공학석사 학위논문

Experimental Study on Throttleable Liquid Centered Swirl Coaxial Injector

추력조절이 가능한 액체중심 동축형 스월 분사기의 분무특성에 관한 실험적 연구

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서울대학교 대학원

기계항공공학부

이 인 규

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이 논문을 공학석사 학위논문으로 제출함
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Abstract

Experimental Study on Throttleable Liquid Centered Swirl Coaxial Injector

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In liquid rocket engine, the study on throttling have been conducted since 1930's. The throttleable rocket engine enables the operational possibilities, for example docking of spacecraft, maneuvering in certain orbit and landing on a surface of planet, attitude control, entrance to atmosphereless of planet and etc. To achieve throttling in liquid rocket engine, methods are classified by target variable, such as high pressure drop, change in discharge coefficient, various density, and change in nozzle area

Meanwhile, as rocket engine employed bi-propellant instead of mono-propellant, mixing efficiency became a major criteria in engine design stage. In order to mix fuel and propellant, impinging type injector, coaxial type injector, etc. were developed. For a coaxial type injector, the injector, such as shear coaxial injector and swirl coaxial injector, could be classified by injection type. And liquid centered injector and gas centered could be classified by injection position.

To investigate the characteristics of injector, lots of method have been studied.

In liquid rocket engine, rocket engine do not employed a single injector, but tens or hundreds of injector are installed in injector plate. So, interference between spray from injector could be occurred. To avoid the interference, prediction of spray angle is important variable in characteristics of liquid rocket injector. Also the diameter of droplets is considered in design stage since it could influence on combustion instability.

In this study, dual manifold, one of controlling discharge coefficient, was used to control the thrust in liquid phase. And liquid centered coaxial injector was employed to mix liquid and gas simulant. To investigate variation of mixture ratio F/O ratio increased 0, 1/10, 1/8, and 1/6 in the experience. In order to comparative study between dual manifold injector and single manifold injector, the spray angle, mass flow rate, diameters of droplets, and mean diameter of droplets which are representative characteristics in spray, were investigated.

Keywords: liquid centered coaxial injector, dual manifold, throttleable, spray angle, SMD
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Nomenclature

Alphabet

A_e	cross-section area of exit nozzle
C_d	discharge coefficient
d_p	diameter of tangential inlet
D	exit nozzle diameter
D/W	non-dimensional radial disatance.
D_{32}	Sauter Mean Diameter
F	thrust
$\dot{m}$	mass flow rate
N	number of drops
n_T	number of tangential inlet
L	distance from exit nozzle
P	pressure
p_e	pressure at exit nozzle
p_a	pressure at atmosphere
R	chamber radius
SMD	Sauter Mean Diameter
$\overline{SMD}$	Mean SMD
v_e	velocity at exit nozzle

Greek

α	spray angle
ρ	density

Chapter 1. INTRODUCTION

The space exploration is the indicator which could represent the national science technology. The lunar exploration is one of the space exploration. Only a few countries succeed in the lunar exploration. Robot and human were sent to lunar by the APOLLO project in the United States.

To achieve the lunar exploration, a change in liquid propellant rocket engine, called throttling, is required as shown in Fig. 1.1 [1]. Also, this change enables the operational possibilities, for example docking of spacecraft, maneuvering in certain orbit and landing on a surface of planet, attitude control, entrance to atmosphereless of planet and etc.

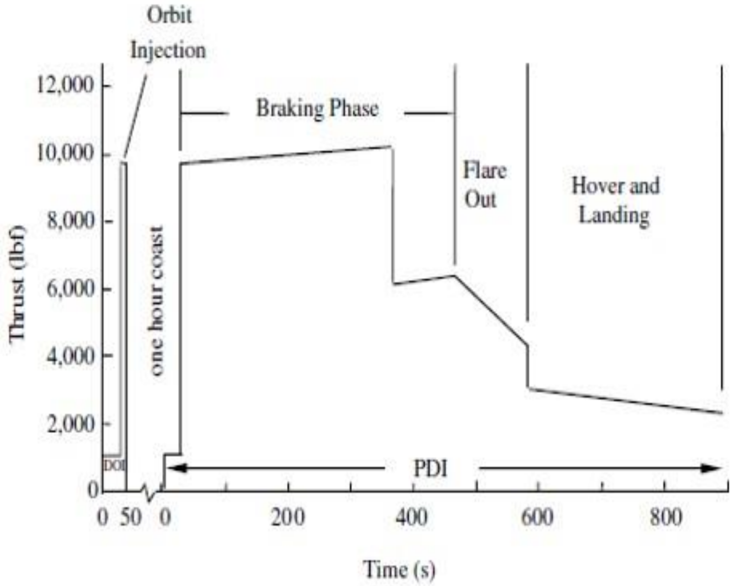


Fig. 1.1 Lunar Module Decent Engine (LMDE) duty cycle

The throttling is derived from regulation of propellant flow rate by control valve. Throttling engine was developed during rocket aircraft experiment and research in Germany in 1930’s and, initially installed at German Heinkel HE-112 fighter. After that, throttling method has developed to focus on applicability in missile defense, weapon system, and space vehicles. Moreover, throttling method have been advanced [2].

Thrust could simply represented in followed equation.

$$\mathrm{F} = \dot{m} \cdot v_e + A_e(p_e - p_a)$$

From this equation, mass flow rate ($\dot{m}$), velocity at exit nozzle (v_e), exit nozzle area (A_e), and pressure difference ($p_e - p_a$) influence on thrust. For mass flow rate modulation method, there are some variables to control.

$$\dot{m} = C_d A_e \sqrt{2\rho\Delta P}$$

Above equation is relationship between mass flow rate and the other variables. Where C_d is discharge coefficient, ρ and ΔP are density of propellant and pressure drop. Mass flow rate modulation methods are categorized by this variables. Examples of controlling exit nozzle is generally pintle injector and also easily predict thrust due to linear area variation. But this type of injector has disadvantages that moving part are located in extreme conditions, so it requires to be durable. When density is modulated, gas injection method is used. This method is not required moving part, but it could lead to instability in liquid flow by bubbles in flow and consumed excessive saturated gas. Pressure drop modulation method is represented by high pressure drop. The high pressure drop method has been investigated for a long time so, related study conducted sufficiently. And it can combined with other method.

However, it has limitation on accurate control and instability problems. Discharge coefficient could be controlled by geometric variation and representative injector is dual manifold type injector. In this injector the mass flow rate is controlled by using different manifold. It required four independent volume and stabilization of spray angle. However, it shows good atomization efficiency in large mass flow rate region and not require moving part. So, in this study, this method was used for throttoling [2].

Meanwhile, to achieve the high mixing efficiency which influence in combustion efficiency, many types of injector, such as pintle injector, impinging injector, and coaxial injectors have been investigated. In case of coaxial injector, it provides high atomization quality and stable operation in wide thrust range. Current rocket engine use liquid fuel & liquid oxidizer or liquid fuel & gaseous oxidizer or gaseous fuel & liquid oxidizer as a propellant. Coaxial injector can be classified by the propellant phase or injection type. The injector classified based on injection type includes shear coaxial, liquid centered swirl coaxial, and gas centered swirl coaxial injector. The breakup mechanism of shear coaxial injector is due to shear force between central stream and annular stream. The shear coaxial injector generally with a central liquid jet and the annular gas jet has been conducted and applied to the Space Shuttle Main Engine (SSME), LE-7A engine [3] [4]. The breakup mechanism in swirl injector is caused by hydraulic instability on liquid sheet. However the breakup mechanism of liquid-gas coaxial injector is caused by kinetic energy in collision with gas flow and liquid sheet. For the liquid centered swirl coaxial injector with annular jet was used in RL-10 family and XLR-129 programs. And the gas centered swirl coaxial injector with central jet was employed to

RD-170 and other Russian rocket [5].

