic atomization (EHDA) is a technique to produce small size (diameter in the range of μm–nm), mono-disperse particles of liquid under the action of a strong electric field . The EHDA process has several unique advantages due to coulombic repulsion of charged droplets; such as self-dispersion, reduced coalescence, improved mixing with the oxidizer, controlled trajectory of the droplets and reduced risk of the nozzle clogging due to large diameter of the nozzle as compared to the size of the droplets. The droplets generated by the EHDA technique possess electrical charge of few orders of magnitude greater than the elementary charge [1]. The size of the droplets generated by the EHDA technique is controlled by varying the flow rate (Q), applied electrical potential (ϕ) and electrical conductivity (κ) of the fluid [2]. Grace et al. [3] have carried out both experimental and numerical study to demonstrate the behavior of droplets with in the spray. In order to overcome the disadvantage of low throughput, Jaworek et al. [4] extended it to multi-nozzle system and tested three different geometrical configurations. There is growing interest of the electrospray in recent years due to it's diverse applications in surface coatings, fuel/particle atomization, emulsification, microencapsulation, crop spraying, charged droplets scrubbing, printing, energy conversion, ultrasound contrast, mass spectrometry, blood substitute, drug and gene delivery vehicles etc. [5]–[7].

EHDA is achieved by the application of a high voltage to nozzle system (refer, Figure 1(a)). Due to the application of high voltage, a strong electric field is generated and electrical stresses are developed. These electrical stresses cause the elongation of liquid meniscus present at the capillary outlet to form a cone and the cone jet further breaks into droplets. The cone formed at the capillary outlet is known as the Taylor cone [8]. Shtern et al. [9] proposed a simplified model assuming the velocity field to vary inversely from the cone apex. They observed collapse of near-axis jets, vortex dynamo, vortex breakup, splitting of the diverging flow and hysteresis transitions between the flow. A numerical model was developed by Hartman et al. [10] for predicting the shape of cone jet, electric field inside and outside the cone, surface charge density and fluid velocity on the liquid surface. Lastow and Balachandran [11] simulated the flow field inside the Taylor cone for heptane and ethyl alcohol. They observed for the liquids, having very low conductivity and very low viscosity (e.g., butanol, heptane and ethyl alcohol) a toroid-shaped vortex is formed inside the Taylor cone. Their conclusion is consistent with the vortex dynamo described by Shtern et al. [9].

Till now, there are no experimental results available in literature (to the best of our knowledge) demonstrating the flow field inside the Taylor cone. The present work reports the experimentally captured flow field inside the Taylor cone.

II. Methodology

A. Materials and fluid properties

An organic solvent, Ethanol with 99.5% purity is purchased form the Fisher scientific has been used as the working fluid. The physical properties of fluid are as follows: density, $\rho = 789$ kg/m^3; surface tension, $\gamma = 22$

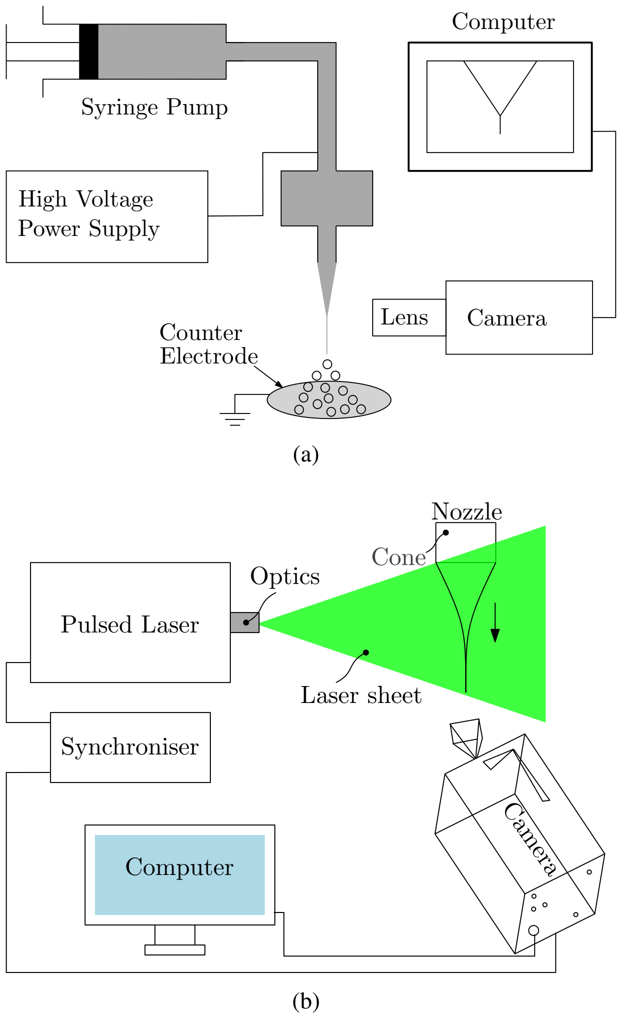

Figure 1: Schematic of experimental set-up for (a) Electro-hydrodynamic atomization and (b) Particle image velocimetry.

