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Experimental Study on the Dynamic Characteristics of Open Type Swirl Injector with Varying Geometry

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Abstract

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Combustion instability can break out any kind of engine that uses combustion process to get power. Liquid Rocket Engine (LRE), especially, operates in extremely high temperature and high pressure condition, combustion instability directly leads to failure of the engine. Combustion instability occurs when heat release from the combustion chamber and acoustic wave interact, acoustic wave from the process causes pressure fluctuation to the fuel or oxidizer flowing into the injector. Additional devices like baffle or acoustic cavity were attached to LREs to suppress combustion instability, necessarily, bringing weight increment of the engine and finally reducing efficiency. If the injector, which is in the middle of the whole combustion process, could act like a damper itself, the engine would stay stable for the outer disturbance. Then it will be possible to manufacture highly efficient, high performance LRE with low cost. This is the reason injector dynamics should be investigated.

Hydrodynamic mechanical pulsator was produced to generate pressure oscillation, electrical conductance was made and installed at the end of the orifice to measure film thickness. Total 7 different open type injector, varying either length or diameter of the swirl chamber, was produced to figure out the effect of geometrical variation.

Experiment for static characteristics was preceded, the behavior of mass flow rate and liquid film thickness along the manifold pressure was measured. Measured liquid film thickness was compared to the empirical equations of previous studies, analyzed the reason for not matching each other.

For the dynamic study, by generating pressure fluctuation to the liquid flowing into the open type swirl injector, we measured the following response characteristics. Liquid film thickness and pressure at the end of the orifice was chosen as output parameters. Effect of swirl chamber length and diameter was also observed on the dynamic characteristics of the injector.

Keywords: Liquid Rocket Engine (LRE), Dynamics, Combustion instability, Pulsator, Open type swirl injector

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Nomenclature

A	Swirl injector geometrical characteristic parameter
	$(S_{SC}R_{TE})/(S_{TE}R_{SC}) = \sqrt{2}(1-\varsigma)/\varsigma\sqrt{\varsigma}$
D	Diameter
f	Frequency
h	Liquid film thickness
L	Length
$\dot{m}$	Mass flow rate
n	Number of tangential entry
P	Pressure
Q	Volumetric flow rate
q	Dynamic pressure
R	Radius
r	Radius
S	Cross-sectional area
t	time
v	velocity
X	Input
Y	Output
μ	Mass flow discharge coefficient
	$\varsigma\sqrt{\varsigma}/(2-\varsigma)$
ν	Viscosity
ξ	Fluctuation of liquid film thickness
Π	Transfer function
ρ	Density
ς	Flow area ratio
	S_l/S_O

Φ	Phase
φ	Phase
ω	Angular speed

Subscripts

a	Axial
l	Liquid
m	Manifold
o	Orifice
Re	Real value
Im	Imaginary value
SC	Swirl chamber
TE	Tangential entry

Superscripts

$\bar{\ }$	Dimensionless parameter
$'$	Pulsation component

Chapter 1　INTRODUCTION

1.1 Combustion Instability

Since the invention of the V-2 rocket during World War II, combustion instabilities have been recognized as one of the most difficult problems in the development of liquid rocket engines. During the development of H-1 engine used in the early version of Saturn rockets, which is regarded as one that opened the space era, manager of the Engine Program Office at MSFC noted combustion instability is one of four major problems during H-1 era [1, 2].

The term “combustion instability” describes an unsteady or abnormal combustion of fuel, a condition that not only reduces engine performance, but could destroy the engine, and the rocket as well. As shown in Fig 1.1, some processes go on to make propulsion power, instability break out when fluctuation of heat release and acoustic pressure from the process interact inappropriately. Within NASA and their engineers, there was early concern about the potential problem of combustion instability, particularly in the improved engines for Saturn I and the even larger engines planned for the Saturn V. They tried to induce combustion instability by fixing a small bomb to the face of injector, which was hoped to suppress the combustion flame front which creates an unstable operating condition. But it failed to effect recovery in 8 of 16 bomb tests [1]. After some research and development work, designers rearranged the injector orifices and added some baffles to the face of the injector as well as made cavities around combustion chamber. The new design worked beautifully, giving satisfactory recovery at various thrust levels.

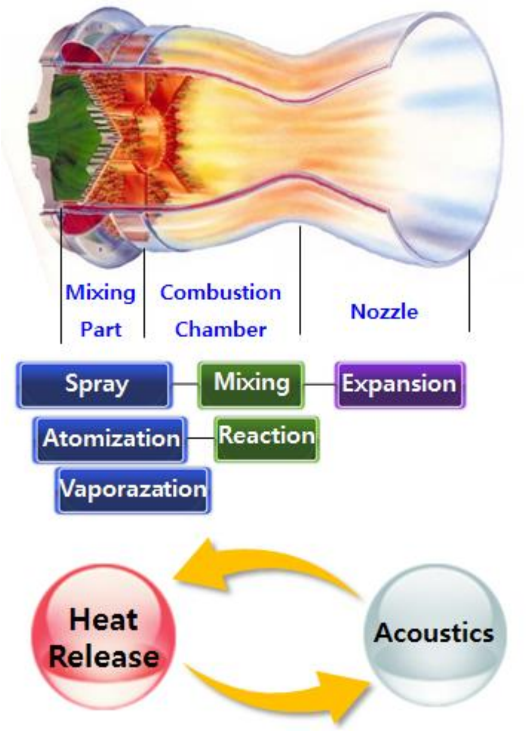


Figure 1.1 Combustion processes of liquid propellant rocket engine

Though their attempt was successful and the design has been using for many decades, the design was based on the concept of suppressing instability by adding extra structure, which means the engine comes to more complex as well as it becomes heavier, causing efficiency drop and cost increase. However, if the injector acted like a damper itself, it could control combustion instability effectively, maintaining stable state without additional structure anymore. This requirement provides motivation to investigate dynamic response of the injector when any kind of disturbance occurs.

In this paper, dynamic characteristics of open-type swirl injector was investigated as a part of whole injector dynamics. It is focused on the effect of injector's geometrical variations on the dynamic characteristics by varying length and diameter of the swirl chamber.