In this study, the water was used for oxidizer simulant and the air was used for fuel simulant in atmospheric condition. The dual manifold type injection was used to modulate liquid mass flow rate and to achieve the high mixing efficiency, central jet was employed.

Chapter 2. APPARATUS AND EXPERIMENTAL METHOD

Spray characteristics of swirl coaxial injector contain the mass flow rate, spray angle, breakup length, drop size and all that sort of things. Spray angle and spray pattern image is were obtained from indirect photography. And SMD distribution is also measured by the same method.

2.1 Experimental Apparatus

The experimental setup is followed in Fig 2.1. The liquid centered swirl coaxial injector installed at cold flow test rig. To supply water to each liquid manifold, two water line is connected to top part of the injector and air to gas manifold, one gas line is linked to side of bottom part of the injector. For water supplying system, the pressure of water tank is controlled independently, so each manifold pressure is measured different. The air mass flow rate was measured by a mass flow meter (MFM, Alicat Scientific : M-1500SLPM-D)in real time, and, using gas regulator, to maintain the appropriate range. The water mass flow rate was obtained from total mass flow rate in a 10 sec and 20 sec. The water mass flow rate was controlled by each manifold pressure measured by a static pressure sensor. Also, gas part manifold pressure data was obtained in the same way. Those pressure data was collected about 40,000 samples per second.

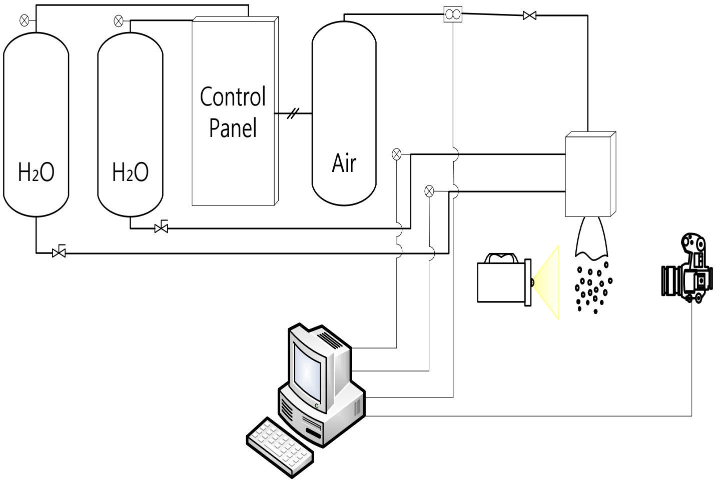


Fig. 2.1 Experimental Apparatus

As shown in Fig. 2.2 dual manifold liquid centered swirl coaxial injector and single manifold liquid centered swirl coaxial injector were designed. The only difference between dual and single manifold injector is existence of the barrier separating top manifold and bottom manifold. It’s because of minimizing the effects of geometric difference.

For the liquid part injector, the top manifold has 3 tangential entries with diameter of 1.2mm at every 120 deg and the bottom manifold has 2 tangential entries with 1.0mm at 180 deg. The area ratio between top and bottom manifold is 2:1, so this ratio helps mass flow rate modulation. As a result of this method, throttling range of dual manifold injector is 5:1 and that of single manifold injector is 2.6:1.

At the gas part, design of tangential entry area was considered not to excess the gas line area. The diameter of nozzle was considered gas state at the nozzle is under incompressible conditions.

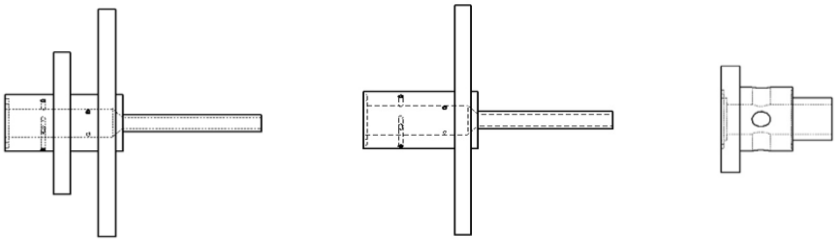


Fig. 2.2 Schematic of liquid and gas injector

2.2 Indirect Photography

To define the spray angle and measure the droplet diameter, indirect photography was used. This method has an advantage in measuring the spray characteristics due to use averaged data. In this method, a digital camera (Canon EOS 7D) and stroboscope (SUGAWARA; S-124M) was set at the opposite position. The frequency of stroboscope is fixed to 600 Hz. The exposure time of the digital camera was not synchronized with strobescope, so some images has blacked out. Therefore, those images were excluded in image processing.

When the images for investigating spray characteristics were taken, lens were differed in accordance with purpose. As the spray pattern is purpose of the experience, 24-70mm Lens (Canon EF 24-70mm f/2.8L USM) was used for lens. On the other purpose, drop size measurement, high-resolution images are required. For a high enlargement ratio, 180mm Macro lens (Canon EF 180mm f/3.5L Macro USM), two 2 magnification tele-converters (Vivitar), and two extension tube (31mm and 21mm) was used for the experiment. Moreover, the target position was 10cm from exit of nozzle or L/D = 17 where almost spray is breakup.

2.3 Image Processing Method

As mentioned fore chapter, two image processing method were used in accordance with the purpose. Spray pattern and spray angle are the general parameters in identifying the injection characteristics. For a rocket injection system, not a single injector but a bunch of injectors are set. So the rocket injector is running, the spray from each injector can affect to each other. Therefore, spray angle information is required to design efficiency injection systems. First method was used for the measuring the spray angle and spray patterns. In this method, the image information is followed. The size is 3456×2304 and ISO is fixed to 320 for sufficient brightness. Also, exposure time of digital camera was 1/10 sec, but it was not synchronized with storoboscope. The spray angle was analyzed by summation of left half-spray angle and right half-spray angle. The half-spray angle is measured from photoshop program. To obtain accurate value, 30 images were taken and averaged for this one experimental case.

In spray characteristics, drop size affect combustion efficiency [5]. Therefore drop size is the important parameter in injector design. Second method was for measuring the diameter of droplets. In this method magnified images were acquired using the high-resolution digital camera. The image information is the same only except ISO value and magnification. As mentioned in last chapter, the images are magnified using some converters and extension tube and the ISO is set to 320. Then, acquired images were analyzed through post-processing procedures. While the image processing procedure, some undesired objects can be filtered. Also, some drops that is out of focus and non-spherical aspects can be filtered out. Overview of the image processing method for the measuring the droplets is followed in Fig. 2.3. In the first step, acquired original images are converted into raw images. Then, the images are converted into binary images that gray level intensities between droplets and background are distinguished from threshold level determined as 50% gray level from the intersection point between maximum gradient line and x-axis on gray level histogram of images [6]. In the third step, drop boundary is detected from the same intensity levels of adjacent pixels on every side of object pixel. Then, the boundaries of droplets are identified. While this step, the unconnected boundaries such as drops were partially out of image frame are excluded. In the next step, the detected boundaries with closed curves are filled. In the last step, some drops are excluded which are non-spherical or out of focus. So the images acquired finally have only appropriate droplets to calculate the size of drops [5] [7].