mN/m; viscosity, $\mu = 1.16$ mPa·s; electrical conductivity, $\kappa = 5 \times 10^{-6}$ S/m and the dielectric constant, $\beta = 25$. The surface tension of the fluid has been measured by using a manual tensiometer (Kruss Gmbh, K6), which is based on a ring method principle having a direct scale reading of 1 mN/m. The dielectric constant of the fluid is measured by using a dielectric constant meter (Brookhaven Instruments corporation, BI-870) with an absolute accuracy of $\pm 2\%$. The electrical conductivity of the fluid is measured using a conductivity meter (Eutech, Con 110). The values of ρ and μ has been adopted from the company data-sheet.

B. Experimental facility and measurement techniques

A block diagram of the experimental facility used for the EHDA (also for electrospraying) is shown in Figure 1(a). The nozzle is made of stainless steel with inner and outer diameter of 2.7 and 3.4 mm respectively. A solid copper disc of diameter 35 mm and thickness of 3 mm is used as a counter or ground electrode. A high voltage power supply (30 kV and 4 mA, GBS Elektronik, GmbH) has been used as a power supply. The positive terminal of the high voltage power supply is connected to the nozzle and the negative terminal is connected to the counter electrode. The working distance between the nozzle and counter electrode is set equal to 12 mm. The working fluid is introduced into the nozzle through a baby feeding tube and the fluid flow rate is controlled with the help of a programmable syringe pump.

The schematic of experimental setup used for flow visualization and particle image velocimetry (PIV) is shown in Figure 1(b). The PIV system comprises of a zoom lens (Navitar Inc. USA, 12X) mounted on a high speed camera (Vision Research Inc. USA, Phantom V341), a high speed pulsed laser (DS-532-10, Photonics Industries International, Inc.), a synchronizer and a pulse generator (BNC 565). The flow is seeded with the polystyrene particles of diameter of 10 μm and density of 1100 kg/m^3. The visualization images are captured at 10 frames per second (fps) with multiple exposure of laser light. The images for PIV are acquired at 500 fps with a resolution of 1280$\times$1024 pixel^2. The PIV images are processed by using VidPIV software supplied by Oxford Lasers. The cross-correlation has been performed on an interrogation window size of 128$\times$128 pixel^2 with an overlap of 50%. An adaptive cross-correlation is further applied on a reduced interrogation window size of 64$\times$64 pixel^2 with a 50% overlap. Global velocity filters followed by interpolation of outliers are used to extract the final results. An ensemble of 400 image pairs are used to estimate the time averaged behavior of the flow filed.

III. Results and Discussion

Figure 2 show the instantaneous visualization images (top row) and instantaneous flow field obtained form PIV (bottom). The visualization images acquired at meridional plane reveals the presence of at least one explicit vortex inside the Taylor cone at all time instants. These are the toroidal vortex. The visualization images further reveal that the flow pattern is not constant over the time. The vortical motion in counter-clockwise direction at time, $t = 0$ transforms into a clockwise rotating vortex at time, $t = 0.1$ s. This can be also observed from the instantaneous PIV flow field. At time $t = 0.3$ s, both clockwise and counter-clockwise are found with symmetry about the central axis. The variation in flow field can be attributed to disturbance inside the nozzle and disturbance due to surroundings of Taylor cone. The velocity vector shows