1.2 Injector Dynamics

1.2.1 Mechanism of injector dynamics

Injector dynamics contains researches to control combustion instability by examining dynamic characteristics of the injector. As shown schematically in Fig 1.2, combustion instability occurring in the combustion chamber affects other processes rather than staying quietly in the chamber. The actual process of mixing is typically takes place in the place of highly developed fluctuations, as the feedback coupling (loop 1 in Fig 1.2) affects the processes occurring in the combustion chamber and forms a self-oscillating circuit [3]. Pressure fluctuation developed during loop1 then directly affects the injector, forming another feedback coupling (loop 2 in Fig 1.2). Subsequently, this interaction makes variation of the instantaneous velocity of propellant flowing through the injector, which excites oscillation of pressure in the feeding system (loop 3 in Fig 1.2).

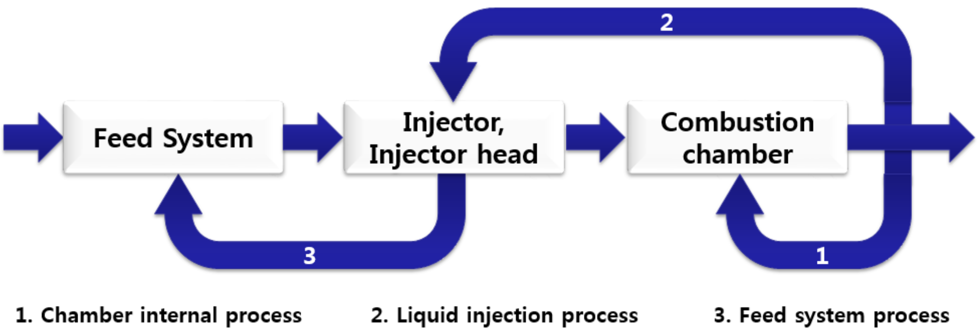


Figure 1.2 Interactions of dynamic processes in LRE

From this mechanism of injector dynamics, we are interested in the dynamic response of the injector when pressure fluctuation breaks out in the combustion chamber. Finally, the key goal of injector dynamics is to figure out whole transfer function of the injector so that we can control combustion instability by designing injectors.

1.2.2 Transfer function

Transfer function is widely used to find out the relationship between input parameter and following output parameter as a reaction of its input. In this study, the input is determined as pressure oscillation of the feed system or manifold, while the output is orifice pressure oscillation as well as fluctuation of liquid film thickness at the end of the orifice. The input and output data were collected as a form of time-domain at first, and they were converted into frequency-domain with Fast Fourier Transform (FFT). Mathematically, the transfer function of the injector can be described as follows.

Input : $X(t) = X_i sin\, wt \quad \xrightarrow{\text{FFT}} \quad X(f)$

Output : $Y(t) = Y_i sin(wt + \varphi) \quad \xrightarrow{\text{FFT}} \quad Y(f)$

$$\textit{Transfer Function}: \; G(f) = \frac{Y(f)}{X(f)} = G_{Re}(f) + G_{Im}(f) \qquad (1.1)$$

Then amplitude and phase of the transfer functions are defined,

Amplitude : $|G(f)| = \sqrt{[G_{Re}(f)]^2 + [G_{Im}(f)]^2}$ (1.2)

Phase : $\Phi(f) = \tan^{-1}\left[\frac{G_{Im}(f)}{G_{Re}(f)}\right]$ (1.3)

The concept of transfer function looks simple, nevertheless, LRE is extremely complex system to figure out the whole response mechanism at once. The complexity can be reduced by dividing whole function into each part of the injector, i.e. swirl chamber length and diameter, tangential passage length and diameter, number of tangential entry, etc. The theoretical derivation of the whole transfer function was suggested by Bazarov V.G. [4], as written below. And further experimental work is still going on to complete the transfer function.

$$\Pi = \frac{\bar{Q}'_O}{\Delta\bar{P}'} = \frac{P_c}{\Delta P} \cdot \frac{\Pi_{\mathrm{TE}}\Pi_O\Pi_{\mathrm{SC}}}{2\Pi_{\mathrm{TE}}\Pi_{\mathrm{SC}}+1} \tag{1.4}$$

1.3 Overview of Present Works

Even though injector dynamics is the core element to control combustion instability, this field has not been spotlighted until recently.

A significant contribution to the study of the injector dynamics was introduced by V.G. Bazarov [5,6]. He provided theoretical and experimental results for dynamic analysis of swirl and impinging jet injector, needed to ensure the stable operation of the engine as a whole. Based on the analysis of fluid flow in the swirl chamber, the concept was provided for injectors as a fluid damper, designed to dampen oscillations in the injectors and pipelines. The study of time-dependent processes in the liquid swirl injector in linear formulation allowed to build the transfer function of the change in its basic parameters and showed the possibility of the instability of fluid flow in pipes equipped with liquid centrifugal nozzles.

Li-jun Yang et al. performed experimental and theoretical study about injector dynamics [7,8]. Their experiments involve analyzing dynamic characteristics of both closed and open type swirl injector, which has one tangential entry each. They also carried out numerical simulation about some kind of injectors, including injectors which have two rows of tangential passage also.

Khil et al. demonstrated experimental study about closed type swirl injector at various input pressure condition, following Bazarov's analyzing method [9,10]. They found out input gain effect for low (5-75Hz) and mid (100-250Hz) frequency range, applying Klystron effect to explain the tendency at low frequency range. They also got Phase-amplitude diagram along the frequency range of 5-250Hz.