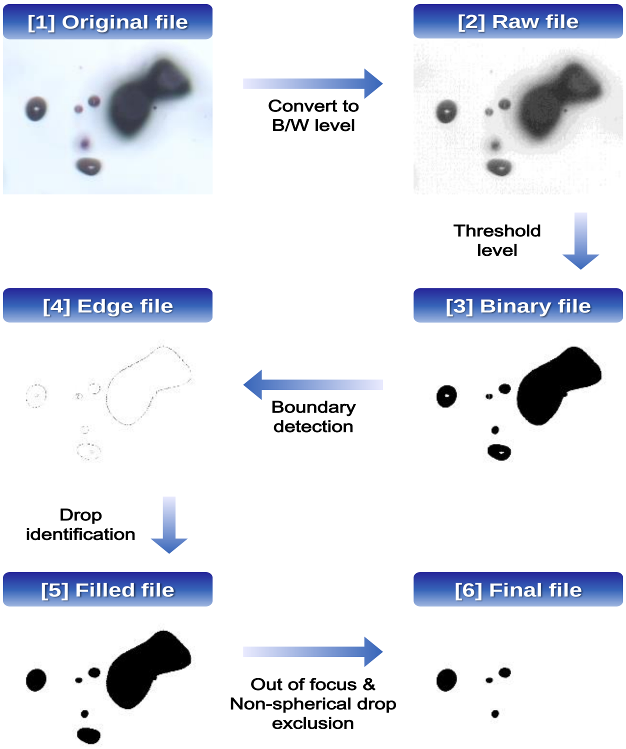


Fig. 2.3 Procedures of image processing method for drop size measurement

To calculate the diameter of droplets, the spatial resolution of an image is 3.225 μm/pixel. Moreover, seven hundreds images were taken and averaged for each experimental case.

2.4 Experimental Condition

In this study, the liquid manifold pressure and F/O ratio was used as variables for each injector. The liquid part manifold pressure was significant parameters in pressure swirl injector. The liquid mass flow rate is mainly influenced by the manifold pressure [8]. The pressure in liquid was varied with 1 ~ 8 bar because of limitation on material solidity. And the other variable, F/O ratio, has 4 cases (0, 1/10, 1/8, 1/6). While the F/O ratio is fixed, mass flow rate of injected gas was varied with increase of liquid mass flow rate.

Followed Fig. 2.4 shows dual manifold flow control mechanism which are two different types. The parallel valve scheme enable the flow controlling in both primary and secondary manifolds at once. When the chamber pressure is in transition, the secondary manifold is cut off and the throttle valve in opened in accordance with the proper mass flow rate. But this system has some difficulties in operation. It requires four valves to operate simultaneously to ensure a smooth thrust variation. The series valve scheme allow flow controlling independently to each manifold. Throttling can be achieved by reducing the flow through the one valve with the other valve opened simultaneously. This scheme provide an advantage on performance at the mid-thrust range prior to throttling down through the predetermined chamber pressure [1], [9]. Compared to above two controlling method, series valve scheme was used for flow controlling in order to deep throttling.

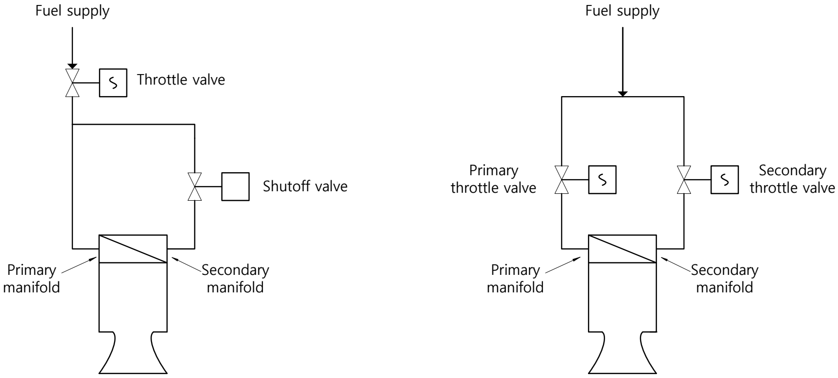


Fig. 2.4 Schemes about flow controlling using dual manifold

Chapter 3. Result and Discussion

3.1 Mass Flow Rate

Liquid mass flow rate was measured in each injector with varying pressure. Fig. 3.1 (a) shows liquid mass flow rate varying with the pressure in manifold. The mass flow rate is increased with manifold pressure. And for mass flow rate of dual manifold injector has three types of mass flow rate at the same manifold pressure. Relatively mass flow rate in bottom manifold is lower than top manifold. It' because tangential entry area is smaller than top manifold. The area ratio between top manifold and bottom manifold is 2.16. Due to this area ratio, mass flow rate ratio between both manifold is 1.58. The area ratio and the mass flow rate ratio is not similar. Because the liquid injected from each manifold have collision in swirl chamber. Also, mass flow rate of single manifold injector is higher than that of dual manifold injector using both manifold. Detailed description about this phenomena is explained with spray angle in next chapter.

Gas mass flow rate was measured by mass flow meter (MFM) during the experiment, but it could not save the data. So controlling the mass flow rate of gas was manually controlled. It was set to fixed F/O ratio (0, 1/10, 1/8, 1/6). The result of this part can be verified in Fig. 3.1 (b).

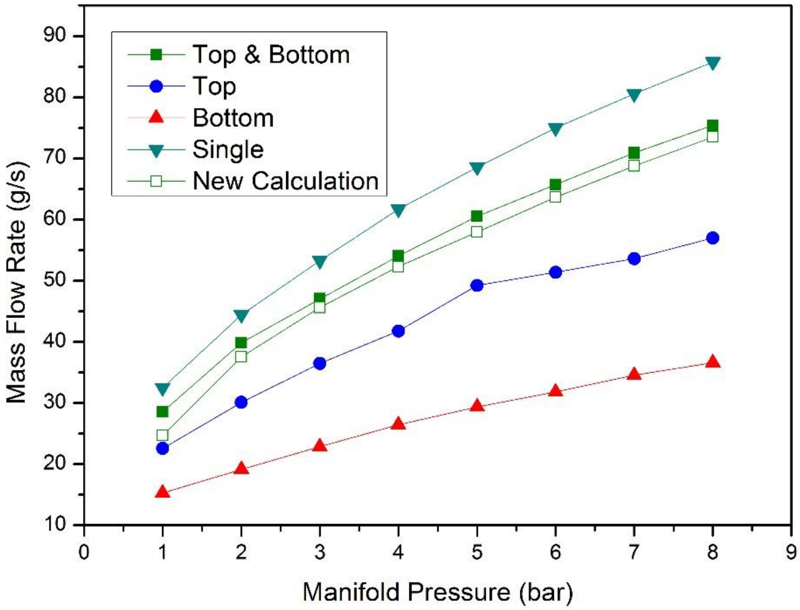
A throttling range of dual manifold injector is 20.25% to 100 % (15.27 g/s ~ 75.40 g/s) and single manifold injector increased from 37.8 % to 100% (32.47

g/s ~ 85.78 g/s).

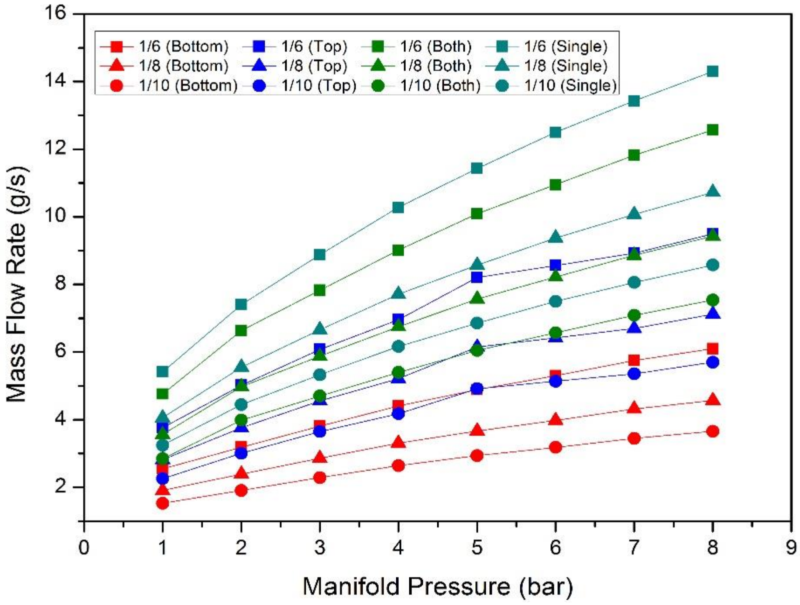
The liquid mass flow rate using both manifold could be predicted. It can be predicted from result of single manifold injection. When the one manifold was pressurized, the other manifold also pressurized [9]. Also in this experiment, the same phenomena was occurred and it was shown in Fig. 3.2. The mass flow rate prediction was based on the pressure difference between target manifold and the other manifold. The simple relationship between mass flow rate and pressure difference is followed.

$$\dot{m} = C_d A_e \sqrt{2\rho\Delta P}$$

The pressure difference (ΔP), density (ρ), tangential entry area (A_e) and, mass flow rate ($\dot{m}$) is already known. So discharge coefficient (C_d) can be calculated and it was 0.45 and 0.46. Using these discharge coefficients, the mass flow rate through both manifold was calculated. It was not the exactly same, but this procedure is worthy to predict mass flow rate.



