# Effects of Injector Geometry on Discharge Coefficients of Bi-Swirl Coaxial Injectors

*Kyubok Ahn*, Munki Kim** and Hwan-Seok Choi***
**Department of Mechanical Engineering, Chungbuk National University*
*1 Chungdae-ro, Seowon-gu, Cheongju, Chungbuk 362-763, Korea*
***Combustion Chamber Department, Korea Aerospace Research Institute*
*169-84 Gwahak-ro, Yuseong-gu, Daejeon 305-806, Korea*

## Abstract
An experimental study has been performed to investigate the effects of injector geometry on the discharge coefficients of bi-swirl coaxial injectors. Liquid oxygen (LOx) and kerosene (Jet A-1) were burned in small gas generators which operated in very fuel-rich conditions. Each gas generator was equipped with seven liquid-liquid swirl coaxial injectors where LOx flowed through the inner close-type swirl injector and kerosene passed through the outer open-type swirl injector. The discharge coefficients obtained from hot-firing tests were compared with those from cold-flow tests. The result showed that as the geometric constant ($K$) of the inner swirl injector increased, the discharge coefficient of the inner swirl injector in the hot-firing test became lower than that in the cold-flow test. On the contrary, the geometric constant ($K$) of the outer swirl injector seldom affected the discharge coefficient of the outer swirl injector in the hot-firing test.

## Nomenclature

| | | |
|---|---|---|
| $A$ | = | area, mm$^2$ |
| $A_h$ | = | area of tangential holes, mm$^2$ |
| $Cd$ | = | discharge coefficient |
| $d$ | = | diameter, mm |
| $K$ | = | geometric constant of swirl injector |
| $L_1$ | = | injector recess length, mm |
| $L_2$ | = | distance between oxidizer post tip and colliding point of oxidizer sheet on fuel nozzle wall |
| $n$ | = | number of injector tangential holes |
| $OFR$ | = | oxidizer-to-fuel mixture ratio |
| $p_c$ | = | chamber pressure, bar |
| $\Delta p_{inj}$ | = | pressure differential through injector, bar |
| $R$ | = | radial distance from swirl chamber axis to center of tangential holes |
| $r$ | = | radius |
| $\varphi$ | = | filling coefficient in orifice |

*Subcripts*

| | | |
|---|---|---|
| *cold* | = | cold-flow test |
| *hot* | = | hot-firing test |
| *o* | = | injector orifice (nozzle) |
| *s* | = | injector swirl chamber |
| *K* | = | kerosene (fuel) |
| *L* | = | liquid oxygen (oxidizer) |

## 1. Introduction

An injector is a device that atomizes and disintegrates liquid (water, oil, gasoline, kerosene, etc.) converting pressure energy to kinetic energy. Since petroleum was discovered, injectors have been considerably studied and successfully used in combustion devices of transportation systems such as cars, airplanes, and liquid rockets. Specifically, in a

Copyright © 2015 by First Author and Second Author. Published by the EUCASS association with permission.

