Spray Characteristics of Electrostatic Pressure-Swirl Nozzle for Burner Application

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ABSTRACT

Electrostatic pressure-swirl nozzle for practical oil burner application has been designed. The charge injection method has been used in this design, where the nozzle consists of a sharp pointed tungsten wire as a charge injector and the nozzle body grounded. The spray characteristics of the nozzles have been investigated by using an insulating liquid, i.e. kerosene without active surface agent. Breakup length of liquid decreased with an increase in applied voltage and injection pressure, while the spray angle increased with an increased in both applied voltage and injection pressure. An empirical equations have been suggested to predict the breakup length for electrostatic pressure-swirl atomizer. The experimental result was within the range of the predicted equations. The SMD decreased between the ranges of 2.8 ~ 33% when the conventional nozzle was compared to the electrostatic with -10 kV applied to the electrode at a radial distance from 5 to 20 mm.

Key Words : Electrostatic, Charge injection, Pressure-swirl nozzle, Burner, Hydrocarbon fuel, Breakup length, Droplet size

Nomenclature

d_o	Diameter of the nozzle orifice	m_l	Mass flow rate
I	Total current	ΔP	Differential injection pressure
I_L	Leakage current	P_i	Injection pressure
I_s	Spray current	V	Applied voltage
L_b	Breakup length	μ_l	Dynamic viscosity of liquid

1. Introduction

The conventional atomization techniques in oil burner for combustion rely mostly on air or any other form of mechanical disturbance in order to disintegrate bulk liquid fuel into required droplets. It is known that one of the methods to improve combustion efficiency of liquid fuel is to reduce the droplet size and hence to improve the quality of atomization. It has been predicted for a typical boiler burner that, a reduction of the mean drop size by

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10% while retaining all other spray characteristics would result in reduction of 35% unburned hydrocarbon [1].

An improvement of spray quality and a reduction of droplet sizes can be achieved by using electrostatic atomization. The presence of free charge within a liquid is the most significant factor in determining its electrostatic dispersibility but the difficulty in the liquid fuel disperse may be due to their long charge relaxation time.

There are two cases of electrostatic atomization: 1) Electrostatic forces are too small to atomize the liquid but drops receive a large electric charge. 2) Electrostatic forces are large enough to atomize the liquid and drop charging is not relevant [2].

These techniques have been applied in the field of agriculture, medicine and other industries, but the practical applications for combustion were very limited due to many factors such as low throughput, high viscosity and high resistivity of the liquid fuel. Jones and Thong (1971) were unable to spray kerosene with resistivity of 10^{12} Ωm. However, it was made possible by adding 3% of active surface agent (ASA-3) to the fuel which lowered the resistivity to 10^{6} Ωm.

The charging injection mechanism that have been designed and investigated were a single electrode [1, 3-6], diode [7] and triode [8, 9] in combustion system. Atomizers that have been applied in electrostatic combustion were the plain orifice and twin-fluid types. This paper presents the spray characteristics of a developed electrostatic pressure-swirl nozzle for burners by using the existing commercial nozzle.

2. Theoretical analysis

Han et al. [10] suggested the equation to model the breakup length of a conical liquid sheet issued from a pressure-swirl injector as

$$L_b = B\left[\frac{\rho_l \sigma h \ln\left(\frac{\eta}{\eta_o}\right)\cos\theta}{\rho_g^2 U^2}\right]^{0.5} \qquad (1)$$

where $\ln\frac{\eta}{\eta_o} = 12$

h : Liquid sheet thickness

U : Liquid sheet velocity

θ : Spray half angle

σ : Surface tension.

ρ_g : Density of gas.

ρ_l : Density of liquid

The liquid sheet thickness has been estimated by Han et al. [10] to be

$$h = \left[A\frac{12 m_l \mu_l}{\pi d_o \rho_l \Delta P_l}\left(\frac{1-X}{1-X^2}\right)\right]^{0.5} \qquad (2)$$

A = 40 has been used in their study to relate the nozzle geometry and X is defined as the ratio of the orifice area to the air core area and can be calculated by the following equation when experimental spray half angle θ is available.

$$\cos^2\theta = \frac{1-X}{1+X} \text{ or } X = \frac{1-\cos^2\theta}{1+\cos^2\theta} \qquad (3)$$

The sheet velocity U is defined as

$$U = K_v\left[\frac{2(p_1 - p_2)}{\rho_l}\right]^{0.5} \qquad (4)$$

where K_v is the velocity coefficient and can be derived based on inviscid analysis as [11]

$$K_v = C\left(\frac{1-X}{1+X}\right)^{0.5}\frac{1}{\cos\theta} \qquad (5)$$

where C = 1.1 is used to account for discrepancy between the theory and experiments [10].