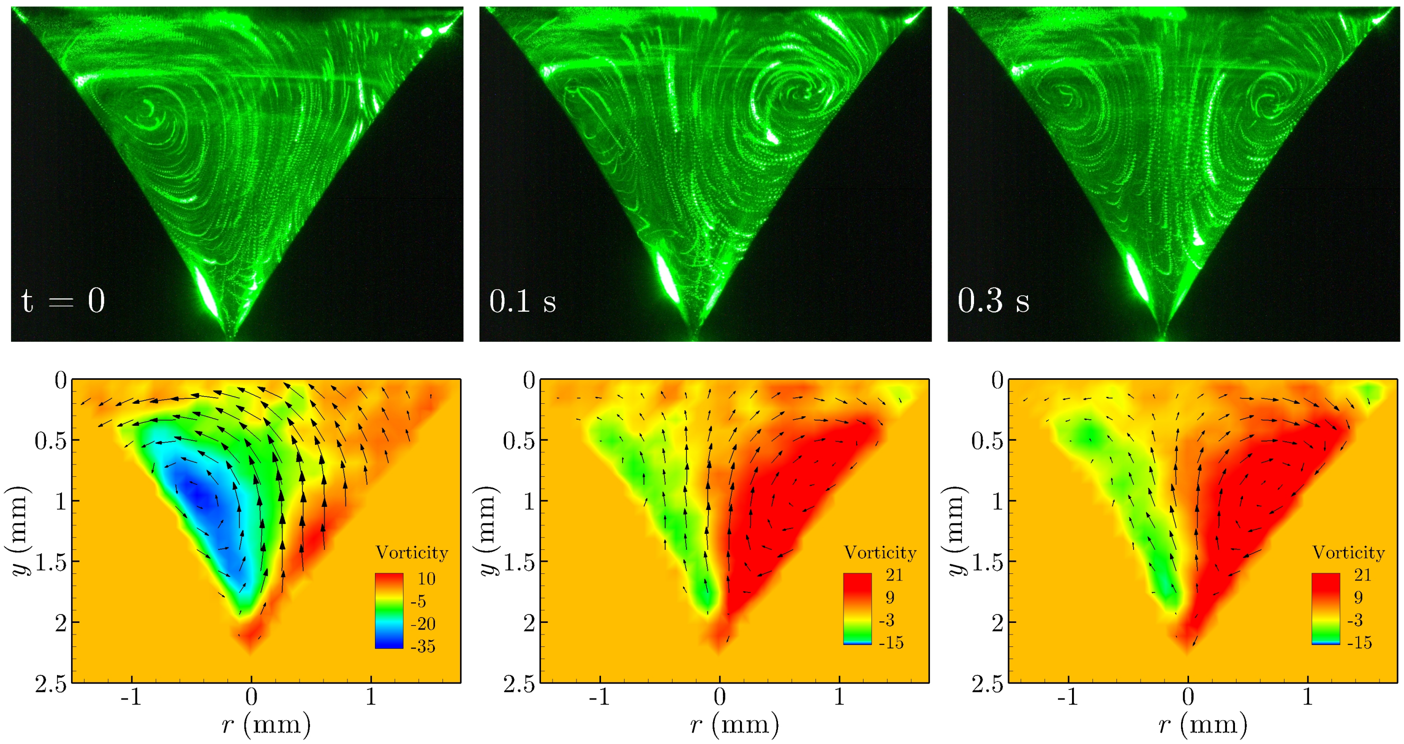

Figure 2: Instantaneous flow visualization images (top row) showing the flow behavior inside a Taylor cone and the vorticity (1/s) field superimposed with the velocity (mm/s) vectors (bottom row) at three different time intervals. The operating test conditions are: Q = 2 ml/hr and ϕ = 5.25 kV.

the back flow on the central axis at the apex of Taylor cone and the main flow contributing to the jet comes from the sides of the cone.

The time averaged PIV results of absolute velocity, vorticity and Q–criterion are shown in Figure 3. The results are shown as a function of increasing applied potential, ϕ at three different voltage levels. The Taylor cone becomes smaller in it's size with increase in ϕ due to force imbalance and consequently, the flow field inside the cone is also modified. The location of maximum absolute velocity changes with the applied potential. The velocity maximum occurs in the middle of the Taylor cone for the symmetric flow field about the central axis. The order of magnitude of velocities are in mm/s suggesting a very slow speed motion inside the cone. The presence of a toroidal vortex on a meridional plane is observed as shown in vorticity vector plot for all the test cases. The nature of vortex is both positive (counter-clockwise) and negative (clockwise). Counter-clockwise and clockwise vortex is found for case1 and case3 but for case-2 two symmetric vortices are found. It is found that both the positive and negative vorticity are of same order of magnitude. The maximum and minimum value of the vorticity are 18.7 s^{-1} and -18.3 s^{-1} respectively. The vorticity field further conforms symmetry of the flow field. The results of symmetric flow field supports the numerical work carried out by Lastowa and Balachandran [11]. The Q–criterion results further conform the presence of vortex. Only the positive values of Q–criterion are shown that precisely locates the vortex core.