liquid rocket engine (LRE), the injector is well known as one of the most important components that affect engine performance and stability because it directly influences on atomization and mixing of propellants in a combustion chamber [1].
Historically, four different types of injectors have been usually utilized in LREs: impinging-type, swirl-type, shear-type, and pintle-type injectors [2]. In the United States, impinging injectors, shear-coaxial injectors, and pintle injectors have been favourably used in the F-1 engines, the Space Shuttle Main Engines, and the Merlin engines, respectively. In the former Soviet Union and Russia, swirl or swirl-coaxial injectors have been adopted in the RD-0110, RD-107, and RD-170 engines [3].
Differently from the other injectors, the swirl injector has the air core in the discharging nozzle induced by the centrifugal force. This makes the discharge coefficient of the swirl injector be much lower than those of the other injectors. Previous researchers such as Taylor [4], Rizk and Lefebvre [5], and Jones [6] in the Western world found that the discharge coefficient is a function of the inlet port diameter, the swirl chamber diameter, and the exit orifice diameter. Independently, from the principle of maximum flow rate, Abramovich [7], Bazarov et al. [8], and Khavkin [9] in Russia suggested their empirical equations composed of the tangential hole diameter (inlet port diameter), the radial distance from the swirl chamber axis to the center of the tangential holes, and the exit nozzle diameter. Recently, Ahn and Choi [10] compared their experimental results with the empirical equations from the previous researchers [4–9] to evaluate their empirical equations.
Among swirl-type injectors, a bi-swirl coaxial injector which consists of two swirl injectors with tangential holes in each swirl chamber is a special type for a LRE. Swirl coaxial injectors which discharge liquid oxygen (LOx) and kerosene have been successfully applied in Russian rocket engines and intensively developing in Korea for the Korea Space Launch Vehicle-II. Kim et al. [11], Sivakumar and Raghunandan [12], and Soltani et al. [13] studied the bi-swirl coaxial injectors concentrating on mixing, spray cone angle, film thickness, and drop size under cold-flow tests changing injector geometry, recess length, injection pressure drop, ambient pressure, mixture ratio, etc.
Recently, the research group at Korea Aerospace Research Institute has published several papers about the effects of a recess length in bi-swirl coaxial injectors on discharge coefficient [14], combustion performance [15], combustion stability [16–18], and heat transfer [19] under hot-firing tests. In thrust chamber-like combustors with multi-element bi-swirl coaxial injectors, Ahn et al. [14] showed that the longer recess length gradually reduced the discharge coefficients and found that the discharge coefficients of the outer fuel-side injectors decreased more remarkably than those of the inner oxidizer-side when the LOx film collided with the kerosene film inside the fuel nozzle. An injection pressure drop, which is one of the important requirements for an engine design, is inversely proportional to the square of a discharge coefficient. Thus, one should be able to predict a discharge coefficient for designing a new swirl coaxial injector.
In spite of abundant previous research, our knowledge is not enough to understand the physics in the bi-swirl coaxial injector, especially under hot-firing condition and under fuel-rich combustion. Therefore, the objective of this study is to investigate the effects of the injector geometry on discharge coefficients in multi-element combustors employing LOx-kerosene swirl coaxial injectors. Combustion tests for each combustor were repeated two times at almost similar condition of chamber pressure and fuel-rich mixture ratio.

## 2. Experimental methods

### 2.1 Bi-swirl coaxial injector and combustor

Figure 1 is a schematic diagram of the present bi-swirl coaxial injector consisting of the inner close-type swirl injector (LOx-side) and the outer open-type swirl injector (kerosene-side). For example, the diameter of the swirl chamber is greater than that of the orifice in the close-type swirl injector, but the diameter of the swirl injector is equal to that of the orifice in the open-type swirl injector. The injector configuration is similar to that of the previous research [18]. LOx enters the swirl chamber through six tangential holes, forms a swirl motion, and discharges through the inner oxidizer post into the combustion chamber. Kerosene (Jet A-1) is supplied via six tangential holes, swirls down, and passes through the outer fuel nozzle to come into the combustion chamber. A total of three different injectors have different geometries except for the recess length, 4 mm, between the inner oxidizer post tip and the outer fuel nozzle tip.

