SPRAY CHARACTERISATION IN ELECTROSTATIC ATOMIZATION

A.Srikanth¹, J. Karnawat² and A. Kushari³

¹ Graduate Student, Dept. of Aerospace Engineering, I.I.T. Kanpur E-mail: srik@iitk.ac.in
² Graduate Student, Dept. of Aerospace Engineering, I.I.T. Kanpur E-mail: karnawat@iitk.ac.in
³ Assistant Professor, corresponding author, Department of Aerospace Engineering, Email: akushari@iitk.ac.in
Indian Institute of Technology, Kanpur – 208016, India.

ABSTRACT This paper illustrates the variation in the droplet size with the change in the parameters considered for electrostatic atomization. The various parameters considered were the voltages, flow rates, break down distance and electrodes distance. The experiments were conducted to study the effect of these parameters which play an important role in electrostatic atomization. The experimental set up consists of a capillary needle with a ground electrode which causes the atomization to take place. A series of experiments were conducted with water as working fluid for flow rates of 3.5 ml/min and 4 ml/min. The voltage used for the characterization of spray in atomization was raised from 2 kV to 5 kV. The atomization process was studied for both AC voltage component super imposed on DC field as well as only DC component by placing a capacitor in the circuit. Image processing techniques were used to determine the droplet size. It was done by capturing the spray images under different conditions using a CCD camera facilitated by a diode LASER source. These spray images were then analyzed using an image analysis code developed in MATLAB⁶.

Keywords: Electrostatic atomization; Spray Pattern; Droplet generation; Electrostatic Charge; Electrode gap; Droplet Size.

1. INTRODUCTION

During the last few decades the interest in electrostatic atomization has shown a rapid increase because of the great advantages gained from this system. The various applications where electrostatic atomization plays an important role these days are fuel atomization, colloid thrusters, spray painting, ink jet printers, spray for fire fighting, agricultural spray, emulsion formation, aerosol generation, thin film coating. The mechanism that controls atomization has not yet been determined but several have been proposed. No perfect theory has been developed for high speed jets where as some theoretical understanding of low speed jets have been developed [1]. Electrostatic sprays are smarter when compared to conventional sprays as they are self dispersive and they can be controlled electronically.

In the normal state, the jet coming out the small diameter needle is disintegrated as droplets and scatter after a small distance from the orifice due to the surface tension force acting on the jet. When high voltage is applied to the needle, there will be a transformation of the jet and it starts to scatter more due to the repulsive forces acting between the droplets. The charge which is transmitted to the jet by a high voltage supply is taken by the droplets and causes a strong repulsive force to act between each adjacent droplet in the jet and causes to scatter after a certain distance from the orifice. This is because the seat of sensitiveness is not at the root of the jet but at the place where jet breaks into drops. But if an electrode of opposite polarity is brought near the charged jet, it causes the jet to scatter more than the one without electrode because of the concentration of opposite charge which causes the jet to pull apart and cause atomization. The tendency of the electrically atomized droplets is to coalesce after a certain distance when the potential between the droplets gets reduced. When viscosity is present in the fluid to be atomized, it will form long threads and these will not be divided into droplets at mutual distances but give way to attenuation at few distant places. This adds the same effect as inertia plays on the fluid.

1.1. Theory of Atomization

The study of electrostatic atomization needs the knowledge of electro hydrodynamic surface stability. The field induced motions lead to deformation of interface and these motions depends on the type and amount of electric field applied and these also lead to several dynamic effects on the liquid interface which affect the jet behavior and drop formation. The droplet formation from capillary tube is generally achieved from Rayleigh instability. The technique defined by this instability is called a continuous droplet generation since a capillary stream is broken into continuous stream of droplets [2].

