The Atomization Characteristics of a Liquid-Liquid Swirl Coaxial Injector

Dongjun Kim 1, Sunghyuk Kim 2, Poonggyoo Han 3 and Youngbin Yoon 4

1School of Mechanical and Aerospace Eng., Seoul National University, KOREA, kan31@snu.ac.kr
2School of Mechanical and Aerospace Eng., Seoul National University, KOREA, inas97@snu.ac.kr
3School of Mechanical and Aerospace Eng., Seoul National University, KOREA, ihans2001@gmail.com
4Institute of Advanced Aerospace Technology, Seoul National University, KOREA, ybyoon@snu.ac.kr

ABSTRACT The influences of injection conditions and recess configurations of liquid-liquid swirl coaxial injector on the spray characteristics were investigated. It is revealed that the interaction between two conical liquid sheets gas considerable influence on the spray characteristics. The coaxial spray characteristics like as spray angle and breakup length were determined to be close to the side having larger momentum between inner and outer spray. Also, it is known that the recess can augment mixing efficiency and flame stabilization through the internal mixing of propellants. In the internal mixing injection region, spray angle and breakup length increase with increase of recess length, and which can be explained by the formation and decay of wave inside the recess region. As the recess length increases, the mean drop size increases due to the increase of effective film thickness and the decrease of spray angle.

Keywords: Swirl Coaxial Injector, Spray Characteristics, Spray Angle, Breakup Length, Recess, SMD

1. INTRODUCTION

Fast atomization, uniform mass distribution and mixing of propellants have great influence on combustion and its efficiency in liquid rocket engines, and the injector is the essential device for pre-combustion stage: atomization, evaporation and mixing. Many types of injectors, such as a like- or unlike-doublet, triplet, pintle and coaxial injectors have been used for liquid rocket engines and extensive studies have been carried out to characterize its performance and effect of injection and geometric conditions during several decades. Coaxial injectors, consist of an inner injector surrounded by a concentric annular outer injector, are widely used in liquid rocket engines due to their advantages: high performance and stability with broad ranges of operation due to the efficient atomization and mixing of uniform distributed propellants, and also lower precision level of manufacturing technology.

Coaxial injectors can be classified by the combination of propellant phase, such as gas-gas, gas-liquid and liquid-liquid. Many investigations on the spray and breakup characteristics of a coaxial injector with central liquid jet and annular gas jet have been performed [1][2]. The atomization of this shear coaxial injector is achieved due to the transfer of kinetic energy by gas stream of high speed on the liquid jet. Hadalupas and Whitelaw [1] observed the variation of mean drop size and spray width with changing the injection and geometric conditions, and supposed that the optimal injector design could be establish by considering the drop size and spread of spray at once. Sankar et al. [2] reported that the flow properties, such as surface tension and viscosity had a crucial role in atomization process.

When the combination of propellants is liquid-liquid phase, the swirl injector was mainly used as both inner and outer injector for efficient atomization and mixing. Liquid-liquid swirl coaxial injectors have been widely used in liquid rocket engines to take advantage of their higher mixing efficiency within a short length of the combustion chamber [3][4][5]. The interaction of two swirling liquid sheets from a liquid-liquid coaxial injector and its influences on the spray characteristics could be quite different from those observed in gas-liquid coaxial injectors. Seol et al. [6] performed a visualization study on the interaction of the inner and outer sprays of a dual-orifice injector. They observed the spray interaction affected by the distribution of ambient pressure around the spray, but the study is restricted to low injection pressure at which the conical liquid sheets are not diverging. In addition, systematic experimental studies on the mutual interaction of thin coaxial, conical liquid sheets were carried out by Sivakumar and Raghunandan [4][5]. They concluded that the merging and separation process of liquid sheets which exhibits hysteresis leads to a drastic variation in the drop size which will have serious implications on the engine throttling.