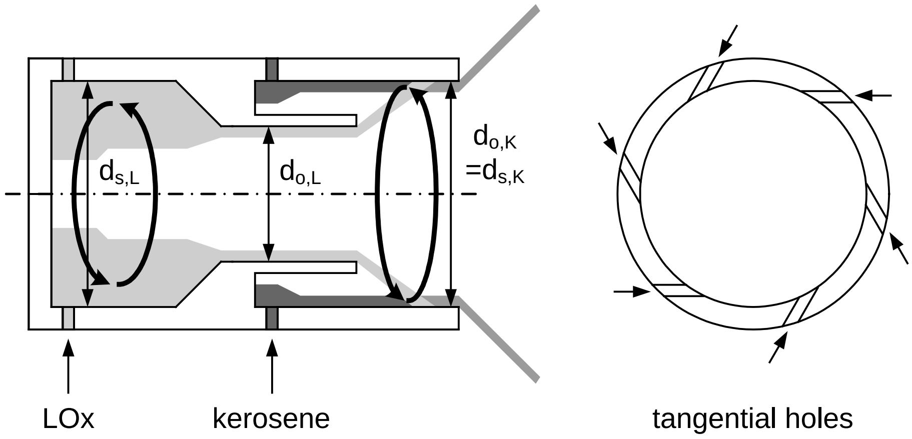


Figure 1: Schematic of the present bi-swirl coaxial injector

The recess number (RN) is a dimensionless parameter and is defined as $L_1/L_2$. Since three different injectors have recess numbers greater than 1.0, the LOx film impinges against the kerosene film inside the fuel nozzle, so-called internal mixing [15]. The geometric constant of the swirl injector which is very important parameter characterizing discharge coefficient and spray angle, is defined as:

$$K = \frac{A_o R}{A_h r_o} = \frac{(1-\varphi)\sqrt{2}}{\varphi\sqrt{\varphi}} \quad \textbf{(1)}$$

The geometric dimension of the bi-swirl coaxial injector and the calculated values of recess number and geometric constant, are summarized in Table 1.

Table 1: Geometric dimensions and calculated values of the bi-swirl coaxial injectors

| | **Inj_1** | **Inj_2** | **Inj_3** |
|---|---|---|---|
| $n_L$ | 6 | 6 | 6 |
| $d_{o,L}$ | 3.30 | 3.30 | 3.75 |
| $d_{s,L}$ | 6.15 | 6.05 | 6.65 |
| $K_L$ | 1.69 | 2.00 | 2.79 |
| $n_K$ | 6 | 6 | 6 |
| $d_{o,K}$ | 8.00 | 8.00 | 8.75 |
| $d_{s,K}$ | 8.00 | 8.00 | 8.75 |
| $K_K$ | 2.86 | 3.28 | 3.75 |
| RN | 2.00 | 2.09 | 2.26 |

The multi-element combustor consists of an injector head, a combustion chamber, and a choked nozzle, as illustrated in Fig. 2. The configurations of the combustion chamber and the choked nozzle are the same as those of the previous research [18]. The injector head has seven identical swirl coaxial injectors, which are distributed uniformly along one concentric circle: one is located at the center and six on the first row. LOx is supplied into the oxidizer manifold through one central tube at the oxidizer dome. Kerosene is fed into the fuel manifold via two symmetrically-installed tubes. The internal diameter of the cylindrical chamber is 74 mm and its length is 146 mm. The length from the faceplate to the nozzle throat is 252.4 mm and the throat diameter is 20.8 mm. The chamber and nozzle are made of stainless steel and have no cooling system since the combustion temperature is approximately 900 K. All of the parts are bolted together and sealed with inserted copper gaskets.

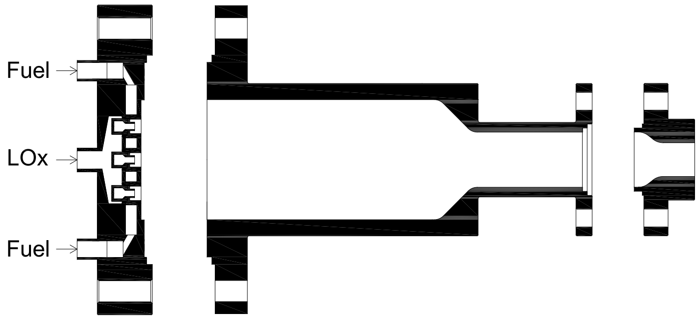


Figure 2: Schematic of the multi-element combustor

### 2.2 Experimental conditions

Static pressure, temperature, and dynamic pressure data in the propellant manifolds and combustion chamber were acquired during hot-firing tests. Static pressure and temperature were recorded at 1000 Hz using a data acquisition system (National Instrument, PCI). Each propellant flow rate was gauged by two volume flow meters (Hoffer) and one mass flow meter (Micro Motion) installed on each propellant supply line. Pressure and mass flow rate measurement uncertainties were confirmed to be less than 0.25% in the area of interest [16]. Combustion tests for each combustor were repeated two times at almost similar condition of chamber pressure, 57.9 bar, and fuel-rich mixture ratio, 0.322. The propellants were fed into the combustor from LOx and kerosene run tanks which were regulated to predefined pressures by high pressure gaseous nitrogen. A preset programmable logic controller (Allen Bradley) automatically controlled the on/off sequences of all the valves. The propellants supplied into the chamber were ignited using a gaseous methane/oxygen torch flame.