IV. Conclusion

The present study demonstrates the nature of flow field inside a Taylor cone formed during EHDA. The flow field is found to be a function of applied potential. It has been found that for a given applied potential, flow field shows transient behavior. The temporal changes are attributed to external perturbation inside the nozzle and disturbance caused by surroundings flow. The strength of the toroidal vortex increases with increase in applied potential.

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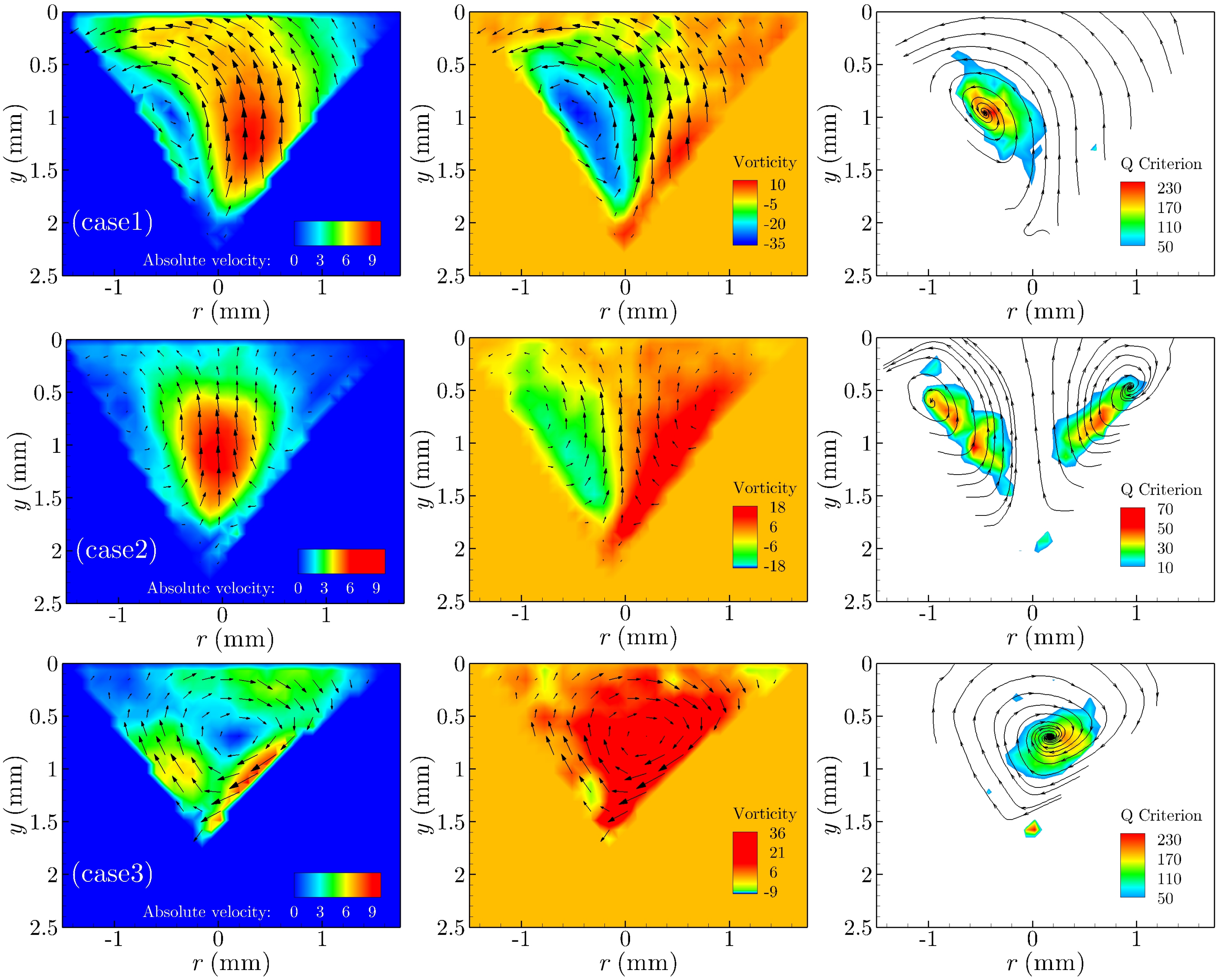

Figure 3: Time averaged PIV results of absolute velocity (mm/s), vorticity (1/s) and Q-criterion (left to right column) as a function of increasing applied potential, ϕ (top to bottom) . The operating test conditions are: ϕ = 5.25 kV (case1), 5.5 kV (case2), 6.25 kV (case3) and flow rate, Q = 2 ml/hr is same for all.

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