The geometric parameters as well as injection conditions are very important in a coaxial injector. Especially, recess in a coaxial injector is the configuration that exit of an inner injector is located inward at a certain length from the exit of an outer injector, and this recess has been popularly used to increase both atomization and mixing efficiency and various investigations on the effect of the recess have been performed in gas-liquid coaxial injectors [7][8]. In the case of liquid-liquid coaxial injector, Sivakumar and Raghunandan [3] conducted the experiments on drop size measurement with varying the recess length of an inner injector in liquid-liquid swirl coaxial injectors. Interestingly, they found that the recess had a negative effect on the atomization because the internal interaction of two liquid sheets leads to the increase of effective sheet thickness. Unfortunately, the previous studies on the spray characteristics including the effect of recess in gas-liquid coaxial injector have been much performed, while the literatures on the liquid-liquid swirl coaxial injector nearly exist. The main objective of this study is to investigate the spray characteristics of a liquid-liquid swirl coaxial injector with injection conditions and recess configurations. Ultimately, we would like to understand the phenomenon on the interaction between two...
liquid sheets as varying the injection pressure of each inner and outer injector and the effect of recess as fixing the injection condition by observing the spray shape, spray angle and breakup length.

2. EXPERIMENTAL METHODS

The liquid-liquid swirl coaxial injector, used in the experiments, consists of three part; an inner injector, outer injector and injector case, as shown in Fig. 1. The interior orifice diameters of an inner and outer injector were 2mm and 6mm. An inner injector has three tangential entries with the diameter of 1mm at every 120 degree and an outer injector has two tangential entries with the diameter of 0.8mm at every 180 degree. Table 1 shows the experimental conditions and parameters. Water was used as the simulants of LOX and kerosene. The injection pressure differential of each injector was varied from 1 to 6 bar, which corresponds to the mass flow rate range of 8.73 to 25.51 g/s for an inner injector and 4.72 to 12.64 g/s for an outer injector, respectively. For the experiments on effect of recess, the experiments have been performed for 8 cases of recess length. For all cases, the mass flow rates of an inner and outer injector are each 25.6g/s and 10.76g/s, which corresponded to the injection pressure drop of 6 bar as shown in Fig. 2 and thus, O/F ratio was fixed at 2.38.

![Fig. 1 Swirl Coaxial Injector Design](image)

We observed the spray patterns and measured the spray angle and breakup length by using instantaneous spray images taken by indirect photography. The stroboscopic light whose luminous time is less than 4 μs was illuminated through a translucent paper. The exposure time of a CCD camera (KODAK ES1.0, 1008 × 1008) was set to be identical to the flash interval of the stroboscope to taken an image per flash without extra synchronization. Sixty images were taken for one experimental case, and the deviations of data were less than 10 percent from their mean values.

The SMD of the droplets was measured with PDPA(Phase Doppler Particle Analyzer). As a light source, an Ar-ion laser (514nm, SpectraPhysics) was utilized. The number of samples at each location was set to be typically 10,000, except for the center and peripheral region of cone spray where data rate drops abruptly. Mechanical patternator was used to measure mass distribution and mixing efficiency of swirl coaxial injectors. Spray is collected through flat 180(15 X 12) lattice cells the side length of which are 10mm uniformly in lows and columns. 180 transparent rubber tubes are connected with the lattice cells and measuring devices respectively.

3. DEFINITION OF RECESS NUMBER

The recess is a geometric variable of coaxial injectors. In some previous studies, the recess length was normalized by the interior diameter or length of an inner injector orifice, but these can be only adopted for their own specific injector design. In a swirl coaxial injector using liquid-liquid propellant, the spray angle of an inner injector has a great influence on the spray characteristics combined with the recess due to the position of the impingement and the momentum loss. Thus a new dimensionless recess number, RN, in a swirl coaxial injector, considering the spray angle and breakup length, is defined as the ratio of the recess length, $L_R$, to the contact length, $L_C$, as shown in eq. (1).

$$\text{RN} = \frac{L_R}{L_C} = \frac{r_o - r_i}{\tan \theta_i}$$

Here, the contact length, $L_C$, means the length from an inner injector exit to the position where the liquid sheet injected from an inner swirl injector impinges the nozzle wall of an outer injector. $r_o$ is the orifice radius of an outer injector and $r_i$ is the orifice radius of an inner injector. The half spray angle, $\theta_i$, of eq. (1) was obtained from the backlit stroboscopic photography and measured as 77.32°. Thus the recess lengths are converted to the dimensionless recess numbers, 0, 0.8, 1.2, 1.6, 2.0, 2.4, 2.8 and 3.2, respectively.

