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BREAKUP LENGTH OF CONICAL EMULSION SHEET DISCHARGED BY PRESSURE-SWIRL ATOMIZER

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ABSTRACT− Many researches on pressure-swirl injectors due to the variety of application have been conducted on the effects of nozzle design, operating conditions, properties of liquid and ambient conditions on the flow and spray characteristics. The breakup length of conical emulsified fuel sheet resulting from pressure-swirl atomizer using in the oil burner was investigated with the digital image processing method with neat light oil and emulsion with water content of 10–40% and the surfactant content of 1–3%. The injection pressure ranged from 0.1 to 1.2 MPa was selected. The various regimes for the stage of spray development within the experimental conditions selected in this study is newly suggested in terms of Ohnesorge number and injection pressure. The breakup length for both criteria show the same tendency even though the random nature of perforation and disintegration process of liquid sheet. The stage of spray development is widely different with the physical properties of liquid atomized, mainly viscosity of liquid. The breakup length decreases smoothly with increase in the injection pressure for the lower viscous liquid.

KEY WORDS : Breakup length, Liquid sheet, Pressure-swirl atomizer, Shadowgraphy

1. INTRODUCTION

Many different types of pressure-swirl atomizers are employed in utility boiler, industrial furnaces, spray cooling, chemical processing, fire protection, foam breaking, vegetable cleaning. Recently pressure-swirl atomizers are recognized to be one of the best atomiser for the direct injection spark ignition (DISI) engines, sometimes called as the gasoline direct injection (GDI) engines because they generally generate a fine fuel spray with SMD ranging from 14 to 25 μm by moderate injection pressure in the range from 5.0 to 10 MPa. Moreover, the spray distribution of pressure-swirl atomizers is generally more axisymmetric than that obtained without swirl (Zhao *et al.* 1999). In a pressure-swirl atomizer, angular momentum is imposed on the liquid to form a swirling motion. Under the action of centrifugal force, the liquid spreads out in the form of a conical sheet as soon as it leaves the nozzle, and a hollow cone spray is formed due to breakup of the sheet. Many researches on pressure-swirl injectors due to the variety of application have been conducted on the effects of nozzle design, operating conditions, properties of liquid and ambient conditions on the flow and spray characteristics theoretically and experimentally. Those works on mean drop size, spray angle, discharge coefficient, film thickness, flow number, and velocity coefficient in the pressure-swirl atomiser were precisely summarized by Lefebvre (1989) and Bayvel and Orzechowski (1993).

Dombrowski and co-workers (Briffa and Dombrowski, 1966, Dombrowski and Hooper, 1962) correlated the breakup length of liquid sheet on the basis of theoretical relation developed from the first order theory of Squire (1953). Clark and Dombrowski (1972) extended that work by taking into account the nonlinear effects and suggested the theoretical expression for the disintegration of liquid sheet. Recently Han *et al.* (1997) introduced the expression by Dombrowski and co-workers (Briffa and Dombrowski, 1966, Dombrowski and Hooper, 1962) and recasted it for modelling the breakup length of a conical sheet resulting from the pressure-swirl injectors for the application of DISI engines. On the other hand, Benatt & Eisenklam (1969) and Dombrowski & Wolfsohn (1972) conducted the experimental studies on the measurement of breakup length of sheets and suggested the empirical correlations. Dombrowski and Fraser (1954) provided useful and basic insight into the manner of disintegration of liquid sheet by the use of photographic technique for the various type of liquid sheets with different physical properties. Lee (1985) studied experimentally the effect of condensation of an ambient gas on the disintegration mechanism of water sheet for the swirl spray nozzle, fan

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Corresponding author. e-mail: sooyoung@chungbuk.ac.kr spray nozzle and solid-injection nozzle with conical deflector. Arai and Hashimoto (1985) investigated the breakup of liquid sheets injected into a coflowing high speed air stream. Recently, the sheet thickness and breakup length of conical liquid sheets discharged by pressure-swirl injectors was studies by Cousin *et al.* (2000). By introducing the method based on electrical liquid conductivity, they found that for relatively low injection pressures ranging from 0 to 7 MPa for the application of GDI injection, a sharp decrease of breakup length was observed with increase in the injection pressure

