SPRAY CHARACTERISTICS OF CHARGE INJECTED ELECTROSTATIC PRESSURE-SWIRL NOZZLE

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Abstract
This paper presents an investigation for spray characteristics of charge injected electrostatic pressure-swirl nozzle. The work forms part of the design and development of electrospray nozzle for practical oil burner application. The designed nozzle used in the experiment consists of a sharp pointed tungsten wire as a charge injector and the nozzle body grounded. The spray characteristics of the nozzle have been investigated by using a kerosine without active surface agent. The liquid breakup length decreased while the spray angle increased with an increase in applied voltage and injection pressure. An empirical equation to predict the breakup length for electrostatic pressure-swirl nozzle has been suggested. The experimental result was within the range of the predicted equation.

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 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 resistivity of the liquid fuel.

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

Experimental Setup

In this experiment, the small oil burner was selected which presently is used for drying agricultural products, industrial heat processing equipment and boiler incinerator, etc in Korea. The specification of the oil burner selected, properties of the tested fuel and the developed electrostatic pressure-swirl nozzle have been presented elsewhere [10]. A tungsten wire of diameter 1.0 mm point sharpened to radius of 25 μm was used as an electrode and fed concentrically into the fuel pipeline. Injection pressures ranging from 0.7 to 0.9 MPa with flow rates between 69.0 to 77.6 ml/min was used.

The hydrocarbon fuel is assumed to contain negative ions (due to the high affinity), therefore it was necessary to apply a negative polarity to the electrode. This will increase the ions in the liquid as electrons may flow directly to the tip of the pointed electrode. High voltages were applied to the electrode ranging from -4 to -12 kV by using a DC high voltage power supply. A Keithley electrometer 6514 was connected to a Faraday pail with a wire -wool placed inside to collect all the spray without any rebounce, in order to measure the spray current in the Faraday chamber. The experiment was performed within a range of temperature and humidity of 12-16 ^{o}C and 70-78 % respectively. A schematic diagram of the experimental setup is presented in Fig. 1.

A 3-CCD video camera (SONY) was used to capture multiple images of the spray for measurement purpose. A 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 at $20d_o$ were measured.

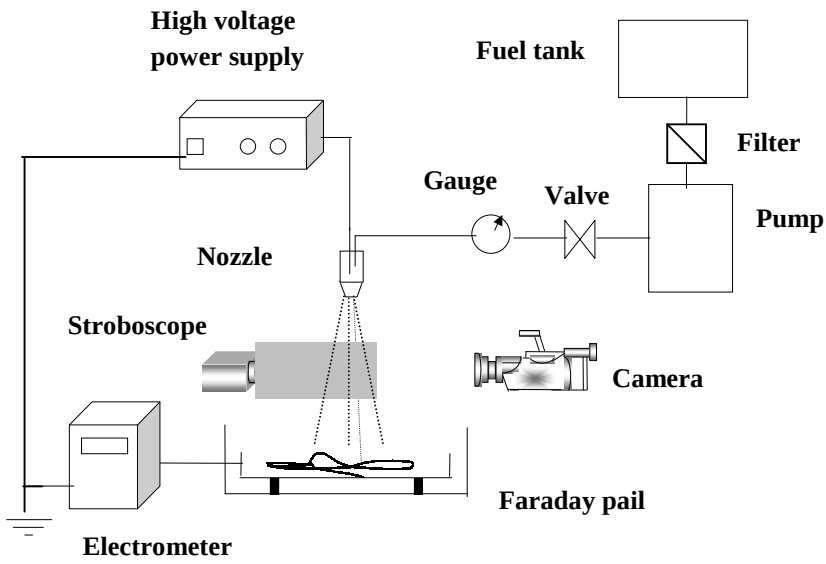

Figure. 1 Schematic diagram of the experimental setup

Results and Discussion

Effect of applied voltage on specific charge density

The spray current was measured by using an electrometer. The specific charge density was calculated by dividing the spray current with the volumetric flow rate. The specific charge density increased with an increase in applied voltage as presented in Fig. 2. 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. This behaviour may be described that, at lower injection pressures, a complete electrical breakdown occurs due to the accumulation of the charged liquid inside the nozzle and an increase in current leakage to the grounded nozzle body. With an injection pressure of 0.9 MPa, the applied voltage breakdown occurred at -12 kV.

This may be due to the increase in the hydrodynamic pressure over the electrical pressure which prevents early space charge to build up inside the nozzle. This means that a good atomization can be achieved by proper regulation of the injection pressure and the applied voltage in order not to discharge much current to the nozzle body.