![Fig. 2 Definition of Recess Number](image)

4. EFFECT OF INJECTION CONDITIONS

4.1 Spray Shape

Typically, if the mixing and interaction of coaxial spray began inside the injector, namely recess region, we called as an internal mixing injection, otherwise we called as an external mixing injection. In Fig. 3, the coaxial spray shapes of both internal and external mixing injections were shown as increasing the injection pressure of an inner injector at a fixed injection pressure of outer injector, 2bar. In general, the spray shape formed by a swirl injector undergoes an onion, tulip stage and grows to a fully-developed cone as the $We$ increases. It is known that the pressure difference between the liquid sheet causes an onion or tulip shape at low $We$. Once the spray was discharged, the entrainment of ambient gas was generated at the inner and outer surfaces of the spray. However, the interior gas volume was limited by the spray, so the pressure difference between the inner and outer gas was produced, which caused the contraction of the spray.

In the external mixing injection of coaxial injector...
without recess, the interior ambient gas volume of outer swirling sheet is smaller than that of outer spray alone due to the existence of inner spray. And thus, the outer spray in the case of coaxial discharging spray got bent more toward the centerline (external mixing injection, $\Delta P_i = 1\text{bar}$ and $\Delta P_o = 2\text{bar}$) as compared with the single outer injection ($\Delta P_o = 2\text{bar}$). Though it is expected that the inner and outer spray cannot meet because the spray angle of an outer injector is larger than that of an inner injector, the coaxial sprays were always merged except at very low injection pressure of inner injector, $\Delta P_i = 1\text{bar}$. The pressure drop in the region between outer and inner liquid sheets, caused by the entrainment of ambient gas, made two liquid sheets to approach each other. As the injection pressure of an inner injector increases, the spray angle of outer spray continuously increases, while the spray angle of outer spray decreases by the reduction of interior volume. Also, the spray characteristics of individual swirling spray, like as the spray angle and breakup length are significantly changed, which could influence on the merging behavior of coaxial spray. From the overall spray in external mixing injection, the breakup length decreased and spray angle increased as increasing the injection pressure of an inner injector.

![Fig. 3 Coaxial Spray Shape](image)

In the internal mixing injections of coaxial injector with recess, separate discharging phenomena were not found even at very low injection pressure of an inner injector, because the inner and outer sprays were coalesced and mixed on the outer injector wall. Compared to the coaxial sprays in external mixing injection, the coaxial spray of internal mixing injection shows the relatively uniform shape having a narrower spray angle and slightly longer breakup length at the same injection conditions. As increasing the injection pressure of inner injector, the decrease of coaxial spray angle was observed. On the other hand, the breakup length of coaxial spray was decreased due to the increase of injection velocity.

### 4.2 Spray Angle

The spray angle produced by a swirl injector is important in combustion systems. The spray angle characterizes the spatial distribution of droplets, and thus it has a strong influence on the ignition performance and interactive characteristics of a multi-element injector and on the cooling of the injector plate in rocket engines. Figure 4 show the measured individual spray angles of inner and outer injectors. In the case without recess, the inner spray shape undergoes a tulip stage, and grows to a fully-developed cone of about $77^\circ$ after $W_e = 400$. In a simple sense, the spray angle can be determined by the ratio of tangential velocity, $w$ to axial velocity, $u$ at the orifice exit. In the case with recess, however, since the inner spray was ejected after impinging on the outer injector wall, whose interior diameter was three times larger, the tangential velocity of the inner spray at the final exit plane, by the angular momentum conservation, $w = \text{const.}$, was about three times lower. Consequently, the fully-developed inner spray angle in case with recess was measured as about $32^\circ$. And the development of inner spray angle according to injection conditions seemed to be similar for both cases with or without recess. An outer spray also undergoes the tulip stage and grows to a fully-developed cone of about $110^\circ$ after $W_e = 200$.

![Fig. 4 Spray Angle Variations](image)
To identify the change of coaxial spray angle by merging phenomenon, the spray angle was measured with varying $We_o$ at a fixed $We_i = 109$, like as Fig. 4(b). Two liquid sheets were merged at $We_o = 47$, but thereafter the inner and outer spray was separately injected, and after $We_o = 255$, two liquid sheets merged again. During separated injection, the outer spray angle was smaller and inner spray angle was larger than each individual spray angle. This is due to the pressure drop in the region between two liquid sheets. On the other hand, the merged spray angle was the medium-sized angle between the individual inner and outer spray, but it is to be noted that the merged spray angle at $We_o = 47$ was close to individual inner spray angle, while those after $We_o = 255$ were close to individual outer spray angle. Therefore, one could expect that the merged spray angle was determined to be close to the side having larger momentum between inner and outer spray.