(a) Liquid mass flow rate



(b) Gas mass flow rate

Fig. 3.1 Mass flow rate via injection pressure

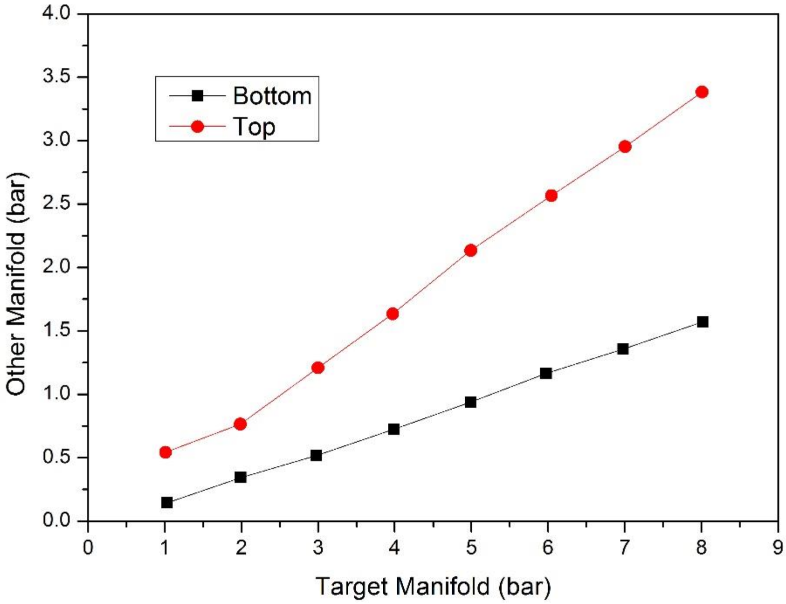
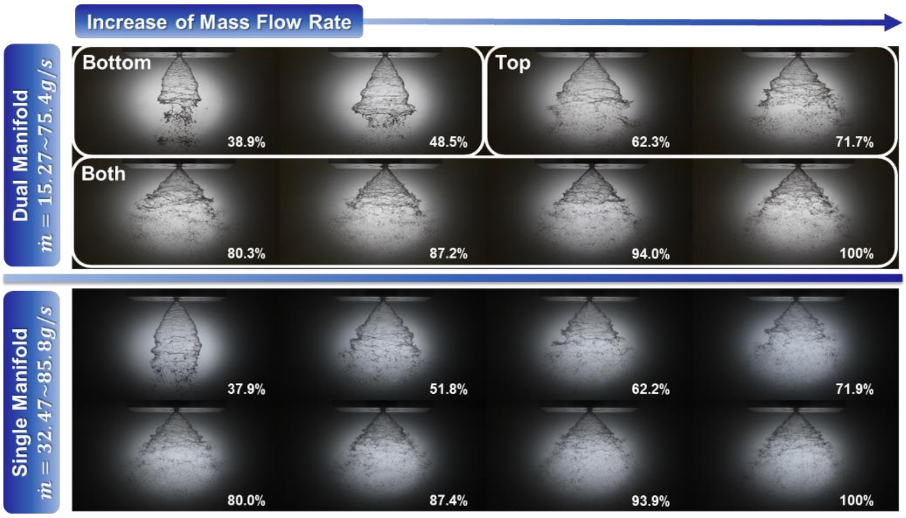


Fig. 3.2 Pressure relations between target manifold and the other manifold

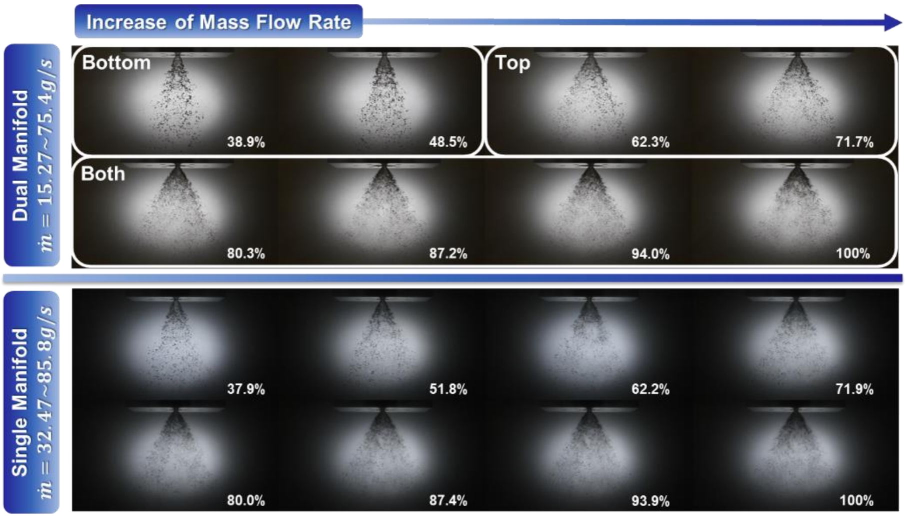
3.2 Spray Pattern

The spray pattern was measured by the indirect photography. The spray angle was measured by summation of left half-spray angle and right half-spray angle. And to obtain accurate value, 30 images were taken and averaged for this one experimental case. The spray angle is significant parameter in combustion system using swirl injector. It influence the droplet distribution that affect the ignition greatly, and interaction of multi-elements injector [9].

Following Fig. 3.3 shows the spray shape of the dual manifold injector and single manifold injector. It is arranged in mass flow rate order and this order is in accordance with actual operation. To meet this actual operational condition, mass flow rate is controlled by using different manifold. It means that for a low thrust (low mass flow rate) region, the bottom manifold was used. For a mid - thrust region (mid mass flow rate) region and high thrust region, the top manifold and both manifold were used for each region. Fig 3.3 (a) shows the spray shape without gas injection. It is not for actual condition, but for comparison target. However, condition in Fig. 3.3 (b) is the similar to actual operation. The spray angle is increased with increase of mass flow rate for dual manifold injector and single manifold injector, and regardless of gas injection. But influence of gas injection is that the spray angle is smaller compared to injection without gas injection.



(a) Injection without gas injection



(b) Injection with gas injection

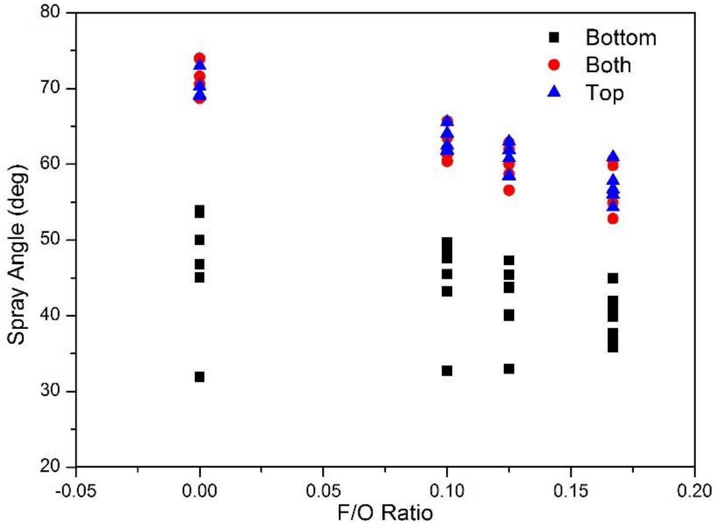
Fig. 3.3 Spray pattern at various mass flow rate

In dual manifold injection, the spray angle is quantified via F/O ratio and mass flow rate in Fig. 3.3, Fig. 3.4, and Fig 3.5. This comparative study is based on averaged 30 images.