The objective of this study is to investigate the stage of spray development and the breakup length of conical emulsified fuel sheet discharged by the pressure-swirl atomizer with the variation of water and surfactant contents

2. EXPERIMENTAL APPARATUS

The schematic diagram of experimental apparatus used in this study is shown in Figure 1. The water-in-oil emulsified fuel (w/o emulsion) as a test fuel was pumped from the fuel tank by the oil pump to the nozzle. The nozzle used in this study was a commercial Hago simplex swirl nozzle (type 3.50 45H) widely used for oil burners, rated at 13.3 l/h with hollow cone spray. The nozzle was mounted vertically on a test rig. The emulsified fuel was injected vertically downstream through an atomizer with the injection pressure of 0.1-1.2 MPa into the room temperature and atmospheric pressure environment.

In order to measure the disintegration of the liquid sheet, a shadowgraphy technique was employed by capturing multiple images of the spray with 640 by 480 pixel 3-CCD digital video camera (SONY DCR-VX 1000). Stroboscope was used as light source and the tracing paper was used as diffuser. The captured spray images were stored in a PC for off-line analysis. The breakup length was obtained by averaging the value of 10 images for each experimental condition.

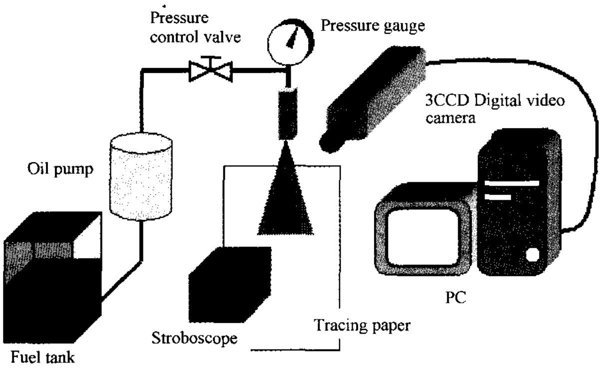

Figure 1. Schematic diagram of experimental setup.

There are some criteria for determining the breakup length of liquid sheet as mentioned above (Dombrowski and Hooper, 1962). In this study, the breakup length of liquid sheet was determined with two different criteria (*i.e.* perforation and drop formation). The former criterion was defined as the distance from the nozzle tip to where the liquid sheet was first seen with perforation. And the later was defined as the distance from the nozzle tip to the region of drop formation.

The fuel used was a commercial light oil with density, surface tension, and kinematic viscosity of 812.4 kg/m^3, 2.62×10^{-2} N/m, and 2.4×10^{-6} m^2/s, respectively. The emulsion were prepared by blending mixtures of fuel, water, and surfactant by means of a high-speed mixer (Tokushu Kika Kogyo M Spec B) for 10 minutes at 6000 rpm. The surfactant was prepared by mixing 75% of SPAN 80 (Showa Chemicals, HLB 4.3) and 25% TWEEN 85 (Yakuri Pure Chemicals, HLB 11) and had an HLB (Hydrophile-Lipophile Balance) of 5.95. To investigate the effect of surfactant content on spray characteristics, the total amount of surfactants used was varied from 1 to 3% by volume. The emulsified fuels were tested employing four volume fractions of water (10, 20, 30 and 40%) (Rhim *et al.*, 2000).

The surface tension and viscosity of emulsion were measured by surface tensiometer (Kyowa Interface Sci. CBVP-A3) and viscometer (Tokyo Keiki B8H), respectively. It is evident that the addition of water changes fuel properties which are the key parameters influencing the atomization of the spray.

3. RESULTS AND DISCUSSION

The development of the spray passes through several stages such as dribble, distorted pencil, onion, tulip stages and fully developed spray as the liquid injection pressure is increased from zero (Lefebvre, 1989). The stage of spray development for the neat light oil and emulsified fuels are illustrated in Figure 2. For three kinds of liquid tested in this work, the dribble and distorted pencil stages does not appear under the experimental conditions. The onion stage occurs below 0.2 MPa for neat light oil and emusified fuel with water content of 20%. The tulip stage occurs between 0.2 and 0.4 MPa for neat light oil, between 0.2 and 0.6 MPa for the emusified fuel with water content of 20%, and between 0.1 and 0.8 MPa for the emusified fuel with water content of 40% respectively. It is clear that the partly developed spray stage exists between tulip and fully developed spray stage for the experimental conditions selected here. This result suggests that the stage of spray development for the liquid sheet is strongly affected by the physical properties of liquid atomized.