Chapter 2 APPARATUS AND EXPERIMENTAL METHOD

2.1 Experimental Setup

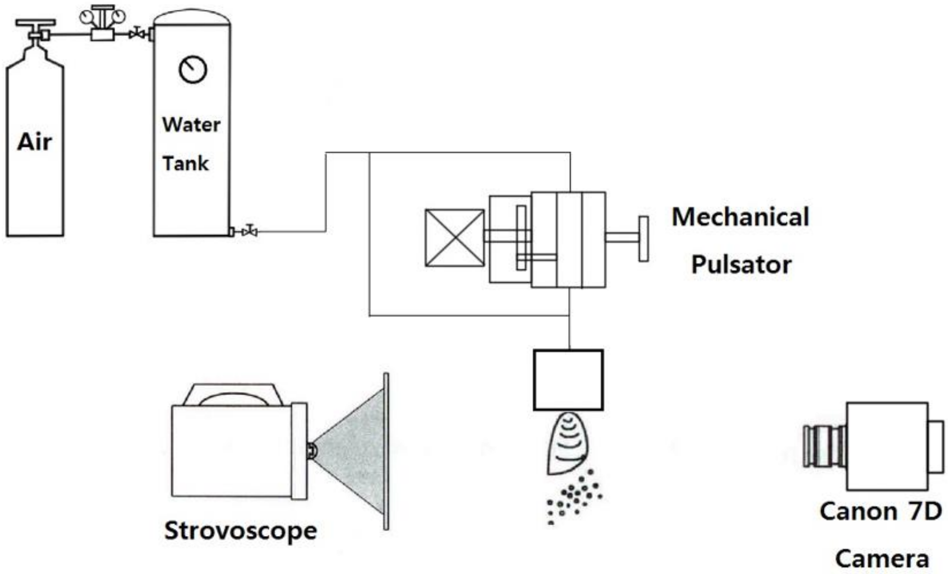
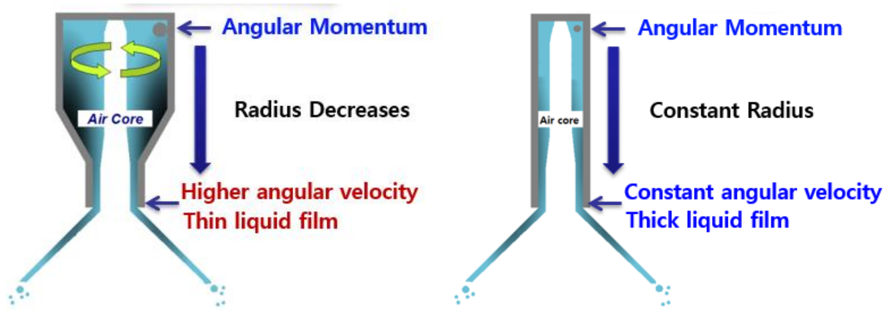


Figure 2.1 Schematics of experimental setup

Fig 2.1 shows schematics of total experimental setup. High pressure air pressurized water tank to inject water through the injector. Mechanical pulsator was used to make pressure oscillation to the working fluid. More details will be described about the mechanical pulsator in the next chapter. Instantaneous spray images were taken in the static state to obtain spray angle. Canon EOS 7D digital camera was used to take pictures.

2.2 Swirl Injector

2.2.1. Open-type swirl injector



a) Closed-type swirl injector **b) Open-type swirl injector**

Figure 2.2 Closed-type and open type swirl injector

Liquid swirl injectors are widely used and is almost impossible to list the areas where they are used. Open-type swirl injectors are also commonly used in Russian liquid rocket engines, especially in oxidizer rich staged combustion cycle engines. In the static state, there is little advantages in using open-type swirl injector compared with closed-type swirl injector. Fig 2.2 shows the internal flow process of each type of injector. As described in Fig 2.2 (a), fluid entering through the tangential entries have angular momentum as it rotates in the vortex chamber. As the radius of injector decreases, but still angular momentum is conserved, fluid have higher angular velocity at the end of the orifice, which means thinner liquid film; high atomization performance. On the other hand, open-type swirl injector has constant radius from the manifold to the orifice as shown in Fig 2.2 (b), liquid film thickness at the orifice is thicker than that of closed-type injector, resulting in low atomization performance. While these characteristics are confined to the static state, dynamic characteristic of each injector has been investigated very little. In this research, open-type swirl injector is used to find out dynamic characteristics of the injector.

2.2.2. Injector geometry variation

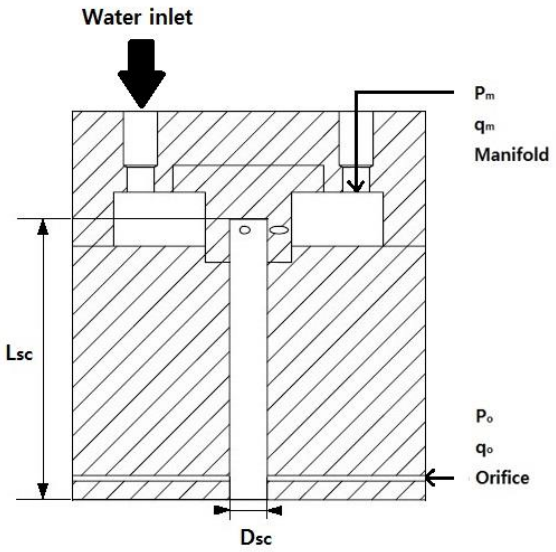


Figure 2.3 Schematic of a open-type simplex swirl injector

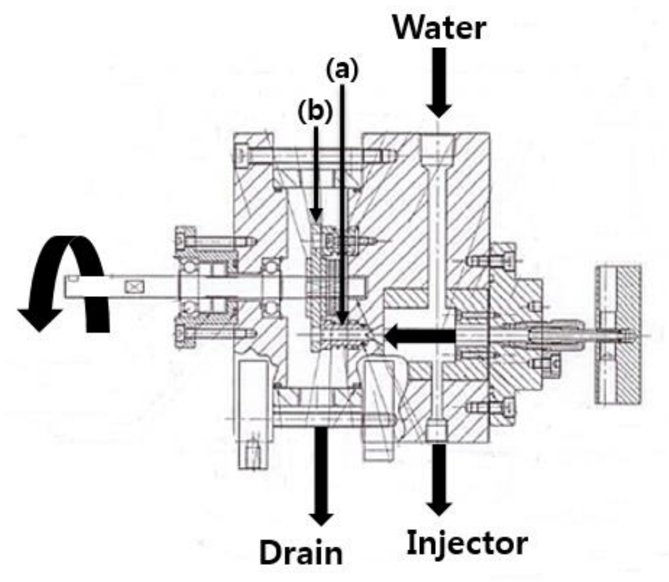
Open-type simplex swirl injector was designed and produced for the experiment. The schematic of the injector is shown in Fig 2.3. It was designed to be able to change the lower part – under manifold part – and the tangential entry part so that the swirl chamber length and diameter could be changed and following effect could be investigated. Swirl chamber length was varied from 50mm to 65mm, spacing 5mm apart, when the swirl chamber diameter was fixed at 7mm. Swirl chamber diameter was also varied from 6mm to 9mm at 1mm interval, when swirl chamber length was fixed at 55mm. Number and length of tangential entry was decided as 3 and 5mm respectively. These values were determined to major parameters, for example, L/D and injector geometry parameter A, can be satisfied to be set in the reasonable range, compared with open-type injectors put in practical use in LRE, or experimental injectors of other research groups. More details are shown in Table 2.1 below.