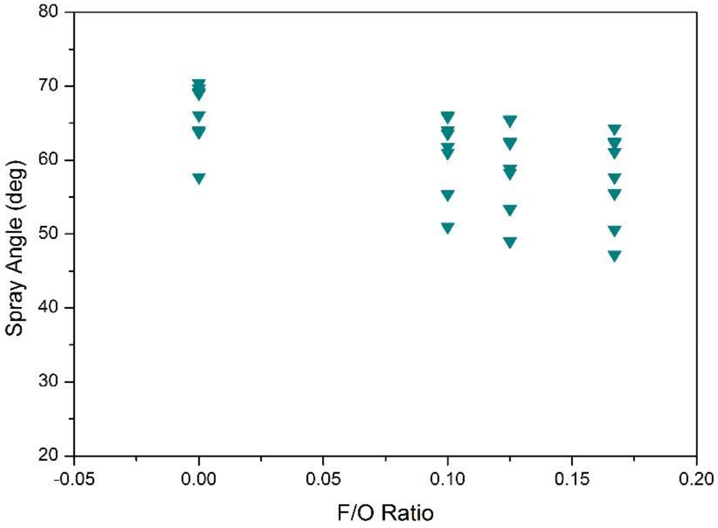
In this study, the difference via F/O ratio increase is shown in Fig. 3.3. As shown in figure, the range of spray angle is decreased with F/O ratio increase in dual manifold injector. But in single manifold injector, the tendency of spray angle exhibit opposite aspect. To analyze the phenomenon, therefore, spray angle variation (Δα) was introduced. This parameter shows variation range of spray angle in certain F/O ratio.

$$Spray\ angle\ variation\ (\Delta\alpha) = \frac{\alpha_{max} - \alpha_{min}}{\alpha_{max}} \times 100$$

For the dual manifold injector, as F/O ratio increased, spray angle variation decreased from 41.1% to 25.1%. On the other hand, incased of the single manifold injector, spray angle variation increased from 12.7% to 17.1% with increase of F/O ratio. As mentioned before, the spray angle stabilization is important in rocket when the rocket system design. In other words, lower spray angle variation helps minimization of combustion instability in chamber. Therefore increase of F/O ratio has stabilization effect on spray.



(a) Dual manifold injector

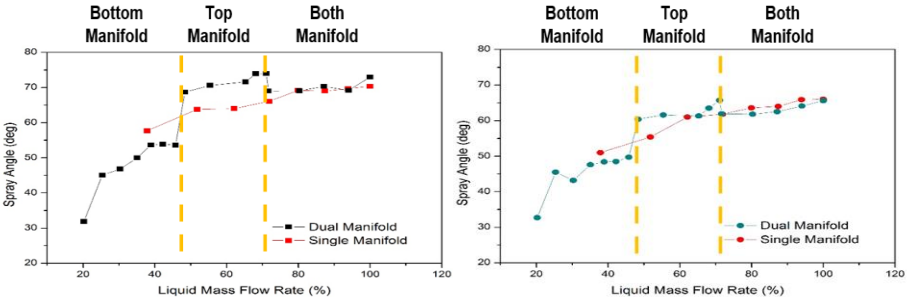


(b) Single manifold injector

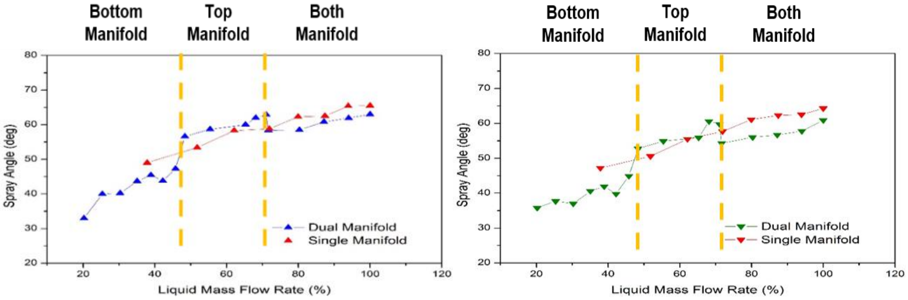
Fig. 3.4 Spray angle variation via F/O ratio

The spray angle via mass flow rate increase is shown in Fig. 3.4. For the both dual manifold injector and single manifold injector, spray angle shows tendency of increase with mass flow rate. However, because of mass flow rate control system in dual manifold injector, the bottom manifold was used at low mass flow rate region (20.25 % to 45.79%) and the top manifold was used at mid mass flow rate range (48.35 % to 71.08%), and then both manifold was employed at range 71.08 % to 100%. Because dual manifold injector has constant geometry so, when change in spray angle is differed. The spray angle transition was occurred when the manifold is changed. To describe this transition in detail, the angular momentum in swirl chamber is introduced.

$$\dot{m}uR = \frac{\dot{m}^2}{\rho A}R = \frac{4\dot{m}^2}{\rho n_T \pi {d_p}^2}R$$



(a) F/O ratio = 0 (b) F/O ratio = 1/10



(c) F/O ratio = 1/8 (d) F/O ratio = 1/6

Fig. 3.5 Spray angle mass flow rate

The 1st transition is simple to analyze. The mass flow rate from bottom manifold is relatively lower than mass flow rate from top manifold. And the 2nd transition is explained from mass flow rate prediction. This transition is occurred from interaction between the top manifold injection and bottom manifold injection. As shown in Fig. 3.5 and Fig. 3.6, the angular momentum in swirl chamber was calculated from the mass flow rate prediction in last chapter. When using both manifold, the angular momentum from bottom manifold is lower portion than from top manifold in total momentum. So when lower angular momentum is collide with higher angular momentum, it makes higher momentum to be lower. As a result of this collision, angular momentum in high mass flow rate range can be lower than that of mid mass flow rate range.

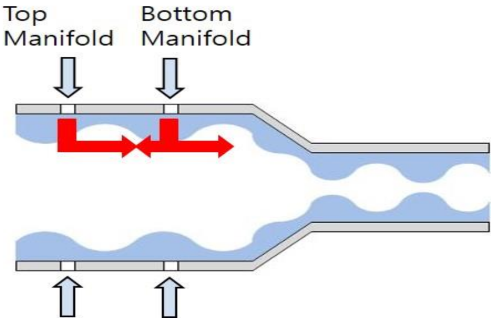


Fig. 3.6 Collision in swirl chamber

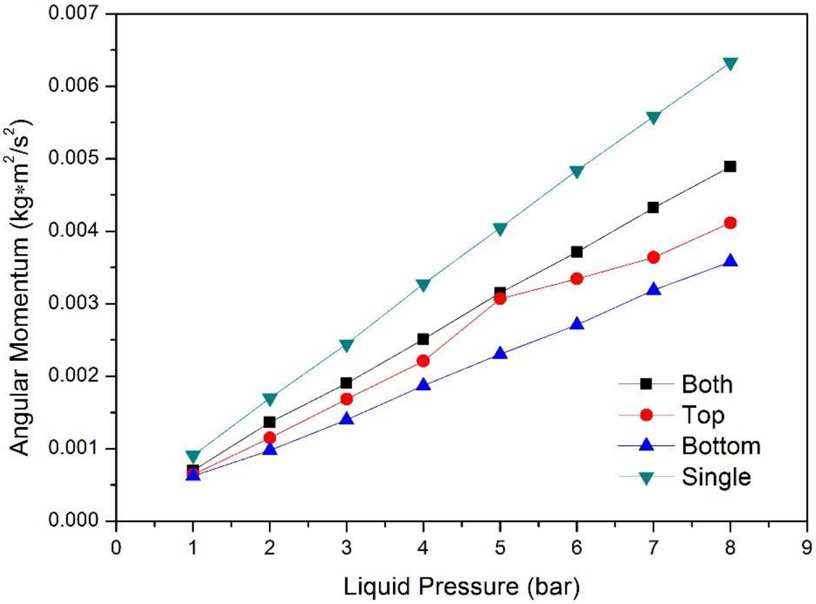


Fig. 3.7 Angular momentum in swirl chamber

3.3 SMD Distribution

The droplet size is important in combustion process. This parameter could be represent the atomization quality and the fine atomization helps rapid vaporization and better mixing efficiency. The Most previous studies on spray characteristics have mainly performed the prediction of the 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 atomization characteristics of this injector, the drop size was measured using the image processing method mentioned in chapter 2.