## 3. Results and discussion

### 3.1 Cold-flow tests

For each model of the injectors, 10 or more samples were manufactured and cold-flow tests using tap water were conducted on three different cases by changing pressure differential through the injector (10 ± 2 bar). Cold-flow tests were performed for 60 seconds based on each flow rate and were repeated two times on each condition. The difference of average discharge coefficients with respect to variation of pressure differentials was below 0.5% and the deviation of discharge coefficients in same sample injectors at same pressure differential was lower than 2%.
The average discharge coefficients of each injector model for LOx-side and kerosene-side are presented respectively in Fig. 3 and Fig. 4 as a function of *K*. Here, the discharge coefficient was calculated based on the area of the orifice (nozzle). Since the LOx-side swirl injector is a close-type swirl injector, its coefficient was compared with the previous empirical equation [10] obtained from abundant close-type injectors. As the geometric constant increased, the discharge coefficients for both the LOx-side and the kerosene-side swirl injectors decreased.

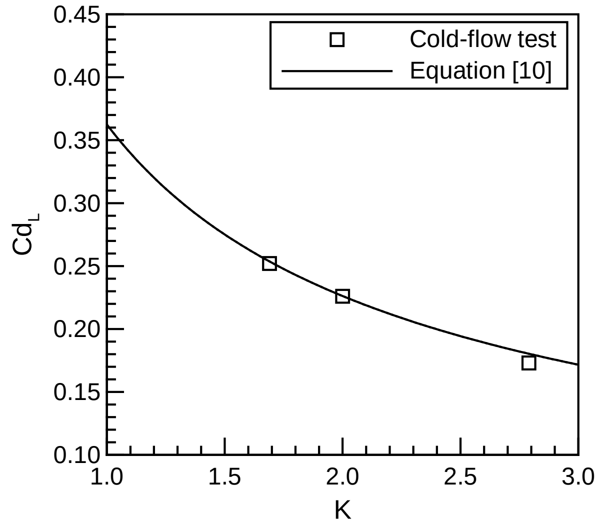


Figure 3: Discharge coefficients of inner (LOx-side) swirl injectors as a function of *K*

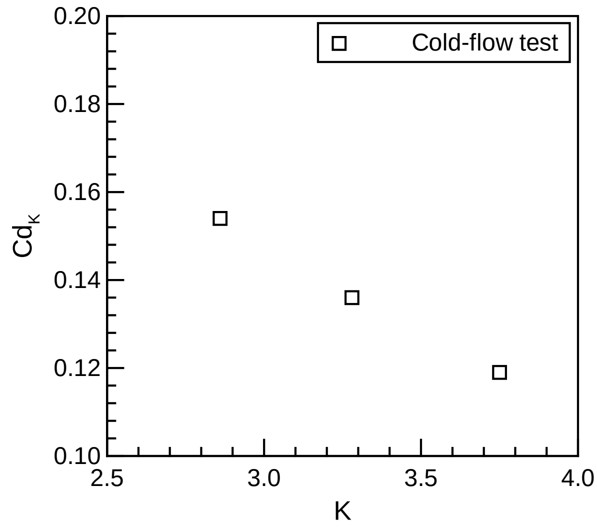


Figure 4: Discharge coefficients of outer (kerosene-side) swirl injectors as a function of *K*