Table 2.1 Injector geometry variation and follwing parameters

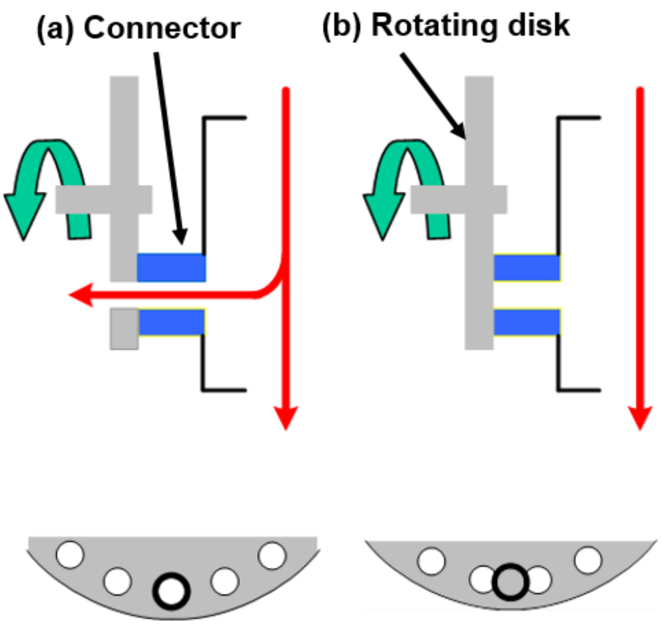
<table>
<tr><th>L_{SC}</th><th>D_{SC}</th><th>L_{TE}</th><th>D_{TE}</th><th>L/D</th><th>A</th></tr>
<tr><td rowspan="4">55mm</td><td>6mm</td><td rowspan="8">5mm</td><td rowspan="8">1.4mm</td><td>9.17</td><td>4.69</td></tr>
<tr><td>7mm</td><td>7.86</td><td>6.67</td></tr>
<tr><td>8mm</td><td>6.88</td><td>8.98</td></tr>
<tr><td>9mm</td><td>6.11</td><td>11.63</td></tr>
<tr><td>50mm</td><td rowspan="4">7mm</td><td>7.14</td><td>6.67</td></tr>
<tr><td>55mm</td><td>7.86</td><td>6.67</td></tr>
<tr><td>60mm</td><td>8.57</td><td>6.67</td></tr>
<tr><td>65mm</td><td>9.29</td><td>6.67</td></tr>
</table>

2.3 Hydrodynamic Mechanical Pulsator

A hydrodynamic mechanical to generate pressure fluctuation to working fluid was designed. The pulsator consists of a (a) connector and (b) rotating disk, as shown in Fig 2.4 (a). Connector has a same size of hole through the body. Rotating disk driven by an electric motor has 20 holes of the same diameter, it aligns periodically with the holes in the connector, as shown in Fig 2.4 (b), allowing the liquid to drain outside of the pulsator. As the space between two sets of holes changes regularly, it generates uniform pulsation frequencies ranging from 0 to 1000Hz.



(a) Hydrodynamic pulsator configuration



(b) Working mechanism of the pulsator

Figure 2.4 Hydrodynamic mechanical pulsator

2.4 Electrical Conductance Method

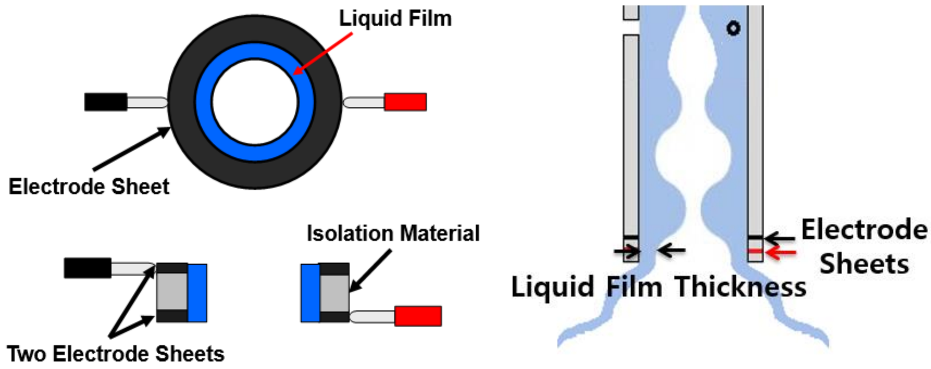


Figure 2.5 Schematic of electrical conductance device

A special device was manufactured to measure the liquid film thickness at the end of the orifice. Fig 2.5 shows the schematics of this device. This method was first proposed by Lefebvre [11], and has been used in actual experiments [12,13].

Two electrodes were mounted at the end of the orifice. The thickness of the liquid film was measured via the electric conductivity between two electrodes in the swirl chamber. As the electric conductance of the liquid flowing between two electrodes of a constant distance only varies with the liquid film thickness, liquid film thickness can be determined by measuring the voltage between the two electrodes. The electrodes used here were made of titanium and they were insulated by Teflon.

The system was calibrated by flowing water through the swirl chamber and electric conductance with a plastic rod inserted along the axis of the swirl chamber. By repeating this measurement with rods of different diameter, the calibration curve could be drawn as shown in Fig 2.6.