There is equilibrium of surface tension, hydrostatic and electrostatic forces at the surface of the film. The break up of jet takes place when the electrostatic force generated is higher than the surface tension force of the jet coming out of the capillary needle. This happens when the electric field enters the bulk of the jet generating an acceleration force and driving it downstream causing it to break [3 -4] and accelerating dripping to occur. Depending on the flow rate and the strength of electric field, different spraying modes
can occur such as dripping, spindling, simple jet, multi jets, and ramified jets. These modes of electrostatic atomization also depend on the liquid which is being atomized, the capillary tube diameter, the distance between the capillary tube tip and the ground electrode, and the liquid properties like the surface tension, electrical conductivity, density, and viscosity [5]. The dripping mode is obtained when the electric field and the liquid flow rate are too low. The transition from dripping mode to spindling mode takes place when the liquid flow rate is increased and the droplet size is reduced. With further increase in flow rate, fully developed jet is obtained.

The tendency of the surface tension property is to restore the jet in to spherical drops. The electric field introduces a force in opposite direction. If Q is the charge of electricity in the electrostatic field, the corresponding formula [6] is

\[ p^2 = \frac{(n(n-1))}{\rho d^3} \left( n+2 \right)^{\frac{1}{3}} \left( \frac{Q^2}{4\pi \sigma^3} \right) \]  

(1)

When Q is greater in Eq. (1), the spherical form becomes unstable for all values of n below a certain limit, and the maximum instability depends on greater ‘n’ but it is finite. Under these circumstances the liquid is thrown out in fine jets whose fineness however has a limit.

The point where the divergence of the jet begins depends on the experimental conditions. The research regarding the understanding of the physics of the electrostatic spray was focused for the last few years on this aspect of electrostatic atomization. Even though the atomization is so important in many applications, the mechanism by which atomization occurs is not well understood [1].

The interaction between the electric field and the liquid jet coming out the capillary tube creates the unstable wave to grow which eventually leads into formation of small drops. Rayleigh has proposed that the long wavelength surface waves are responsible for the break up of jet in low speed inviscid jets and droplet diameter produced is larger than jet diameter. Ranz [7] also proposed that the droplet size is related to the wavelength of the unstable waves.

There are four different regions in electrostatic atomization as described by Sung et al [8]. The region near the needle tip where, the electric field is very intense and the charge carrying velocity is dominated by the mobility velocity. This region is called as charge relaxation region, where the current is mainly due to the conduction process. The current carried by the electro spray is a function of liquid properties and flow rate [9-11]. A square root dependence has been found experimentally and theoretically but the dependence of current on dielectric constant has not been found yet [12]. It has been taken as proportional to \( 1/\varepsilon^{1/2} \) or to \( \varepsilon/\varepsilon^{1/2} \) with \( \varepsilon \) determined experimentally [13] and current proportional to \( 1/\varepsilon^{1/4} \) [14] and current independent of \( \varepsilon \) [15]. The next region is a transition from one region to another where the conduction through the bulk and the convection along the surface are almost equal. Region 3 is the region where the convection takes over the conduction and the electric field direction is almost perpendicular to the jet flow direction. This region is the start of seat of sensitiveness. The ultimate region is the one where the jet breaks up into droplets.

Fig.1. Regions in the electrostatic atomization process. 

The present study focuses on the initiation of atomization process in an electrically charged water jet and its dependence on the electric power level, liquid flow rate and inter-electrode gap.

2. EXPERIMENTAL SETUP

The schematic of the experimental set up is shown in Fig.2. The set up mainly consists of a liquid feed pump, nozzle, high voltage power supply, ground electrode, a CCD camera and a diode laser source with lens. The liquid flow rate is kept constant for a particular configuration while characterizing the atomization process. The flow rates used for the characterization were 3.5ml/min and 4.6ml/min. The high voltage is applied using a high voltage converter which takes an input voltage of 6-12 volts and gives an output voltage ranging from 2-5 kV. The first test was carried out using this high voltage which has both AC and DC voltage components and the other test was carried out with only DC component by incorporating a capacitor having a capacitance of 20µF in parallel with the output of high voltage power supply. This high voltage is applied between the nozzle tip and the ground electrode. The main aim of the experiment is to atomize a conducting liquid