A semi-empirical equations for the prediction of liquid breakup length in electrostatic have been suggested by Balachandran et al. [1] and Rigit et al. [5].

$$L_b = \frac{40 Q_L \varepsilon_o \varepsilon_r}{\pi d_o^2 x \rho_s} \qquad (6)$$

$$L_b = u_{inj} t_j \ ; \ t_j = \frac{\varepsilon_o \varepsilon_r}{x \rho_s} \qquad (7)$$

Q_L : Liquid flow rate

t_j : Characteristic time

u_{inj} : Flow velocity

ε_o : Permittivity of free spacer

ε_r : Relative dielectric constant

κ : Ionic mobility

The ionic mobility κ depends mainly on the charge density and partially on liquid flow rate, also it was related via an inversely proportionality with the viscosity, $\kappa = A/\mu$ as Waldens'rule [12]. The volume charge density ρ_s can be obtained as $(I_L+I_S)/Q_L$, assuming that the charge is uniformly distributed over the bulk of the liquid inside the nozzle. In their experiment many assumptions were considered for the empirical expression and the expression did not valid within some specific range of flow rate, that is, when it is less than 25 ㎖/min or greater than 200 ㎖/min for kerosene.

In addition, due to lack of charge mobility measurement data, the value for κ was estimated based on the experimental results (ranging from 3 to $7\text{x}10^{-8}$ m^2/V s) [1].

3 Experimental methods and materials

In this experiment, the small Oil Burner G8S CF (conventional flue) was selected and which at present, is used for drying agricultural products, industrial heat processing equipment and boiler incinerator, etc in Korea. The specification of the oil burner and the tested fuel properties are shown in Tables 1 and 2 respectively.

Table 1 Burner specification

Kerosine/Light oil	
Power source[V]	AC 220V/50Hz, 60 Hz
Motor [W]	70
Oil Pump [kcal/kg]	Electric pump
Ignition Trans[kV]	8.5kV/18mA
Pump Pressure[MPa]	0.85
Nozzle Range[ml/min]	53.6 ~ 135.6
Dosage[MJ/h]	125.6 ~ 293.1

Table 2. Kerosene properties at 295K

Surface Tension [kg/s^2]	$2.57\text{x}10^{-1}$
Viscosity [kg/m s]	$1.95\text{x}10^{-3}$
Density [kg/m^3]	812.4
Electrical Conductivity [$\Omega m]^{-1}$	$4.8\text{x}10^{-11}$
Relative Permittivity	2.2

The electrostatic pressure-swirl nozzle developed in this work is shown in Fig.1. A tungsten wire of diameter 1.0 ㎜ sharpened to a point of 25 ㎛ was used and fed concentrically to the fuel pipeline.

Kerosine was injected with pressure ranging from 0.7 to 0.9 MPa with corresponding flow rates ranging between 69.0 to 77.6 ㎖/min from this nozzle.

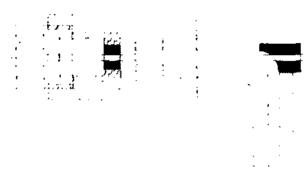

Fig. 1 The designed charge injection pressure-swirl nozzle

The liquid fuel is assume to contain negative ions (due to the high affinity), therefore it was necessary to apply the charge injection mechanism with a negative polarity. This will increase the ions in the liquid as electrons may flow directly to the tip of the pointed electrode and increase the concentration.