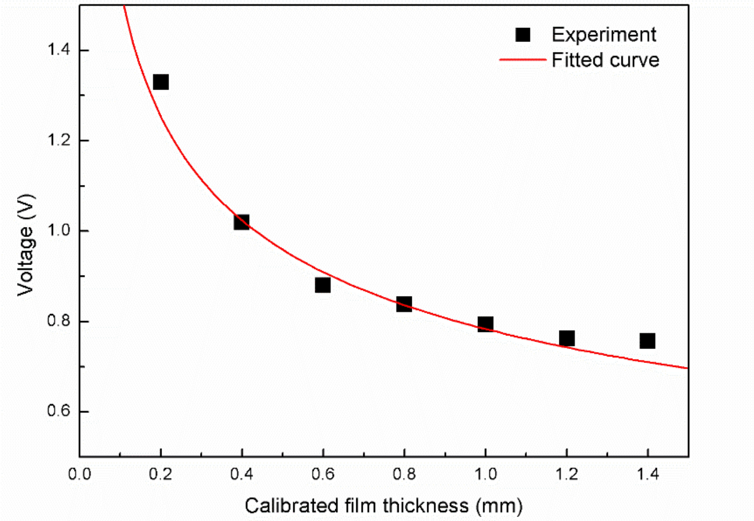


Figure 2.6 Calibration curve of liquid film thickness

2.5 Experimental Condition

Table 2.2 shows the experimental conditions of this study. In static state, manifold pressure was varied from 2 to 6 bar at interval of 1 bar, while it is fixed at 4 bar in dynamic state. There was no pulsation frequency at static state, of course, as the word ‘Static’ means itself. At dynamic state, pressure fluctuation was generated at 7 cases of frequency; 100, 200, 300, 400, 500, 750, 1000 Hz.

Table 2.2 Experimental conditions

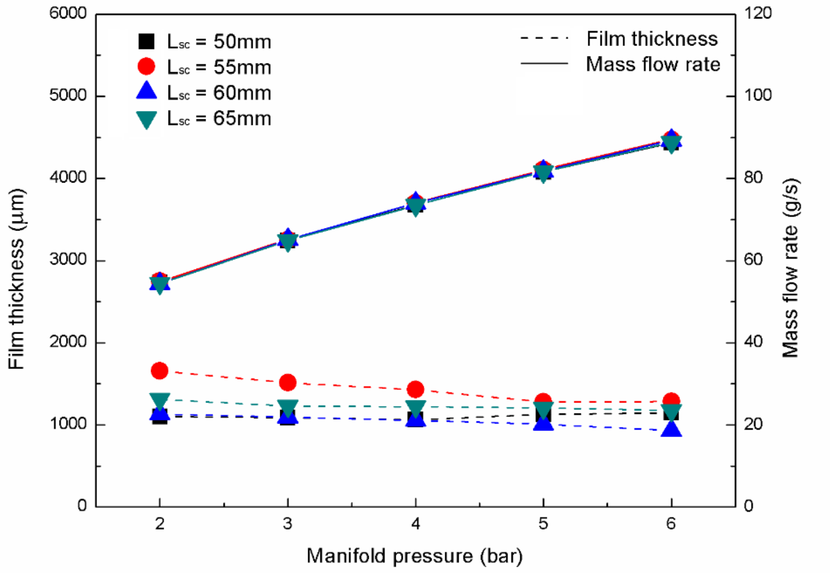
Parameter	Statics	Dynamics
Manifold Pressure [bar]	2, 3, 4, 5, 6	4
Pulsation Frequency [Hz]	-	100, 200, 300, 400, 500, 750, 1000

Chapter 3 RESULTS AND DISCUSSION

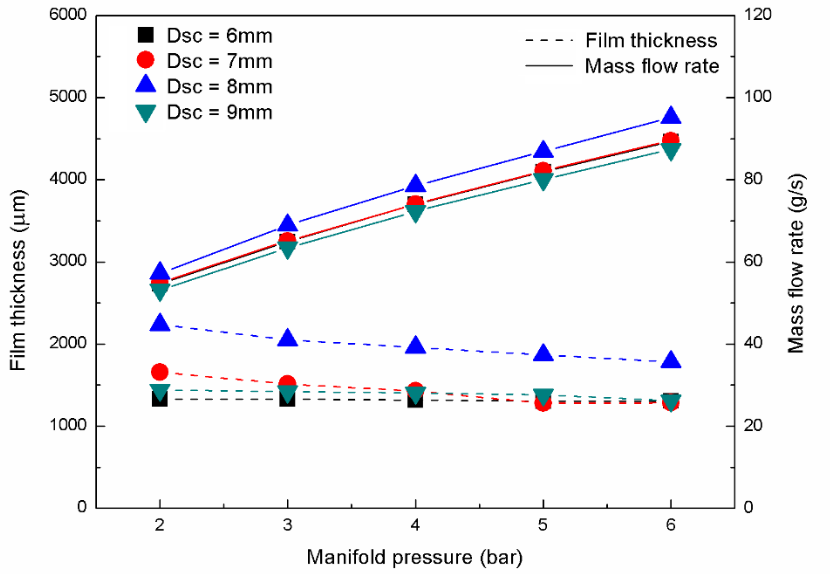
3.1 Static Characteristics

3.1.1. Mass flow rate and film thickness behavior

Experiments for static characteristics were preceded before the dynamic tests. Liquid film thickness and mass flow rate was measured by changing manifold pressure from 2 to 6 bar, while varying swirl chamber length and diameter respectively. Mass flow rate was measured by Hoffer Mass Flowmeter (HO-1/2×1/4A-.35-3.5-BP, ±0.5% Accuracy). Fig 3.1 shows the result. In both case of varying length and diameter of the swirl chamber, as the manifold pressure is getting higher, liquid film thickness goes down and mass flow rate goes up. Mass flow rate changes little with length variation, while it changes more with varying diameter. At constant L_{SC} of 55mm, D_{SC}=8mm has maximum value of mass flow rate, whereas L_{SC}=55mm reaches maximum value of liquid film thickness when D_{SC} is fixed at 7mm.