From the precise observation of many photographs, it

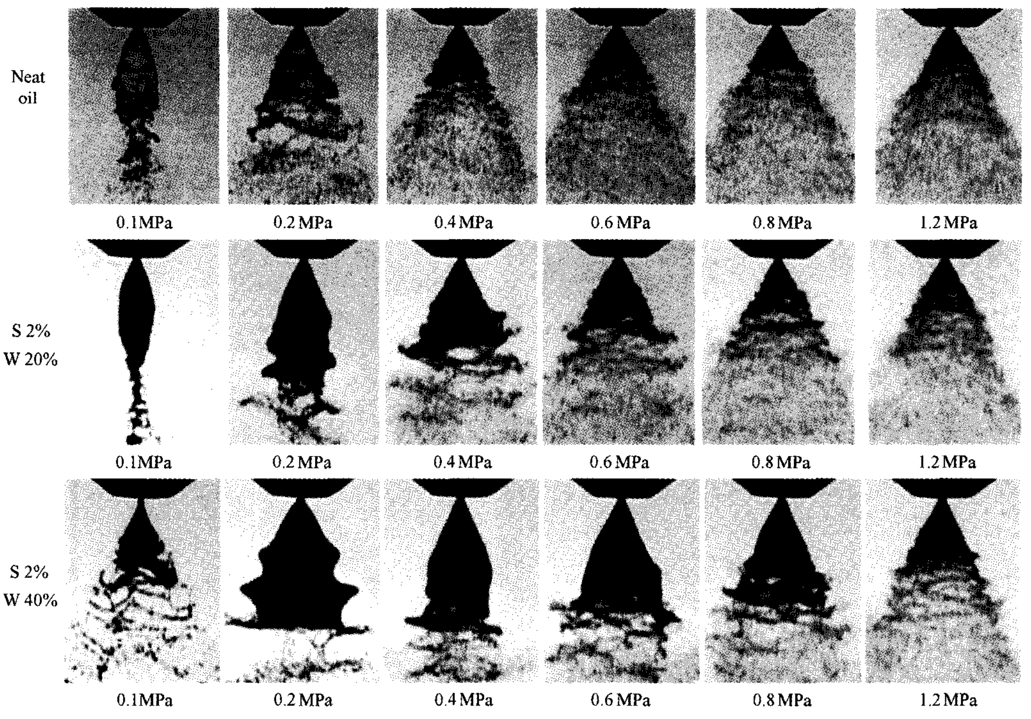

Figure 2. Stage of spray development for neat oil and emulsion fuel.

is noticed that the stage of spray development shows the different regimes with the variation of injection pressure and the kinematic viscosity of liquid. The schematic of the various regimes for the stage of spray development in terms of Ohnesorge number ($\mathrm{Oh} = \mu/(\rho\, \sigma\, \mathrm{d})^{0.5}$) and injection pressure within the experimental condition is shown in Figure 3. In this work, the transition from onion to tulip stage has been defined the injection pressure at which the elliptic shape of spray is first destroyed in the photographs. In addition, the transition from tulip stage to fully developed spray has been defined the injection pressure at which the wavy motion is first disappeared in the photographs. It should be noted here that the regime for distorted pencil stage was not clear in this study and is, therefore, depicted with the dotted line. It is clear that the fully developed spray can be obtained in the range of lower viscosity and higher injection pressure. For example, the liquid with $\mathrm{Oh} < 0.04$ requires the injection pressure more than $\mathrm{Pi} = 0.6$ MPa to obtain the fully developed spray with the pressure-swirl atomizer. Even though more experiment for the effect of ambient conditions is required, this result is still effective and valid for the prediction of spray development.