The measured spray angles for different injection conditions were shown in Fig. 5. Figure 5(a) shows the coaxial spray angle according to $We_o$ and each symbol indicates the same $We_i$. For both cases of external and internal mixing injection, it was found that coaxial spray angle increased with $We_o$, by the increase in the momentum of outer spray, having relatively larger spray angle. Also, the larger variation of coaxial spray angle according to $We_o$ was detected at low $We_i$. Figure 5(b) shows the coaxial spray angles according to $We_i$ and each symbol indicates the same $We_o$. According to the increase of $We_o$, the coaxial spray angles in external mixing injection were nearly invariant, while those in internal mixing injection decreased gradually. In contrast to Fig. 5(a), the variation of coaxial spray angle according to $We_i$ was large at high $We_o$, because the initial spray angle was sufficiently large. As stated earlier, it revealed that the merged spray angle was determined as the medium-sized angle between the individual inner and outer. And, as increasing the mass flow rate or momentum of inner spray with smaller spray angle, the coaxial spray angle approached to the individual inner spray angle and vice versa.

4.3 Breakup Length

Figure 6 shows the measured breakup length of coaxial spray in the case without recess, together with the individual spray of an inner and outer injector.

As for the individual spray, the breakup length of an inner spray decreased as increasing the injection pressure.
While the breakup length of outer spray increased in the early increase of injection pressure and decreased after \( W_{ei} = 120 \). It is supposed that some moderate pressure need for an outer injector to be the developed spray because the orifice diameter of an outer injector is relatively large. The measured breakup length with varying \( W_{ei} \) at each fixed \( W_{oi} \) was shown in Fig. 6(a). In the case in external mixing injection, two distinct trends were observed. When the \( W_{oi} \) was low \((W_{oi} < 419)\), the variations of breakup length were similar with the outer spray. However, if the \( W_{oi} \) was more than 419, the variations of breakup length according to \( W_{ei} \) were nearly invariant. Also, the variations of breakup length according to the \( W_{oi} \) at low \( W_{oi} \) were large, but the increase of \( W_{ei} \) had no influence on the breakup length as the moderate \( W_{ei} \).

The measured breakup length with varying \( W_{oi} \) at each fixed \( W_{ei} \) was shown in Fig. 6(b). As increasing the \( W_{ei} \), the breakup length decreased in both cases of external and internal mixing injection. However, at low \( W_{oi} \) and \( W_{ei} \), the breakup length was nearly invariant in spite of the increase of \( W_{oi} \). Compared with the case without recess, the variations of breakup length according to the injection conditions were small. To some extent, however, it was found that the coaxial spray broke up faster as increasing the injection pressure of either inner or outer injector.

5. EFFECT OF RECESS CONFIGURATION

5.1 Spray Angle and Breakup Length

Figure 7 shows spray patterns of the swirl coaxial injector with the change of recess number in the operating conditions of two propellants as previously stated. According to eq. (1), inner oxidizer sprays exactly meet at the outer injector exit tip when \( L_R \) is the same with \( L_C \). But because the fuel is sprayed forming the thin film on the wall of the outer injector, two propellants meet at the outer injector exit tip at the recess number, a few higher than 1.0. From the experiments, we concluded that the point is recess number of 1.2.

![Fig. 7 Spray Shapes with Recess Number](image)

Typically, if mixing and interaction of propellants began within the recess region, we called as an emulsion injection, otherwise we called as an outer mixing injection. According to this interaction position, the spray and mixing characteristics are changed a great deal. These tendencies could be confirmed by Fig. 7, in the outer injection region, the atomization occurs well by the collision of two thin films outside the injector and wider spatial distributions are observed. On the other hand, in the emulsion injection region, the width of spray decreases considerably due to the momentum loss of tangential direction by the collision on the outer injector wall, but the mixing efficiency is expected to increase.

![Fig. 8 Spray Angles with Recess Number](image)

The change of spray angle with the recess number is shown in Fig. 8. We can know that the spray angle of coaxial injector is much influenced by the interaction position, such as outer mixing and emulsion injection, as observed in Fig. 9. In the outer mixing injection region, the more increase recess number, the more increase the spray angle of coaxial spray. However, in the emulsion injection region, the coaxial spray angle decreases remarkably by half compared with the outer mixing injection region. And as the recess number increases, the coaxial spray angle increases. This can be explained by the formation and decay of waves by the propellants interaction inside the recess region, as shown in Fig. 9.