### 3.2 Hot-firing tests

Combustion lasted for 4 seconds, which was enough to acquire data in the steady-state condition. Mass flow rate, injection pressure drop, orifice area, and propellant density in the manifold should be known in order to calculate the discharge coefficient. Pressures in the propellant manifolds and chamber, and mass flow rates into the combustor were directly gauged from the installed sensors. Though the mass flow meter gave the propellant density in the supply line, its value was obtained from the propellant line, not from the manifold. Specifically for LOx, the density gauged from the mass flow meter was always higher than that calculated from pressure and temperature measured in the oxidizer manifold [14]. The LOx and kerosene densities were calculated from the pressure and temperature data measured in the manifolds [20]. The calculated propellant density was used for obtaining the discharge coefficient. Fig. 5 shows chamber pressure and *OFR* from the hot-firing tests. The calculated discharge coefficients for the inner (LOx-side) swirl injectors and the outer (kerosene-side) swirl injectors are displayed in Fig. 6 and Fig. 7, respectively. Though the values of *OFR* were distributed in the range of OFR from 0.312 to 0.343, it was found that the varaition not significantly affect the discharge coefficients for both the injectors.

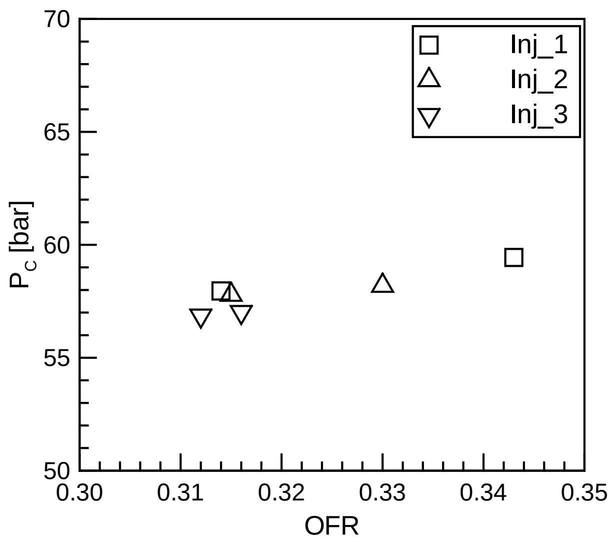


Figure 5: Test conditions for OFR and chamber pressure

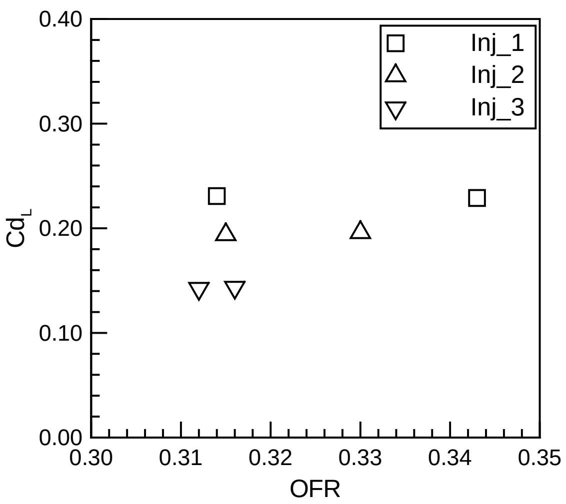


Figure 6: Discharge coefficients for LOx-side swirl injectors

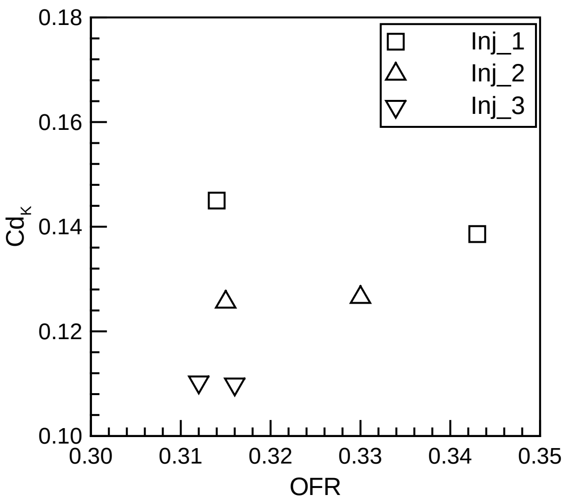


Figure 7: Discharge coefficients for kerosene-side swirl injectors

To investigate the effects of injector geometric constant on discharge coefficients under hot-firing tests, the discharge coefficients obtained from hot-firing tests were compared with those from cold-flow tests. The ratio of the discharge coefficient under the hot-firing test to that under the cold-flow test was calculated and is depicted as a function of K in Fig. 8 and Fig. 9.