High voltages were applied to the electrode ranging from -4 to -12 ㎸ by using a DC generator. A Keithley electrometer 6514 was connected to a Faraday pail with a wire-wool which collects all the spray without any rebounce, in order to measure the spray current. A schematic diagram of the

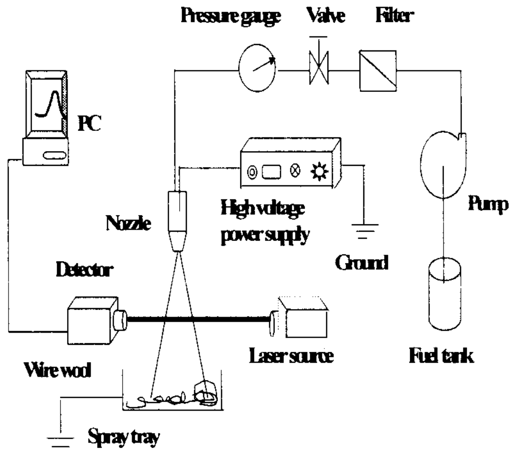

Fig. 2 Schematic diagram of experimental apparatus

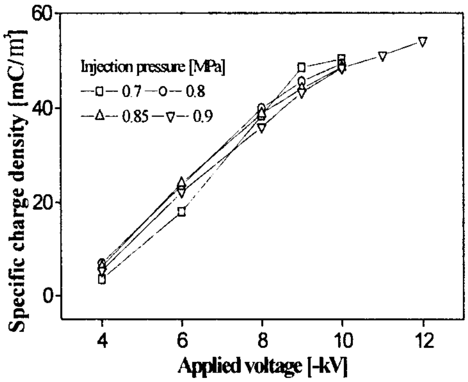

Fig. 3 Relationship between specific charge density and applied voltage

experimental apparatus is presented in Fig. 2.

The digital image processing was introduced by capturing multiple of images of the spray. Direct lighting from the stroboscope was used to illuminate the spray field from a dark background. The captured images were stored in the computer for off-line analysis. Twenty images were processed with the photoshop image analysis software. For each image, the breakup length by drop formation and the initial spray angle were measured.

The spray drop sizes were measured by using the Malvern Particle Sizer (Mastersizer S) at a fixed axial distance of 20 ㎜ from the nozzle to the laser beam and varied the radial distance from 5 to 20 ㎜.

4. Results and discussion

4.1 Spray charge density versus applied voltage

The spray and leakage current were measured by using sensitive electrometers. The spray charge density was calculated by dividing the spray current with the volumetric flow rate.

The spray charge density increased with an increase in applied voltage as presented in Fig. 3. The figure also shows that, at lower injection pressures (up to 0.85 MPa), the critical applied voltage occurs at -10 kV and any gradual increment of the voltage tripped off the high voltage power supply. With an injection pressure of 0.9 MPa, the applied voltage breakdown occurred at -12 kV.

These behaviours may be described that, at lower injection pressures, a complete electrical breakdown occurs due to electrical failure of the liquid inside the nozzle. In case of high injection pressure, the critical voltage occurs at higher applied voltage.

This may be due to the increase in the hydrodynamic pressure over the electrical pressure which prevent space charge to build up in the nozzle as in the case of lower pressures. This means a good atomization can be achieved by proper regulating of the injection pressure and the applied voltage in order not to discharge much current to the nozzle body.

4.2 Spray angle versus applied voltage and injection pressure

Spray cone angle is one of the spray properties to determine an efficient atomization or combustion of fuel. Owing to the effect of air interaction on curved boundaries that dominates the spray cone angle, it has become very difficult to measure accurately the angle of spray issuing from a nozzle. Therefore, the photography method was used to measure the spray cone angle. This can be overcome by defining two straight lines drawn from the discharge orifice to cut the spray contours at some specific distance from the nozzle tip [10].

In Figs. 4 and 5, it can be observed that, the spray angle increased with an increase in the applied voltage and injection pressure respectively.