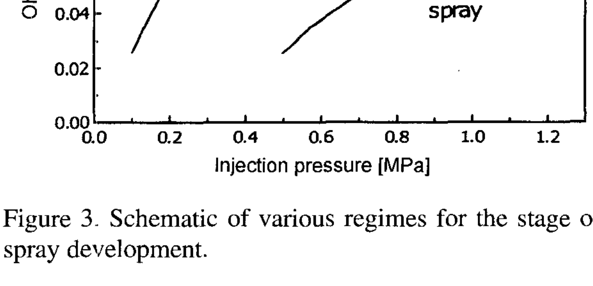

Figure 3. Schematic of various regimes for the stage of spray development.

It is required to find out the difference of breakup length according to the measurement criterion for it. Figure 4 shows the variation of breakup length with the injection pressure for two criteria- perforation and drop formation, As expected, the breakup length based on the drop formation shows the longer sheet than that based on perforation. Both breakup lengths decrease gradually with increase in the injection pressure for the neat oil. It should be noted that the breakup length for both criteria shows the same tendency even though the random nature of perforation and disintegration process of liquid sheet. This result suggests that once the perforation occurs, drop

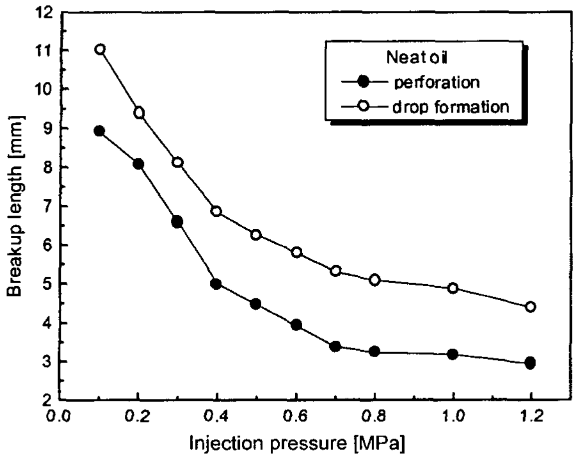

Figure 4. Comparison of criteria for the measurement of breakup length.

can be generated after the short time. It is clear from Figure 4 that there exist around 20% difference of breakup length between two criteria-perforation and drop formation in case of neat light oil.

Meanwhile, the difference between the breakup lengths based on two criteria for the emulsified fuels was varied from 18 to 33% with the variation of water and surfactant contents.

The variation of breakup length with injection pressure for the different water content of emulsion at the surfactant content of 2% is shown in Figure 5. The breakup length based on the perforation is shown in Figure 5(a) and the breakup length based on the drop formation is shown in Figure 5(b). Comparison of Figure 5(a) and 5(b) shows the similiar effect of water content on the breakup length with an increase of injection pressure. The breakup length of liquid sheet decreases smoothly with increase in the injection pressure up to water content of 30%. This result is coincident with the work by Cousin *et al.* (2000). As pointed out by Dombrowski and Fraser (1954) the position of disintegration moves much further away from the nozzle with an increase of viscosity from 2.196×10^{3} N s/m^2 for neat light oil to 10.032×10^{3} N s/m^2 for emulsion with water content of 40% at the given injection pressure. In case of water content of 40% in the lower injection pressure, the breakup length shows the randomly fluctuated tendency. This effect comes from the various stages of spray development as shown in Figure 2. This is due to the difference of the physical properties of liquid, mainly abrupt increase of viscosity of emulsion from the water content of 40%. (Rhim *et al.* 2000).

Figure 6 shows the influence of surfactant content on the breakup length of liquid sheet for the emusified fuel with water content of 10%. It can be seen from this figure that the breakup length decreases with an increase of injection pressure as similar as in Figure 5. It is clear that the surfactant content affects the breakup length just in case of injection pressure under 0.2 MPa. There is no clear effect on the criteria of breakup length for all the case of surfactant content. This is maybe due to the same decrease of viscosity with increase in the surfactant content.