To analyze the drop size distribution, some variation was introduced. First, to measure the drop size, Sauter Mean Diameter (SMD) was used. The SMD is generally used in mass transfer, and reaction field [10].

$$SMD\ (D_{32}) = \frac{\sum N_i D_i^3}{\sum N_i D_i^2}$$

And non-dimensional radial distance (D/W) was used which is radial distance from center-line divided by half spray width. This non-dimensional radial distance helps analyze the SMD distribution related with liquid sheet width.

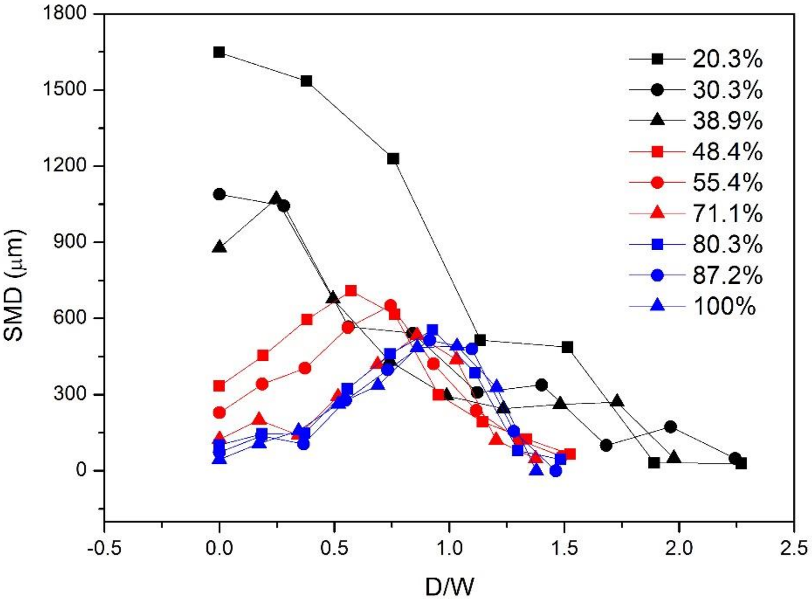
$$Half\ Spray\ Width = 10 \times tan\frac{\alpha}{2}$$

$$D/W = \frac{Radial\ Distance}{Half\ Spray\ width}$$

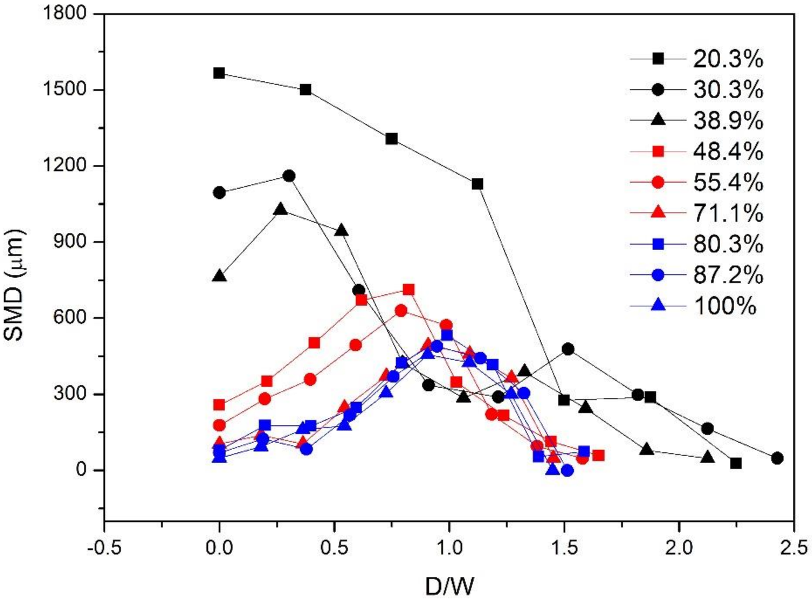
The spray angle (α) was measured in previous chapter, and this was used for non-dimensional radial distance.

The image was taken where horizontal distance is 10 cm (L/D = 17) from exit of nozzle. This position is almost all spray was broken. And the radial point is varied from center line to 8.88 cm at intervals of 1.11cm. Because the magnified image frame size is 1.11 cm, so interval is defined based on image frame size. At the position where horizontal distance is 10 cm, the maximum spray width is less than 8.88 cm.

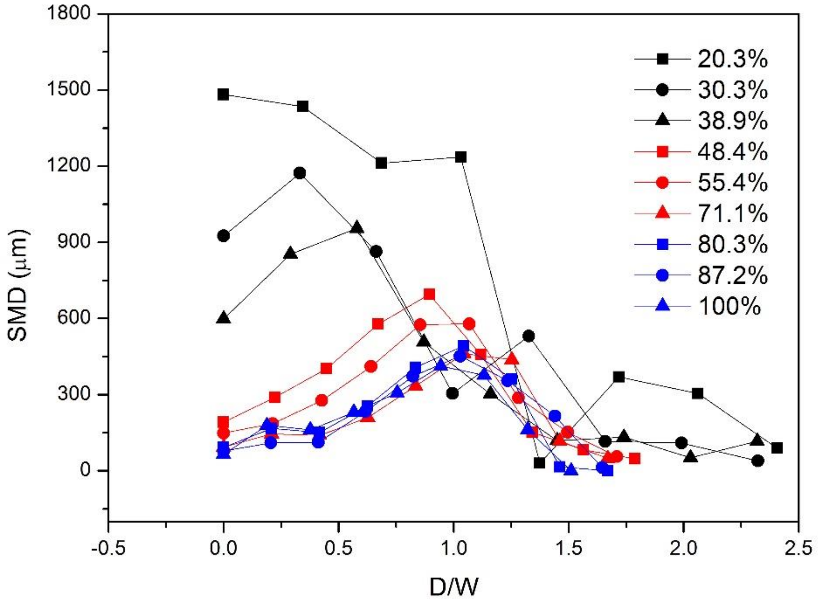
Fig. 3.6 shows the SMD distribution for dual manifold injector. Each graph shows SMD with the F/O ratio difference. For all F/O ratio cases, the SMD using bottom manifold is relatively higher than others and drops were observed out of spray width. Because the angular momentum in too small, so the injected liquid is merged again somewhere in downstream.