(a) Swirl chamber diameter : 7mm ; L_{SC} variation

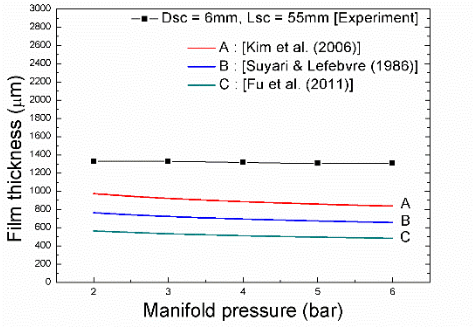


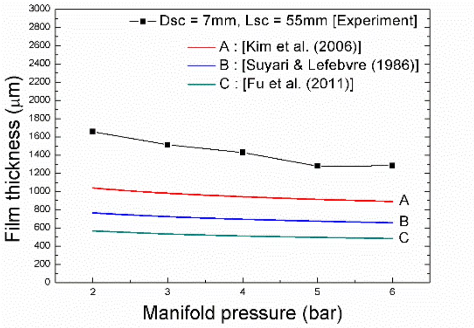
(b) Swirl chamber length : 55mm ; D_{SC} variation

Figure 3.1 Static characteristics with injector geometry variation

3.1.2. Comparison between measurement and previous analytical equations for liquid film thickness

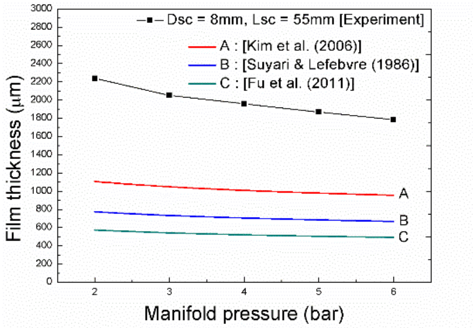
The measured liquid film thickness was compared to the results from the analytical equations which take into account the effect of injection pressure. Fig 3.2 shows the comparison between the measured liquid film thickness and the calculated liquid film thickness with varying swirl chamber diameter, and Table 3.1 below summarizes the analytical equations and corresponding injector characteristics

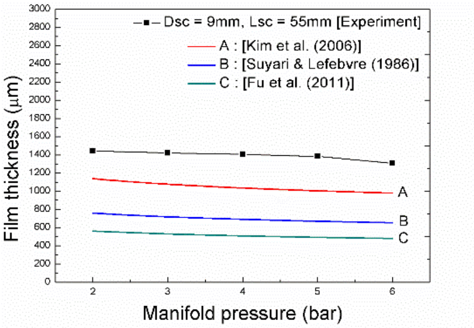




a) Swirl chamber diameter : 6mm

b) Swirl chamber diameter : 7mm





c) Swirl chamber diameter : 8mm

d) Swirl chamber diameter : 9mm

Figure 3.2 Comparison between measured liquid film thickness and estimated liquid film thickness from previous researches.

Table 3.1 Analytic equations and corresponding injector characteristics

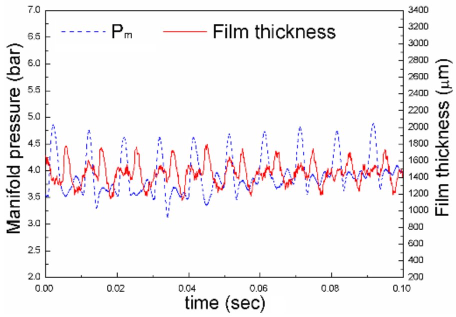
	Equation	Injector characteristics	
		Injector type	Number of tangential entry
Suyari and Lefebvre [11]	$h = 3.66\left(\frac{d_o \dot{m}_l \nu_l}{\rho_l \Delta P}\right)^{0.25}$	Closed	3
Kim et al. [14]	$h = 1.44 d_o \left(\frac{\dot{m}_l \nu_l}{\rho_l \Delta P d_o^3}\right)^{0.25} \left(\frac{l_o}{d_o}\right)^{0.6}$	Closed	3
Fu et al. [7]	$h = 2.7\left(\frac{d_o \dot{m}_l \nu_l}{\rho_l \Delta P}\right)^{0.25}$	Open	1

h = liquid film thickness, ν_l = liquid viscosity, $\dot{m}_l$ = mass flow rate, ρ_l = liquid density, d_o = orifice diameter, l_o = orifice length, ΔP = manifold pressure

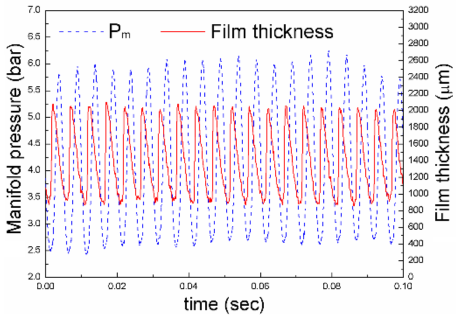
While overall tendencies are all similar within three equations and the experimental result, actual value of measured liquid film thickness does not fit to any of analytic equation. All three equations underestimate the effect of manifold pressure on liquid film thickness. It is thought that this disagreement is caused by difference of injector geometry. The analytic equations of Suyari and Lefebvre, Kim et al. are results induced by closed type swirl injector. As mentioned in the previous chapter 2.2.1, closed type swirl injector has more advantage in atomizing performance than that of open type swirl injector. The comparison of this chapter clearly shows the effect of narrowing swirl chamber. Even though Fu et al. used open type injector when deriving the equation, their device has only one tangential passage, causing relatively little amount of mass flow rate and finally has thinner film.

3.2 Input Pressure Fluctuation and Following Response

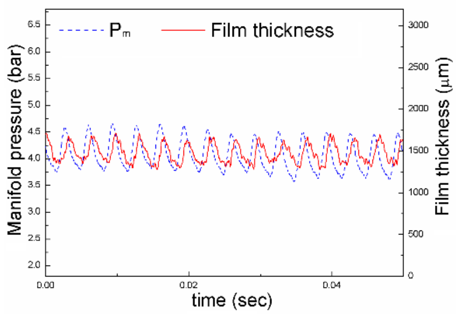
As a response of input pressure oscillation, fluctuating waveform of liquid film thickness is drawn, in the same plane with the input. Measurement results of one sample injector (L_{SC}=55mm, D_{SC}=6mm) are illustrated in Fig 3.3. While phase and amplitude transition between input and output fluctuation can be recognized even by naked eyes, Fast Fourier Transform (FFT) was conducted to gather quantitative values.