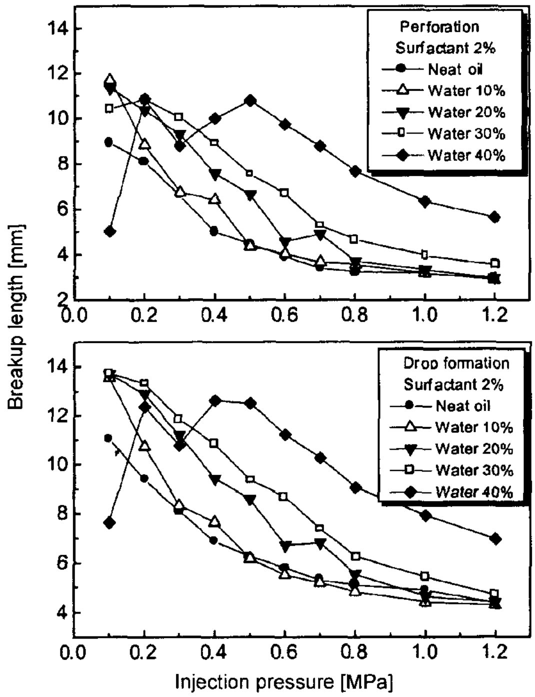

Figure 5. Influence of water content on breakup length for surfactant content of 2%. (a: based on perforation b: based drop formation).

The standard deviation in breakup lengths reported in this paper is estimated as to be a range of 0.2-1.0 mm.

To validate the experimental data, the theoretical or empirical equations can be introduced. Little information regarding the theoretical or empirical formulations could be found in the literature. The theoretical equation by Clark and Dombrowski (1972) and the empirical relation by Dombrowski and Wolfsohn (1972) had been suggested respectively.

Recently, the equation by Clark and Dombrowski (1972) was applied to the estimation of sheet breakup length for GDI injectors (Han *et al.*, 1997, Cousin *et al.*, 2000). The empirical relation by Dombrowski and Wolfsohn (1972) could not be applied in this study because it seems to be dimensionally incorrect. Therefore, the validation of the experimental data obtained in this study will be one of the future works.

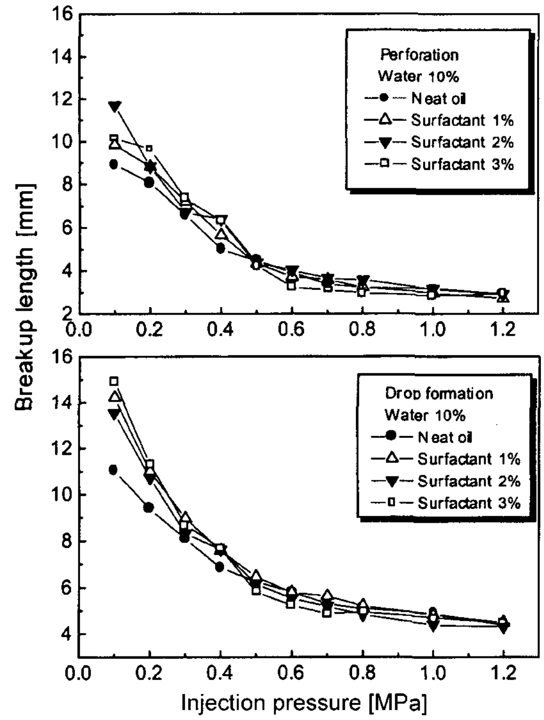

Figure 6. Effect of surfactant contnt on breakup length for water content of 10%. (a: based on perforation b: based drop formation).

4. CONCLUSIONS

The stage of spray development and the breakup length of conical emulsified fuel sheet discharged by the pressure-swirl atomizer with the variation of water and surfactant contents were investigated. The various regimes for the stage of spray development within the experimental conditions selected in this study is newly suggested in terms of Ohnesorge number and injection pressure. The stage of spray development is widely different with the physical properties of liquid atomized, mainly viscosity of liquid.

The breakup length for both criteria shows the same tendency even though the random nature of perforation and disintegration process of liquid sheet. For the measurement of breakup length, two criteria, *i.e.* points based on perforation and drop formation were examined. According to the measurement criteria of breakup length, around 18-33% differences of breakup length was obtained in case of neat light oil and the emulsified fuels considered in this study.

The breakup length decreases smoothly with increase in the injection pressure. The breakup length, however, increases with an increase of water content emulsified fuel due to the increase of viscosity. The effect of surfactant content in the emulsified fuel was negligible within the experimental conditions in this study.

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