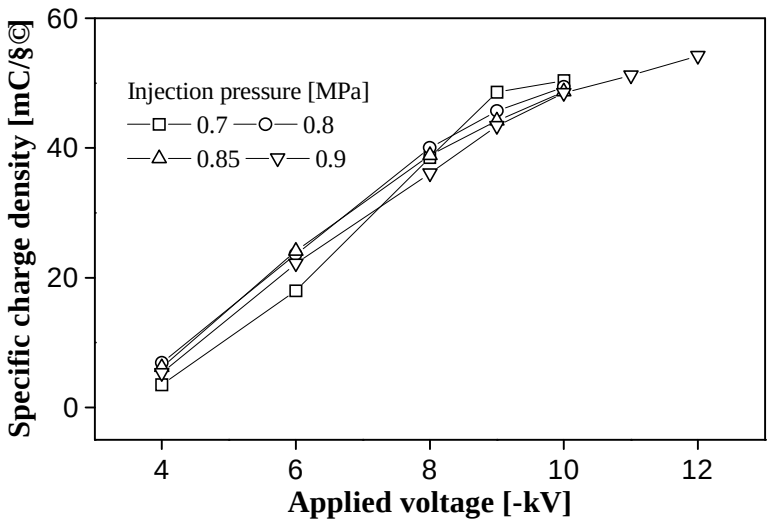

Figure 2. Relationship between specific charge density and applied voltage

Effect of applied voltage and injection pressure on spray angle

Spray cone angle is one of the spray characteristics used to determine an efficient atomization or combustion of fuel. The effect of air interaction on curved boundaries that dominates the spray cone angle determination became very difficult to measure accurately from the nozzle. Therefore, two straight lines were drawn on the captured images from the nozzle orifice to cut the spray contours at a distance equal to 20 d_o from the nozzle tip.

In Fig. 3, it is observed that, the spray angle increased with an increase in applied voltage and also injection pressure. The difference in the spray angles between the conventional and the developed nozzle may be due to the addition of 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 voltage, the temperature of the bulk liquid also increased which may also increase the ionic mobility by reducing the viscosity of the liquid.

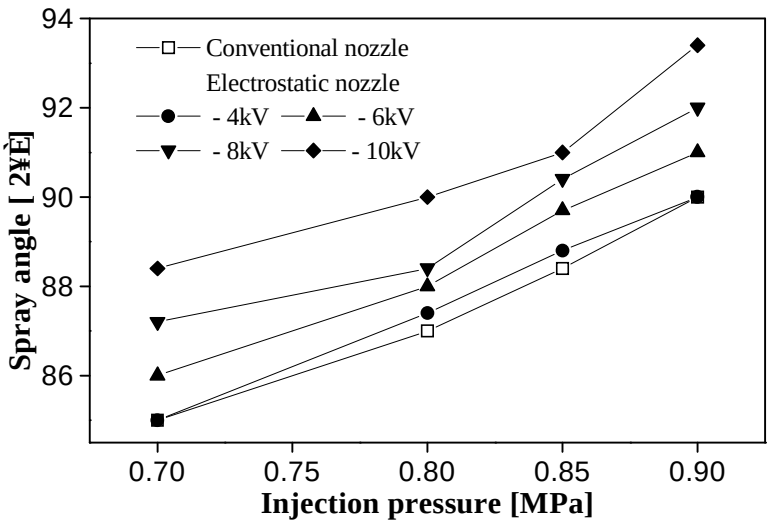

Figure 3. Effect of applied voltage and injection pressure on spray angle

Breakup length versus applied voltage and injection pressure

The theoretical equation suggested to model the breakup up length of a pressure-swirl atomizer by Han et al. [11] of a conical liquid sheet expressed as

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

The liquid sheet thickness has been estimated by Han et al. [11] to be

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

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.

$$\cos^2\theta = \frac{1-X}{1+X} \quad or \quad X = \frac{1-\cos^2\theta}{1+\cos^2\theta} \tag{3}$$

The sheet velocity U is defined as

$$U = K_v\left(\frac{2\Delta P}{\rho_l}\right)^{0.5} \tag{4}$$

The velocity coefficient and can be derived based on inviscid analysis as [12]

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

where C = 1.1 is used to account for discrepancy between the theory and experiments [11].

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

$$L_b = \frac{40Q_L\varepsilon_o\varepsilon_r}{\pi d_o^2\kappa\rho_s} \tag{6}$$

The ionic mobility depends mainly on the charge density and partially on liquid flow rate. According to Waldens'rule [13], it has been related to be inversely proportional with viscosity, as

$$\kappa = \frac{A}{\mu} \tag{7}$$

The volume charge density 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. The validation of the empirical expression was within some specific flow rates, i.e. when 200 ml/min < Q_L < 25 ml/min for kerosine. 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 7×10^{-8} m^2/V s) [1].

The relationship between the breakup length and the applied voltage as well as with injection pressure is presented in Fig. 4. 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.