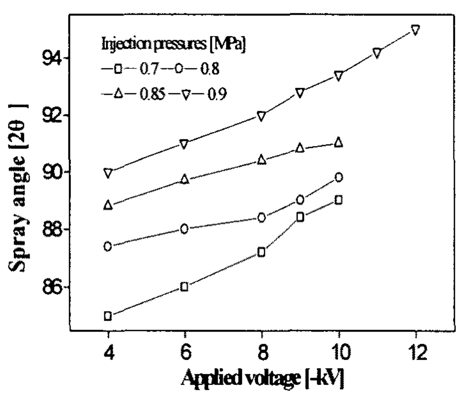

Fig. 4 Effect of applied voltage on spray angle

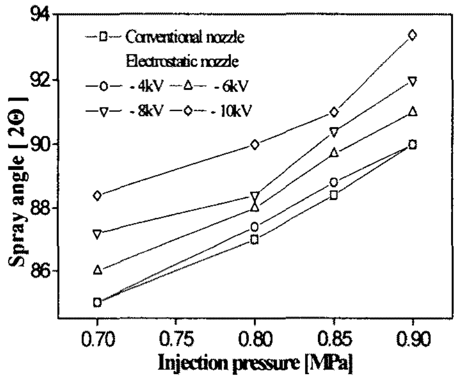

Fig. 5 Effect of injection pressure on spray angle

The difference in the spray angles between the conventional nozzle and the developed nozzle may be due to the combination of hydrodynamic, aerodynamic and electrical forces acting on the spray droplet. In other words, it is said that the coulombic forces causing repulsion dominates the spray trajectory. It is assumed that with an increased in vlotage, the temperature of the bulk liquid is increase which may also increase the ionic mobility.

4.3 Breakup length versus applied voltage and injection pressure

The relationships between the breakup length and the applied voltages as well as with injection pressure are presented in Figs. 6 and 7 respectively.

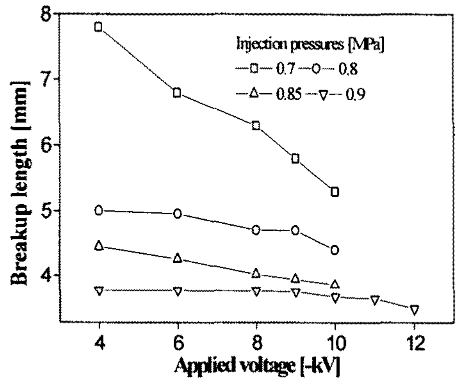

Fig. 6 Effect of applied voltage on breakup length

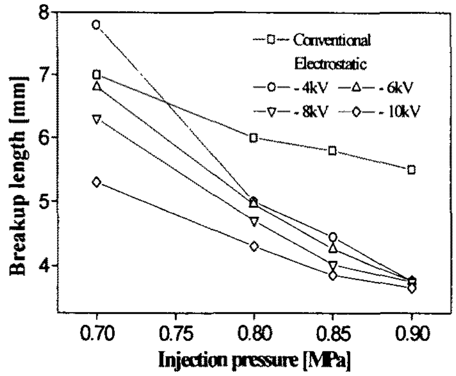

Fig. 7 Effect of injection pressure on breakup length

The breakup length decreased with an increase in both applied voltage and injection pressure. The decrease in the breakup length with an increase in the applied voltage may be due to the coulombic forces which increased the spray angle and shortens the length of the spray.

Figure 8 shows the comparison of experimental results with the calculated one by Eq. (1) for the conventional nozzle. The result was in good agreement with the equation when the constant B of 1.25 was used instead of their suggested value of 3.

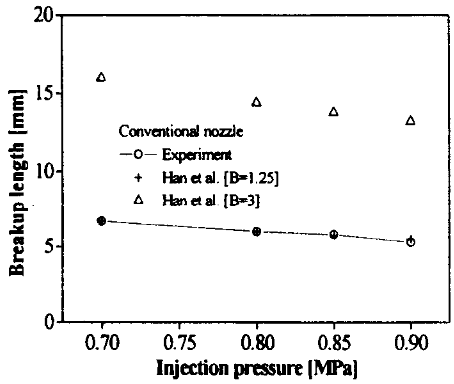

Fig. 8 Correlation of experimental data and equation(1)

The breakup length of the liquid by the electrostatic nozzle from the experiment, when correlated with equations suggested in [1, 4], was in the order of thousands as shown in Fig.9. This may be due to difference in atomizers used and conditions of applications. This, therefore, became necessary to suggest a new empirical equation for the prediction of breakup length for electrostatic pressure-swirl nozzle as

$$L_b = \frac{Q_L}{xV} \tag{10}$$

$$Q_L = A_o C_D \sqrt{\frac{2\Delta P}{\rho}} = \frac{A_o C_D U}{K_v} \tag{11}$$

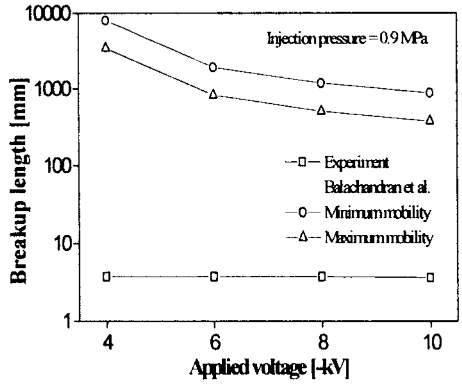

Fig. 9 Correlation of experimental data and equation(6)

and $$C_D = K_v \sqrt{\left[\frac{(1-X)^3}{1+X}\right]} \tag{12}$$

where X and K_v can be calculated from Eqs. (3) and (5).