(a) F/O ratio = 1/10



(b) F/O ratio = 1/8



(c) F/O ratio = 1/6

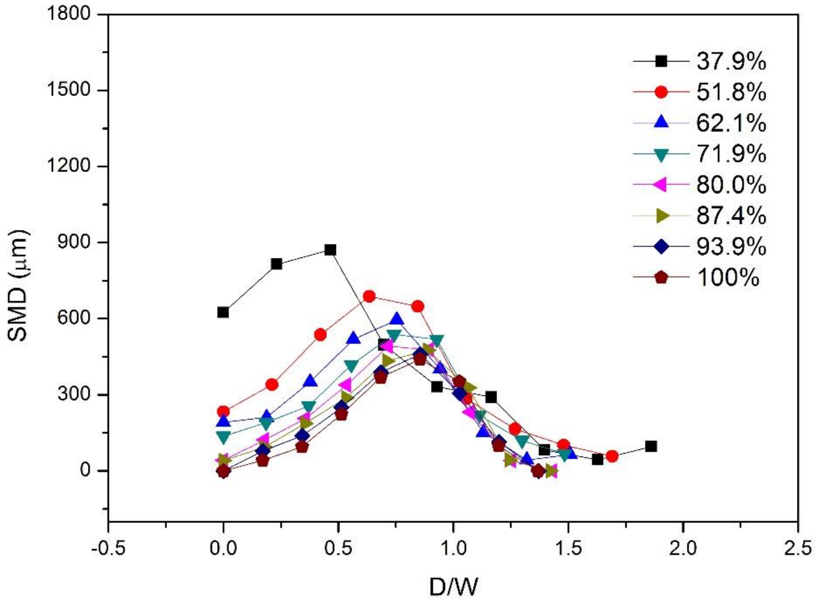
Fig. 3.8 SMD distribution for dual manifold injector

Otherwise, the SMD using the bottom manifold and both manifold where mass flow rate is over 48.4% has the similar aspect. The cause of similar SMD aspect is the spray angle value is relatively similar. The SMD increased until near D/W = 1 and then, decreased. It means the droplet near the spray sheet is the biggest. In detail, the maximum SMD point is moved to right with increase of mass flow rate and the value of maximum SMD is lower.

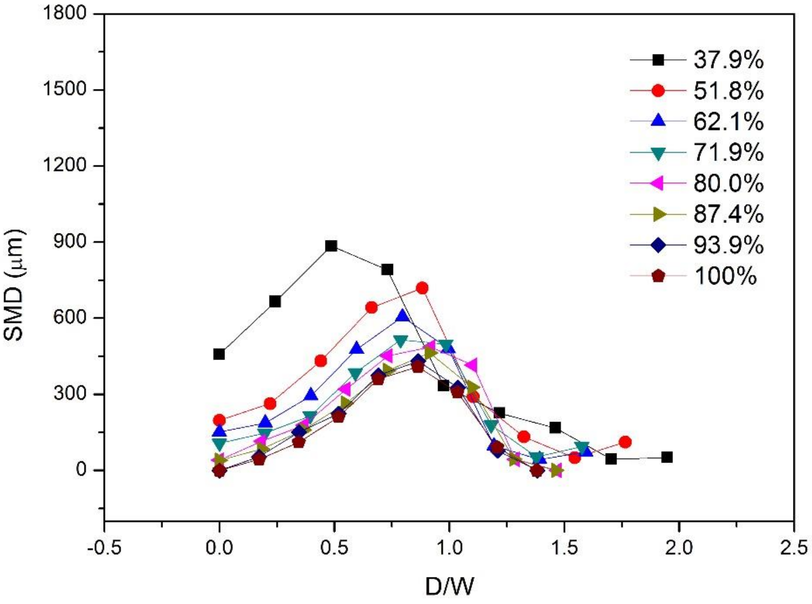
From a point of F/O ratio variation, the maximum SMD radial position is slightly moved to right with increase of gas mass flow rate in range where bottom manifold and top manifold is used. However, the region where the both manifold is used is independent with F/O ratio variation. From this result increase of F/O ratio makes simple to predict the maximum SMD position in spray.

Different from SMD result of the dual manifold injector, SMD distribution for the single manifold injector is shown in Fig. 3.7. In the single manifold injector, all the SMD distribution are similar in other words non-dimensional radial distance of maximum SMD is in 0.75 ~ 0.90. Exceptionally the position of where mass flow rate is 37.9% is relatively lower and also, the SMD value is higher. It is because of the same reason in low mass flow rate range of dual manifold injector.

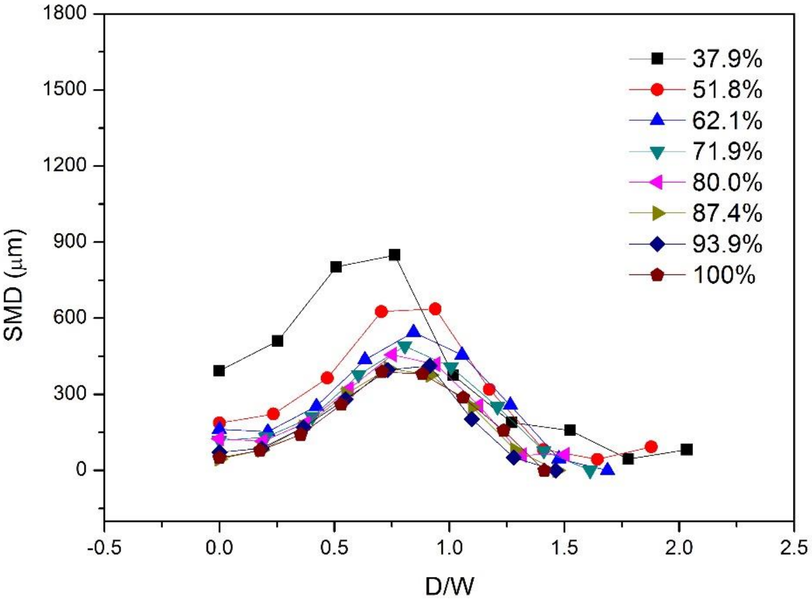
The same as dual manifold injector, D/W point where SMD is max is moved to right with increase of gas mass flow rate until the point is in 0.75 ~ 1.00. That is because liquid has low momentum at the low mass flow rate range. So gas momentum could greatly influence the spray characteristics.



(a) F/O ratio = 1/10



(b) F/O ratio = 1/8



(c) F/O ratio = 1/6

Fig. 3.9 SMD distribution for single manifold injector

Due to limitation of this image processing method that is point data, the measured SMD information is only valid for a specific point. Therefore, the concept of mean SMD is introduced to understand the effect of conditions. Following equation is modified equation for $\overline{D_{30}}$ suggested by Zaller and Klen [11]. $(Data\ rate)_i$ was the number of droplet in this experience.

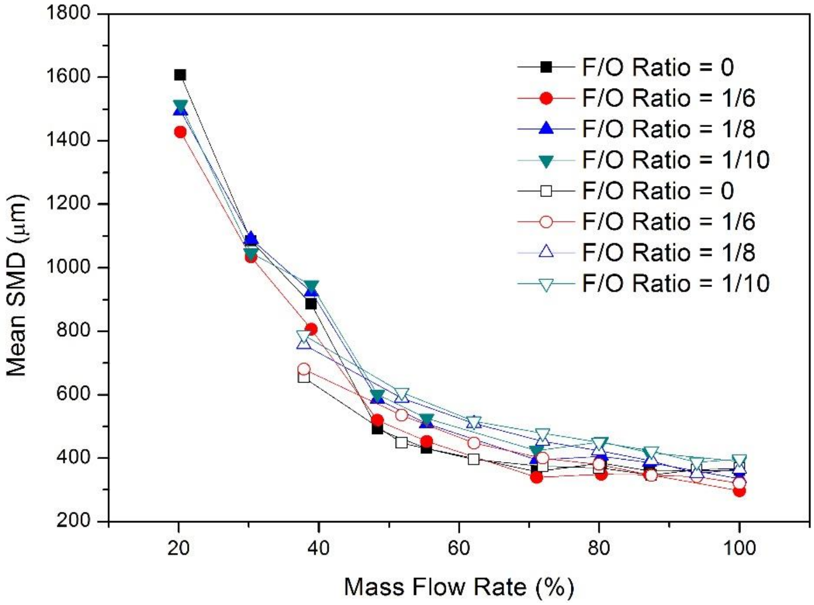
$$\overline{SMD} = \frac{\sum_i (Data\ Rate)_i\ (Area)_i\ (D_{32})_i}{\sum_i (Data\ Rate)_i\ (Area)_i}$$

The mean SMD was calculated to understand effect of mass flow rated, radial position, and F/O ratio. Fig. 3.8 (a) shows mean SMD variation with increase with mass flow rate. The open type symbols represent single manifold and solid type symbols represent dual manifold injector. All mean SMD decreased with increase of mass flow rate. A single manifold injector could not operate deep throttling in under 38 %. But over 38% of mass flow rate region, Mean SMD shows almost same aspect. At the dual manifold injector, where F/O ratio is 1/6, the mean SMD is lowest at almost every range. However, for a single manifold injector, mean SMD of F/O ratio = 0 or 1/6 shows up lowest.