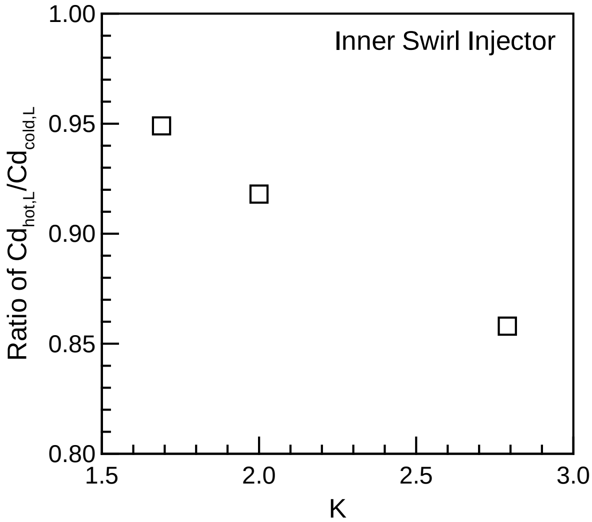


Figure 8: Ratio of discharge coefficients between cold-flow and hot-firing test for LOx-side swirl injectors

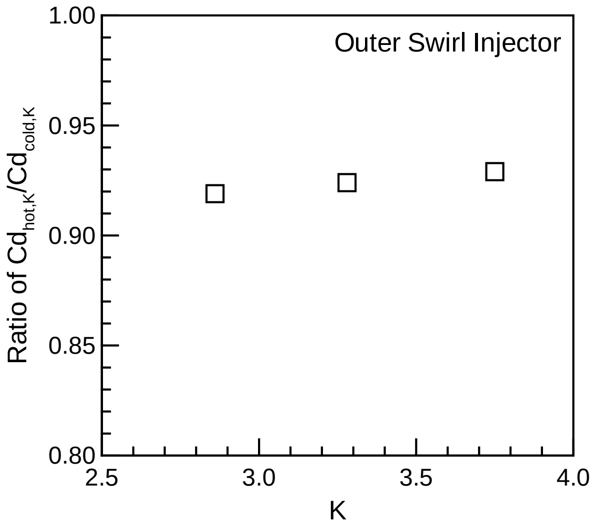


Figure 9: Ratio of discharge coefficients between cold-flow and hot-firing test for kerosene-side swirl injectors

The result showed that as the geometric constant ($K$) of the inner swirl injector was greater, the discharge coefficient of the inner swirl injector in the hot-firing test became lower than that in the cold-flow test. On the contrary, the geometric constant ($K$) of the outer swirl injector seldom affected the discharge coefficient of the outer swirl injector in the hot-firing test. It was thought that the larger geometric constant of the inner swirl injector induced stronger swirl motion in the swirl chamber and the nozzle which caused the radius of gas core to increase and more combustion gas to recirculate into the gas core region. This phenomenon is believed to influence on the discharge coefficient in the hot-firing tests.

## 4. Conclusion

The effects of injector geometric constant on the discharge coefficients of the bi-swirl coaxial injector have been investigated experimentally using multi-element combustors with seven LOx-kerosene swirl coaxial injectors. While changing the geometric constants for both the inner and outer swirl injectors, the static pressure, temperature, and mass flow rate were obtained and analyzed. The discharge coefficients in the hot-firing tests were compared with those in the cold-flow tests.

Compared with the discharge coefficients in the cold-flow tests, the discharge coefficients of the outer fuel-side injectors in the hot-firing tests were seldom changed with the geometric constant, but those of the inner oxidizer-side injectors significantly decreased from $K$ = 1.69 to 2.79. It was thought that the larger geometric constant of the inner swirl injector induced stronger swirl motion in the swirl chamber and the nozzle which caused the radius of gas core to increase and more combustion gas to recirculate into the gas core region. However, this assumption has not yet been confirmed. More quantitative research is required in the future to explain the phenomenon.