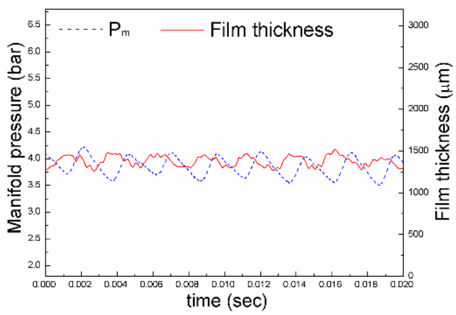
a) f = 100Hz



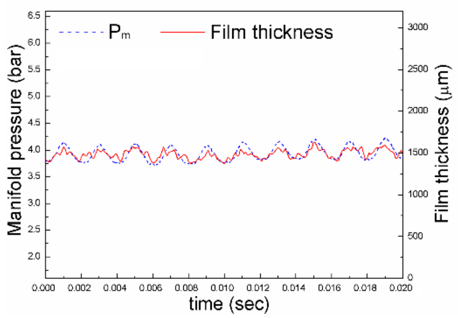
b) f = 200Hz



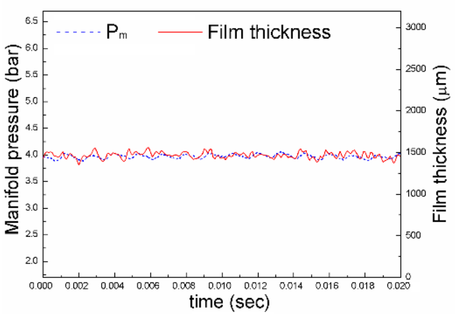
c) f = 300Hz



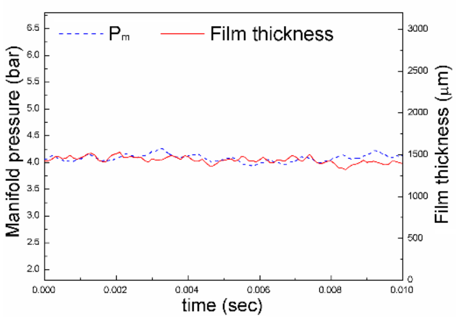
d) f = 400Hz



e) f = 500Hz



f) f = 750Hz



g) f = 1000Hz

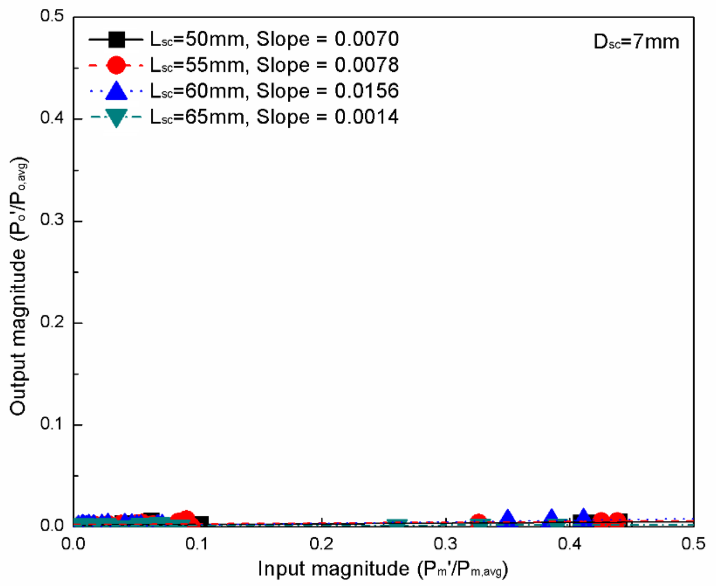
Figure 3.3 Input pressure oscillation and following response of liquid film thickness

3.3 Dynamic Characteristics with Geometry Variation

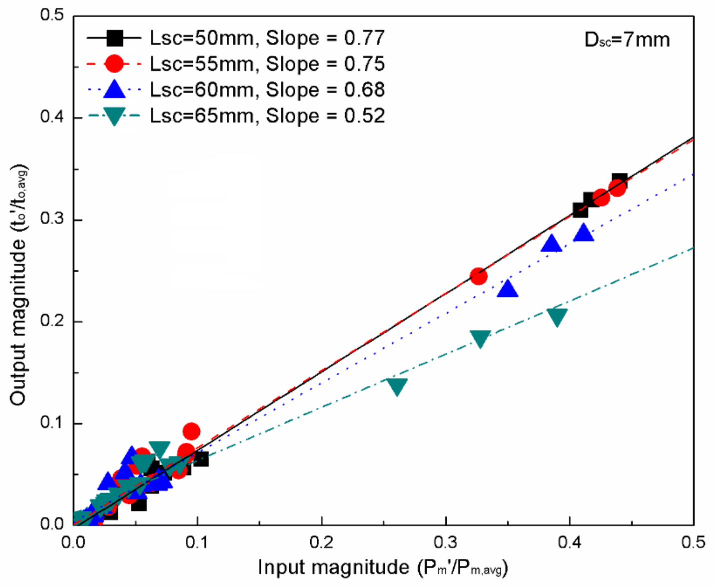
3.3.1 Swirl chamber length variation

A series of experiments were performed at swirl chamber lengths of 50mm, 55mm, 60mm, 65mm with constant diameter of the swirl chamber, D_{SC} = 7mm. Fluctuation magnitude of orifice pressure and liquid film thickness were analyzed as the output parameters, when magnitude of manifold pressure fluctuation with uniform frequency occurs as an input parameter. Fig 3.4 shows the results, the x axis represents the normalized value of input fluctuation magnitudes, while the y axis shows the normalized value of output fluctuation magnitudes.

As shown in Fig 3.4 (a), magnitude of orifice pressure fluctuation is extremely small for any length of swirl chamber, which seems meaningless to compare each other. By the contrast, liquid film thickness fluctuation at the end of the orifice increase linearly as the magnitude of input fluctuation grows larger, as shown in Fig 3.4 (b) The slope of the plot has maximum value at shortest length, L_{SC}=50mm, and it decreases as L_{SC} gets longer, which means the longer swirl chamber length the injector has, it becomes more rigid for disturbance.