If we introduce the electrical force term into the exiting Eq. (1) for the prediction of breakup length, the following equation can be suggested.

$$L_b = B\left[\frac{\rho_l \sigma h ln\left(\frac{\eta}{\eta_o}\right)\cos\theta}{\rho_g^2 U^2}\right]^{0.5} \frac{\varepsilon_o \varepsilon_r}{x \rho_s} \tag{13}$$

where x is the ionic mobility and it ranges from the minimum and maximum values suggested elsewhere in literatures ($3\text{x}10^{-8}$ ~ $1.15\text{x}10^{-7}$ m^2/V s).

Equations (6) and (7) were applied to plain orifice nozzle and jet sprays and not for pressure swirl nozzles and also did not consider the applies voltage as a direct function for the prediction of the breakup length. Equations (10 and 13) were based on liquid flow rate and specific charge density respectively. In Eq. (13), B was set to be 100 s^{-1}.

A typical correlations of the experimental data with the suggested equations are shown in Figs. 10 and 11. There was a significant difference in the breakup length with the variation of applied voltageat 0.7 MPa, this

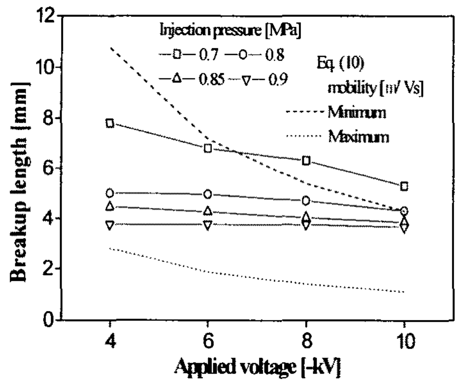

Fig. 10 Correlation of experimental data and suggested equation (10)

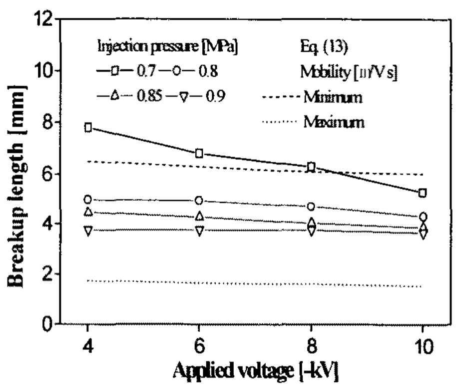

Fig. 11 Correlation of experimental data and suggested equation (13)

may be due to the poor spray formation and polydisperse which the instrument may measure.

4.4 Drop size versus injection pressure

The droplet size was measured at an axial distance of 15 mm from the nozzle tip. From Fig. 12 it was observed that the droplet size decreased with and increase in injection pressure, but increased with an increase in the radial distance. At a radial distance of 20 mm, the increased in the droplet size at lower

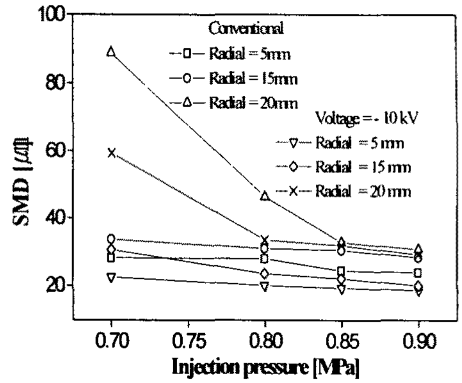

Fig. 12 Droplet sizes of both conventional and electrostatic nozzle at different positions

injection pressure (between 0.7 to 0.8 MPa) may be due to the spray formation which are formed at the edge of the spray. There was a slight difference between the conventional and the electrostatic nozzles when -10 kV was applied. This was due to the electric injection charge and the increased in liquid pressure differential causing the liquid to be discharged at a higher velocity, which promotes a finer spray

5. Conclusions

The specific charge density of the developed pressure-swirl nozzle has been measured and it indicted that the charge density increased with increase in injection pressure. At low pressures less than 0.9 MPa, the electric breakdown occurred at -10 kV and at 0.9 MPa it occurred at -12 kV. This shows the influence of flow rate on the liquid breakdown caused by the electric field. Therefore the flow rate or injection pressure is needed to be regulated in order not to loss the charge on the inside wall of the nozzle.