## Acknowledgements

This research is supported by the National Research Foundation (NRF-2014R1A1A1002057 and NRF-2015M1A3A3A02011346) funded by the Ministry of Science, ICT and Future Planning, South Korea. The authors would like to thank the MSIP for its support.

## References

[1] Huzel, D. K., and D. H. Huang. 1992. Modern engineering for design of liquid-propellant rocket engines. Progress in Astronautics and Aeronautics 147. AIAA.

[2] Gill, G. S., and W. H. Nurick. 1976. Liquid rocket engine injectors. NASA SP-8089.

[3] Rubinsky, V. R. 1995. Combustion instability in the RD-0110 engine. Progress in Astronautics and Aeronautics 169:89–112. AIAA.

[4] Taylor, G. I. 1950. The boundary layer in the converging nozzle of a swirl atomizer. *Quarterly Journal of Mechanics and Applied Mathematics*. 3:129–139.

[5] Rizk, N. K., and A. H. Lefebvre. 1985. Internal flow characteristics of simplex swirl atomizer. *Journal of Propulsion and Power*. 1:193–199.

[6] Jones, A. R. 1982. Design optimization of a large pressure-jet atomizer for power plant. *Proceedings of the 2nd International Conference on Liquid Atomization and Spray Systems*, 181–185.

[7] Abramovich, G. N. 1944. The Theory of Swirl Atomizers. In Industrial Aerodynamic. BNT. ZAGI. 114–121.

[8] Bazarov, V., V. Yang, and P. Puri. 2004. Design and dynamics of jet and swirl injectors, Progress in Astronautics and Aeronautics, 200:19–103. AIAA.

[9] Khavkin, Y. 2004. The Theory and Practice of Swirl Atomizers, Taylor & Francis.

[10] Ahn, K., and H. S. Choi. 2014. Experimental study on discharge coefficient of swirl injector. *Proceedings of the 17th International Conference on Liquid Atomization and Spray Systems-Asia*.

[11] Kim, S. H., Y. M. Han, S. Seo, I. Y. Moon, J. K. Kim, and W. S. Seol. 2005. Effects of LOx post recess on the combustion characteristics for bi-swirl coaxial injector. AIAA Paper No. 2005–4445.

[12] Sivakumar, D., and B. N. Raghunandan. 2003. Formation and separation of merged liquid sheets developed from the mixing of coaxial swirling liquid sheets. *Physics of Fluids.* 15:3443–3451.

[13] Soltani, M. R., K. Ghorbanian, M. Ashjaee, and M. R. Morad. 2005. Spray characteristics of a liquid-liquid coaxial swirl atomizer at different mass flow rates. *Aerospace Science and Technology*, 9:592–604.

[14] Ahn, K., Y. M. Han, and H. S. Choi. 2012. Effects of recess length on discharge coefficients of swirl coaxial injectors. *Combustion Science and Technology*. 184:323–336.

[15] Ahn, K., Y. M. Han, S. Seo, and H. S. Choi. 2011. Effects of injector recess and chamber pressure on combustion characteristics of liquid-liquid swirl coaxial injectors. *Combustion Science and Technology*. 183:252–270.

[16] Ahn, K., S. Seo, and H. S. Choi. 2011. Fuel-rich combustion characteristics of biswirl coaxial injectors. *Journal of Propulsion and Power*. 27:864–872.

[17] Ahn, K., and H. S. Choi. 2012. Combustion dynamics of swirl coaxial injectors in fuel-rich combustion. *Journal of Propulsion and Power*, 28:1359–1367.

[18] Ahn, K., B. Lim, and H. S. Choi. 2014. Stability characteristics of bi-swirl coaxial injectors in fuel-rich combustion. *Transactions of the Japan Society for Aeronautical and Space Sciences*, 57:317–324.

[19] Ahn, K., J. G. Kim, and H. S. Choi. 2014. Effects of injector recess on heat flux in a combustion chamber with cooling channels. *Aerospace Science and Technology*. 37:110–116.

[20] NIST. http://webbook.nist.gov/chemistry/fluid.