The CCD camera is used to obtain the images of the droplet break down and these images were processed using the image processing code developed here in MATLAB. The steps used for obtaining the droplet size from the images are described in Fig.3. As the electrostatic atomization takes
place, the charged molecules of the fluid forming a band of droplets as shown in Fig. 3 (i). The MATLAB code has been developed to accurately demarcate the envelope of these droplets, which follow each other in form of a band, as seen in Fig. 3 (ii). The edge or envelope of the droplets is then extracted from the image, as shown in Fig. 3 (iii), the thickness of which is then estimated as the droplet diameter (d).

The gap between the needle tip and the ground electrode is varied from 10 mm to 15 mm for a particular configuration. The internal diameter of the needle tip used is 0.5 mm. The ground electrode used is in a ring shape with internal diameter of 3 mm and external diameter of 10 mm. The fluid is allowed to pass from the needle into the ring with a constant flow rate for a particular arrangement. The atomization started once the fluid enters the ring and the images were grabbed with the camera along an illuminated plane which is obtained using a laser sheet. The laser light is allowed to pass through a cylindrical lens and a concave lens which release the light in the form a sheet. All the images were obtained on that plane which is inline with the center line of the needle.

The parameters like the voltage applied, the inter electrode distance and flow rates of the fluid were changed for each configuration. The second test was done without a ground electrode and tested for atomization. This was done using a capacitor having a limited break down voltage. There was no atomization taking place until the jet passes through the ring of ground electrode, but when the capacitor was introduced in the circuit the atomization was taking place with out the ground electrode after some break down length of 25 mm. This was also estimated for that narrow range of high voltage for comparison.

3. IMAGE ANALYSIS PROCEDURE

The images obtained using CCD camera were analyzed for the droplet size using the image analysis code in MATLAB®. The procedure /steps that were used are discussed below:

3.1. Extraction of the Envelope of the Droplets

Fig. 3 demonstrates the various steps involved in the droplet envelope extraction process. An original image captured using a CCD camera is shown in Fig. 3(i).

This image is then converted into a corresponding grayscale form, filtering out the spray portion of the image. Through analysis it was found that the pixel intensity greater than 50 for a digitized grey scale image can efficiently separate the spray droplets from its background. Thus, this critical pixel value of 50 was used as the critical value for filtration of the image. Once the droplet band was identified and separated from its background, it was enveloped and demarcated using tangent lines by fitting the coordinates of the periphery of the droplet to the best fit straight line equation, as seen in Fig. 3(ii) and Fig. 3(iii). The perpendicular distance between the tangent lines was termed as ‘d’.

3.2. Droplet Size Estimation

In a processed image obtained from the method discussed above, the distance ‘d’ was measured at different locations between the tangent lines enveloping the droplet band. The maximum value of ‘d’ among these was taken as the droplet diameter value for the image. The values of ‘d’ obtained for a particular image, using the above mentioned process, at a working voltage of 2.6 KV with electrode gap of 1 cm at a flow rate of 4.6 ml/min, are shown in Fig. 4. The droplet diameter obtained from 10 such images was averaged to obtain the Average Droplet Size corresponding
to a particular operating condition. Fig. 5 shows the averaging of droplet diameter at a working voltage of 2.6 KV with electrode gap of 1 cm at a flow rate of 4.6 ml/min. In the analysis for the Average Droplet Size at different operating conditions using sample images, the maximum error was estimated to be 2.2% and the maximum standard deviation was estimated to be 1.35% of the mean value.

4. RESULTS AND DISCUSSION

A series of experiments were performed to study the variation in droplet size with the change in parameters namely the fluid flow rate, the potential difference between the electrodes and the electrode gap. The changes in the atomization characteristics with and without a capacitor in the high voltage power circuit, which was connected to the electrodes of the electrostatic atomization, were studied.