If the inner oxidizer spray collides on the liquid film of outer fuel, the ripple is formed and damped as flowing along the injector wall after collision. As the recess length increases, the amplitude of ripple at the injector exit tip decreases like as eq. (2).

\[
\eta_0 = \eta_i \exp(i k (L_R - L_C))
\]

where \( \eta_0 \) is the wave amplitude at the injector exit tip, \( \eta_i \) is the initial wave amplitude at the collision position, and \((L_R - L_C)\) is the moving distance. The parameter, \( k \), is a imaginary value. In the experiments on effect of recess, the injection conditions of fuel and oxidizer were fixed, and thus \( \eta_i \) was constant but \( \eta_0 \) might be different with recess length. From the eq. (2), the wave amplitude at the injector exit tip decreases as the recess length increases. Therefore, because the energy of initial wave amplitude at the collision position was converted to the swirling momentum, the coaxial spray angle in the emulsion injection region increases with the increase of recess number. This supposed phenomenon inside the recess region was validated by the simple impingement of two liquid sheets, like as Fig. 9(b). The wave caused by the impingement of two liquid sheets was damped out as moving downward.

Figure 10 shows the breakup length with the recess number, measured from the Fig. 7. Like as the results of the
spray angle, the tendency of breakup length is different according to outer mixing injection and emulsion injection. In the outer mixing injection region, the interaction position between propellants is closer from the injector exit and spray angle increases as the inner oxidizer injector is more recessed. And thus the breakup length decreases. By the way, in the emulsion injection region, the breakup length increases with the increase of recess number.

\( (\eta_0)_{\text{shallow}} \) shallow
\( (\eta_0)_{\text{deep}} \) deep

Fig. 9 Internal Interaction of Two Liquid Sheets

According to the Clark and Dombrowski[9], the breakup length is affected by the wave amplitude of the ripple at the injector exit tip, \( \eta_0 \) and their equation could be simplified like as eq. (3). As the recess length increases, the wave is damped as flowing along the outer injector wall. So, the wave amplitude at the injector exit tip decreases, so more stable conical sheet is formed. The comparison of measured breakup length with the simplified analytical relation by Clark and Dombrowski[9] was also plotted in Fig. 10 and showed a good agreement.

\[
x_b^{1/2} = \frac{9 \rho_f KU^2}{32(\rho_s U^2k - \sigma k)} \cosh^{-1}(\eta_0 k - 1)
\]

(3)

Fig. 10 Breakup Lengths with Recess Number

5.2 Atomization Characteristics

Most previous studies on the spray have mainly concentrated on the prediction of the mean drop size and distribution[10]. This is because it has been shown to strongly affect the performance, stability limit and the emissions of pollutants. In order to see the effect of recess in a liquid-liquid swirl coaxial injector on the atomization characteristics, the mean drop size was measured using PDPA. Figure 11 shows the SMD distributions with recess number in the radial direction. As previously stated, if two liquid sheets interact outside the injector, the fuel and oxidizer sheets didn’t perfectly coalesce. And thus the interaction of two thin liquid sheets produces smaller droplets. The coaxial spray width decreases considerably in the case of recess number 1.2, where two propellants meet at the outer injector exit tip, but the measured SMD is not so large because the collision of two propellants has a great effect on the atomization.

Fig. 11 SMD Distributions with Recess Number

In the internal mixing injection region, SMD of coaxial spray increases. Consequently, the recess has a negative effect on the atomization. This is the opposite trend to the previous studies of gas-liquid coaxial injector. The reason is that the internal mixing of propellants leads to the increase of the effective thickness of liquid sheet and thus produces larger droplets. These tendencies are confirmed in the results of Sivakumar and Raghunandan [3].
6. CONCLUSIONS

The influences of injection conditions and recess configurations of liquid-liquid swirl coaxial injector on the spray characteristics were investigated. It is revealed that the interaction between two conical liquid sheets gas considerable influence on the spray characteristics. The coaxial spray characteristics like as spray angle and breakup length were determined to be close to the side having larger momentum between inner and outer spray.

Also, the effect of recess in the case of liquid-liquid swirl coaxial injector was investigated. The spray characteristics of swirl coaxial injectors are much influenced by the interaction position of propellants in the recess, such as external and internal mixing injection. In the internal mixing injection region, spray angle and breakup length increase with increase of recess length, and which can be explained by the formation and decay of wave inside the recess region. As the recess length increases, the mean drop size increases due to the increase of effective film thickness and the decrease of spray angle.

7. REFERENCE