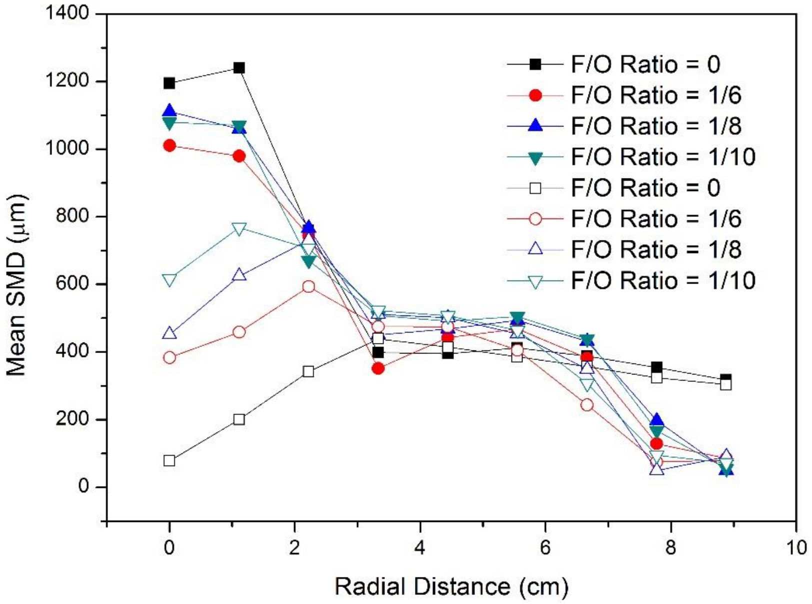
As shown in Fig. 3.8 (b), mean droplet size is decreased with faraway from centerline. In case of dual manifold injector, the mean SMD decreased until 3.33 cm. That is because effect of injection through bottom manifold is significant at those point. Moreover, at the same point, injection via top manifold and both manifold has lower SMD. After the 3.33 cm point, the tendency of mean SMD is the similar to the result in SMD distribution.

In case of the single manifold injector, the mean SMD shows reversed aspect under 3.33 cm range. It means that near the centerline, the large number of drops are distributed when mass flow rate is 37.9 %. However, after the point, those injector has same aspect of dual manifold injector.

The case without gas injection (F/O ratio = 0) demonstrate different tendency in both injector, that is the diameter maintained higher size. Also, the mean SMD is higher over 7.77 cm region. That was driven by the relationships between the spray angle and gas momentum. In other cases, the break mechanism is collision with liquid sheet and gas, so they makes high atomization quality. But the break mechanism is only swirl momentum and frictional force in the case without gas injection (F/O ratio = 0).



(a) Mean SMD via mass flow rate



(b) Mean SMD via radial distance

Fig. 3.10 Mean SMD Distribution

Chapter 4. Conclusion

In this study, the comparative study on spray characteristics of dual-manifold liquid centered swirl coaxial injector and single-manifold liquid centered swirl coaxial injector via F/O ratio variation. The dual manifold injector used in this study has an advantages which could control thrust without moving part and has independent feeding system. The spray angle and Sauter Mean Diameter (SMD) of spray characteristics are examined through various mass flow rate and F/O ratio.

1. The liquid mass flow rate of the dual manifold injector has three types at the same pressure. So, the throttling range was 20.0% to 100 % for the injector. But the single manifold injector throttling range was 37.8% to 100% at the same pressure range.
2. When using dual manifold injector, spray angle variation ($\Delta\alpha$) which could represent range of spray angle and is parameter of spray angle stabilization decreased with increase of F/O ratio. However, using single manifold injector, spray angle variation increased with increase of F/O ratio. Therefore, higher F/O ratio affect positively in spray angle variation.
3. During the throttling process, two transition was occurred due to angular momentum in swirl chamber. 1st transition was caused by using different manifold. 2nd transition was caused by collision between higher angular

momentum from top manifold and lower angular momentum from bottom manifold.

4. For both injector, the SMD increased under D/W = 1.00 then, decreased. In other words, diameter of droplets has maximum within spray width. But at low mass flow condition in both injector, relatively large drops are observed. That is because the liquid has low swirl momentum.
5. For both injector, the maximum SMD point is moved to right (near the liquid sheet) as F/O ratio increase in low mass flow rate range. In case of single manifold injector, moved until D/W = 0.75~0.90 and in dual manifold injector, moved to D/W = 1.0
6. Mean SMD via mass flow rate decreased with increase of mass flow rate. Both injector has similar mean SMD information over 40% of mass flow rate.
7. Mean SMD via radial distance also decreased faraway from centerline for dual manifold injector. Contrariwise mean SMD in single manifold injector increased until 2.22 cm from centerline. Then mean SMD shows similar tendency.

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초 록

액체로켓에서의 추력 조절을 위한 연구는 1930년대 후반부터 꾸준히 이어오고 있다. 추력 조절이 가능한 로켓 엔진으로 우주공간에서의 도킹, 특정 궤도 비행, 행성 표면에 착지, 자세 제어, 대기가 없는 행성으로의 진입 등이 있다. 추력을 조절 하기 위해서는 고압력 강하, 분사 계수 변화, 추진제의 밀도 변화, 분사 노즐 면적의 변화 등의 방법이 있다.

한편 단일 추진제가 아닌 이원 추진제를 사용하는 엔진이 사용됨에 따라 추진제의 혼합효율이 주요한 쟁점으로 대두되었다. 혼합을 위해 충돌형 분사기, 동축형 분사기 등이 개발되었으며, 동축형 분사기의 경우 분사 형태에 따라 전단 동축형 분사기와 스월 동축형 분사기로 구분될 수 있다. 또한 기체와 액체의 분사 위치에 따라 액체중심 분사기와 기체중심 분사기로 구분될 수 있다.

분사기의 특성을 확인하기 위하여 다양한 방법들이 연구되어 왔다. 실제 로켓에서 사용되는 분사기는 단일로 사용되지 않고 분사기 판에 수십에서 수백 개가 장착되어 사용된다. 따라서 분사기들 사이에서 간섭현상이 생길 수 있기 때문에 분무각의 변화는 분사기의 특성을 확인할 수 있는 주요한 변수이다. 또한 연소실 내부에서 액적의 크기는 연소 효율에 주요한 영향을 미치는 변수로 알려져 있다.

본 연구에서는 분사 계수를 조절하는 방법 중 하나인 이중 매니폴드를 사용하여 추력을 조절하는 방식을 통하여 액체의 질유량을 조절하고, 액체 중심 동축형 분사기를 사용하여 기체와 액체를 혼합하였다. 이때 혼합비의 변화에 따른 특성을 확인하기 위해 F/O ratio를 0, 1/10, 1/8, 1/6으로 증가시키며 실험을 수행하였다. 설계한 분사기와 단일 매니폴드를 사용한 분사기의 분무 특성을 비교하기 위하여 대표적인 특성인 분무각의 변화와 액적들의 크기 및 평균 액적 크기를 통하여 분석하였다.

주요어: 액체중심 동축형 분사기, 가변추력, 이중 매니폴드, 분무각, SMD

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