4.1. Study without Capacitor.

Fig.6 shows the variation in the average droplet diameter with the applied voltage for the flow rates of 3.75 ml/min and 4.6 ml/min. It was found that the average droplet size decreases with increase in the applied voltage for a constant low rate. This is attributed to the increase in the electrostatic field force on the surface of the fluid with the augmentation in the applied voltage leading to a better atomization. Also, a decrease in the droplet size with the increase in the flow rate for a constant applied voltage was observed. This is because of the increase in the repulsive forces between the charged fluid molecules that take place due to the enhancement in the charge density resulted from the increase in the fluid flow rate.

Fig.7 shows the change in the average droplet size with the variation in the gap between the electrodes for a constant flow rate of 3.75 ml/min. It was observed that the droplet size increases with the increase in the electrode gap. The increase in the distance between the electrodes for a constant applied voltage results in the reduction in the electrostatic force acting on the fluid surface. This reduction in the electrostatic force does not effectively append to the cohesive forces acting upon the fluid resulting in poor atomization.
Figures 8 and 9 shows the variation of droplet size with the input power for different flow rates and for different electrode gaps respectively. A decrease in droplet diameter has been observed with an increase in the power input. This can be attributed to the increase in charge attained by the fluid molecules which causes them to split apart more effectively due to the repulsive forces among them and form droplets of smaller size.

### 4.2. With Capacitor

In the study using a capacitor in the high voltage power supply, the spray has got a tendency of break up after a certain distance from the needle tip as seen in Fig.10 (ii). No such spray break up behavior was observed using a circuit without a capacitor as seen in Fig. 10 (i). This is because the charge density in the case without a capacitor is not sufficient to overcome the surface tension forces of the fluid.

Fig.11 shows the comparative droplet diameter variation with voltage. It can be seen that similar atomization characteristics namely droplet size can be obtained at a much lower voltage with a capacitor compared to the case where the capacitor is absent. The capacitor has a tendency of accumulating the charge which then gets transferred to the electrodes connected to it. This results in an increase in the charge concentration on the fluid molecules thereby causing the fluid stream to break into droplets at a much lesser voltage.
Fig.11. Variation of droplet diameter with and without capacitor

The variation of the droplet diameter with the input power is shown in Fig.12. It can be seen that the droplet diameter with the introduction of capacitor in the circuit has shown an increase in performance of atomization but needs a higher power than required in the case without a capacitor. Without a capacitor in the circuit, the average droplet size decreased by 31.76 microns with the change of 0.72 kW in input power compared to a change of 10.2 microns in average droplet diameter with 2.62 kW of input power that was obtained when the capacitor was used. The rate of decrease in droplet diameter using a capacitor is not that steep and this case has lower power efficiency in terms of atomization when compared without a capacitor. This is because a large amount of energy remains stored in the capacitor itself reducing its contribution to atomization and also, its output does not show a significant change with the increase in the input power.

Fig. 12 Variation of average droplet diameter with input power.

5. CONCLUSIONS

The paper presents an insight into the droplet formation in electrostatic atomization. It was observed that the droplet size varies with the change in parameters namely the supply voltage and input power for a constant flow rate conditions. Changes in atomization characteristics with fluid flow rate and electrode gap were also observed providing the scope for controlled atomization for low fluid flow rates. Comparing the results of electrostatic atomization with and without the capacitor in the high voltage circuit, it was revealed that similar quality of atomization in terms of droplet size can be obtained at lower voltage with the introduction of capacitor in the circuit. This reduces the need of higher working voltage. On the other hand the use of capacitor induces power inefficiency in terms of atomization bringing in the need of optimization while using a capacitor in the circuit.

6. NOMENCLATURE:

‘a’ droplet diameter. [mm]
‘d’ droplet band width. [mm]
‘ε’ dielectric constant.
‘n’ any integer.
‘p’ angular frequency.
‘Q’ electric charge. [coulomb]
‘T’ surface tension force [N/m]

7. REFERENCES