The spray angle increased with an increase in applied voltage and injection pressure. This was due to the charge on the droplets that caused repulsion in the spray which manipulates the spray trajectory and the hydrodynamic forces. The spray angle was the initial parameter needs to be available in order to predict the breakup length of the liquid sheet.

The breakup length decreased with an increase in the applied voltage and injection pressure. This occurrence may be due to the increased in spray angle caused by the applied voltage. The spray development was influenced not only by the initail velocity which was provided by the injection presure but laso by the electric field.

Two equations for the prediction of breakup length in electrostatic pressure-swirl atomizers have been suggested from the experimental data.

The droplet size decreased with an increase in either applied voltage or injection pressure. In the same experimental condition, the droplet issued from the electrostatic nozzle showed smaller diameters sizes than the conventional nozzle at an applied voltage of -10 kV.

At radial distances of 5 mm, the droplet size decreased in the range between 20 ~ 28%; at 10 mm in the range between 9.3 ~ 29% and at 20 mm the range fall between 2.8 ~ 33.2%.

It is therefore recommended that the designed electrostatic nozzle could be use in a practical combustion burner or boiler since it has these benefits over the conventional nozzle and the proof has been characterized.

6. Acknowledgement

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7. References

[1] W. Balachandran, D. Hu, A. J. Yule, J. S. Shrimpton and A. P. Watkins, "Electrostatically Produced Fuel Sprays for Combustion Applications," *Sixth Int'l Conf. on Liquid Atomization and Spray Systems*, 1994. pp. 994-1001.

[2] L. Bayvel and Z. Orzechowski, "Liquid Atomization," *Taylor and Francis Publishers*, 1993.

[3] A. J. Yule, J. S. Shrimpton, A. P. Watkins, W. Balachandran and D. Hu, "Electrostatically Atomized Hydrocarbons Sprays," *Fuel*, vol. 74, no. 7, 1995, pp. 1094-1103.

[4] J. S. Shrimpton, A. J. Yule and A. P. Watkins, "Performance Data of an Electrostatic Atomizer for Highly Resistive Liquids," *Seventh Int'l Conf. on Liquid Atomization and Spray Systems*, 1997, pp. 625-632.

[5] A. R. Rigit and J. S. Shrimpton, "Electrohydrodynamic of Charge Injection with Applied Bulk Convection," *Seventeenth Proc. of the Institute of Liquid Atomization and Spray Systems-Europe*, 2001, pp. 799-804.

[6] U. Leuteritz, A. Velji and E. Bach, "A Novel Injection System for Combustion Engines Based on Electrostatic Fuel Atomization," *SAE Technical Paper Series* 2000-01-2041, pp, 1-9.

[7] M. Jido, "Burning Characteristics of Electrostatically Sprayed Liquid Fuel and Formation of Combined Droplets of Different Fuels," IEEE Trans. 1989, pp. 2058-2065.

[8] A. J. Kelly, "Charge Injection Electrostatic Atomizer Performance Modeling," *Fourth Int'l Conf. on Liquid Atomization and Spray Systems*, 1988, pp. 125-131.

[9] A. J. Kelly, "The Electrostatic Atomization of Hydrocarbons," *J. of the Institute of Energy*, 1984, pp. 267-274.

[10]. Z. Han, S. Parrish and P. V. Farrell and R. D. Reitz, "Modeling Atomization Processes of Pressure-Swirl Hollow-Cone Fuel Sprays," *Atomization and Sprays*, vol. 7, 1997, pp. 663-684.

[11] A. H. Lefebvre, "Atomization and Sprays," *Hemisphere Pub. Co.*, New York, 1989.

[12] J. S. Chang, J. M. Crowley and A. J. Kelly, "Handbook of Electrostatic Processes", *1st Edition, Marcel Dekkar Inc*, New York, 1995.