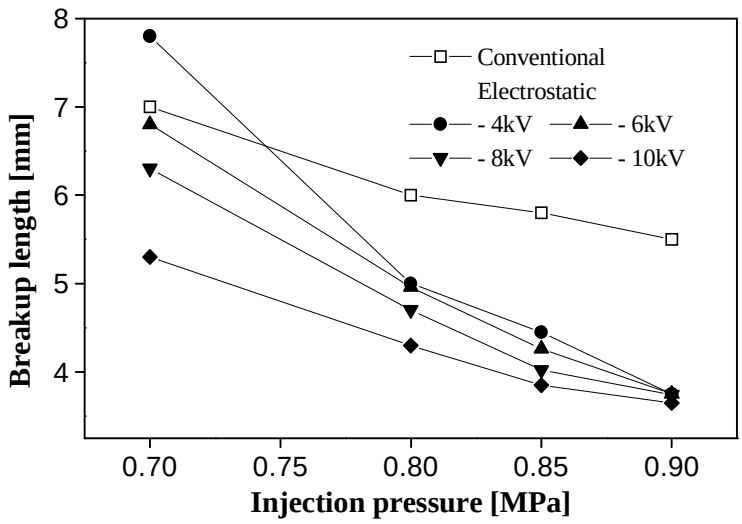

Figure 4. Effect of applied voltage and injection pressure on breakup length

A new empirical equation for the prediction of breakup length for electrostatic pressure-swirl nozzle has been suggested from the experimental data. If we introduce the electrical force term into the exiting Eq. (1), the following equation can be suggested

$$L_b = B\left[\frac{\rho_l\sigma h\ln\left(\frac{\eta}{\eta_o}\right)\cos\theta}{\rho_g^2U^2}\right]^{0.5}\frac{\varepsilon_o\varepsilon_r}{\kappa\rho_s} \tag{8}$$

where the minimum and maximum values of k has been suggested in literatures (3×10^{-8} ~ 1.15×10^{-7} m^2/V s).

Equations (6 and 7) were applied to plain orifice nozzle and jet sprays. In Eq. (8), B was set to be 100 s^{-1}. A typical correlation of the experimental data with the suggested equation is shown in Fig. 5. There was a significant

difference in the breakup length with the variation of applied voltage at 0.7 MPa, this may be due to the poor spray formation.

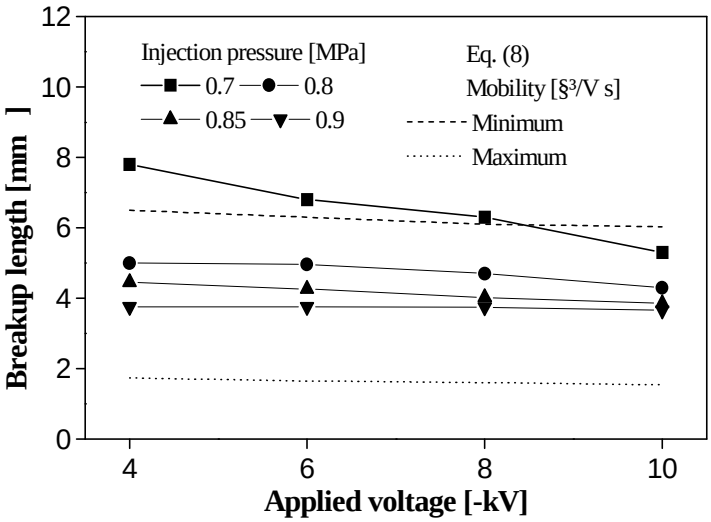

Figure 5. Correlation of experimental data and suggested equation (8)

Conclusions

The specific charge density of the nozzle has been measured and it indicted that the charge density increased with an increase in applied voltage. At injection 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 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 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 initial velocity which was provided by the injection pressure but also by the electric field.

An equation to predict a breakup length of electrostatic pressure-swirl nozzle has been suggested.

Nomenclature

d_o	Diameter of the nozzle orifice
h	Liquid sheet thickness
I	Total current
I_L	Leakage current
Is	Spray current
K	Sheet thickness parameter (K=hx=constant)
K_v	Velocity coefficient
L_b	Breakup length
m_l	Mass flow rate
ΔP	Differential injection pressure
Q_L	Flow rate
U	Sheet-gas relative velocity
u_{inj}	Flow velocity
U_s	Sheet velocity
ε_o	Permittivity of free space
ε_r	Relative dielectric constant
η	Wave amplitude $\ln(\eta/\eta_o) = 12$
κ	Ionic mobility
μ_l	Dynamic liquid viscosity
θ	Spray half angle
ρ_g	Density of gas

ρ_l	Density of liquid
ρ_s	Volumetric charge density
σ	Surface tension
σ_k	Conductivity
τ	Charge relaxation time
τ_j	Dynamic time

Subscripts

g	gas
l	liquid

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