(a) Orifice pressure



(b) Liquid film thickness

Figure 3.4 Input gain effect for parameters with length variation

While swirl chamber length variation appears distinct tendency for the liquid film thickness, it is believed that the reason is energy loss by the friction force as well as the damping effect of the wave itself. As described in Fig 3.5 below, the liquid entering through the tangential entries has some amount of energy. Because the internal structure of open-type injector is just a cylinder, the swirling fluid has no way to develop, or at least maintain, energy initially it has. But the friction force exist along the wall inside the injector, energy loss can be presented as follows.

$$\Delta E = \int F_{friction} dl \tag{3.1}$$

This equation means that the swirl chamber is longer, the more energy loss takes place to the liquid. As the energy moves with wave propagation, energy loss means reduction of the wave amplitude.

The damping effect could be another reason, as the wave has its own property of being damped as it moves, and it depends on the total length it goes on.

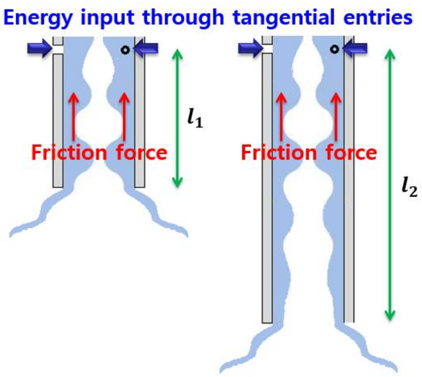
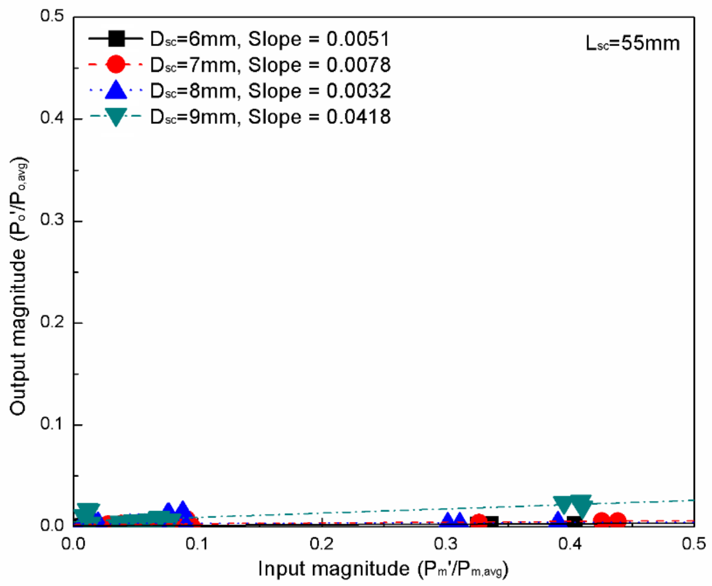


Figure 3.5 Length effect on the liquid film thickness fluctuation

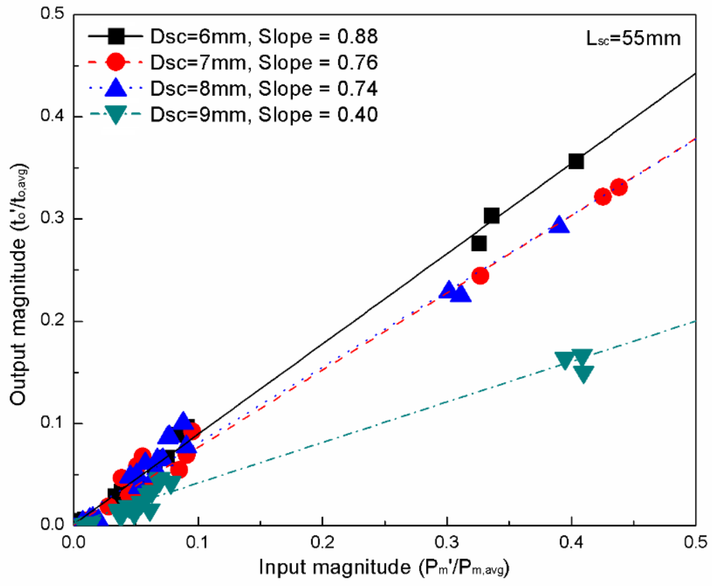
3.3.2 Swirl chamber diameter variation

A series of experiments were conducted with differing swirl chamber diameter D_{SC} while keeping all other geometry and flow conditions the same. The swirl chamber diameter was varied as follows : D_{SC} = 6mm, 7mm, 8mm, 9mm. The result is depicted in Fig 3.6.

Just like the result of previous chapter 3.3.1, orifice pressure gets affected very little by the input fluctuation, while fluctuation magnitude of liquid film thickness is proportional to the input fluctuation magnitude. The slope of the plot has maximum value at smallest diameter, D_{SC}=6mm, and it falls down as D_{SC} gets larger, which means when the open-type injector in this study has larger swirl chamber diameter, it comes to be more rigid for outer perturbations.



(a) Orifice pressure



(b) Liquid film thickness

Figure 3.6 Input gain effect for parameters with diameter variation

The explanation of physics here may be cast by analyzing initially developed wave right after the tangential entries. Schematic of the oscillating fluid inside the swirl chamber is illustrated in Fig 3.7. As the pressure fluctuation occurs, it makes velocity fluctuation flowing into the tangential passages, making wave propagation inside the swirl chamber. The amplitude of surface wave is known as follows [3].

$$\overline{\Omega} = \frac{1}{A\sqrt{2(R_{TE}^2 - A^2\mu^2)}} \frac{v'_{TE}}{v_{TE}} \tag{3.2}$$

where the geometric characteristic parameter A is defined as

$$A := \frac{S_{SC}}{S_{TE}} \frac{R_{TE}}{R_{SC}} = \frac{R_{SC}R_{TE}}{nR_{TE}^2}\,. \tag{3.3}$$

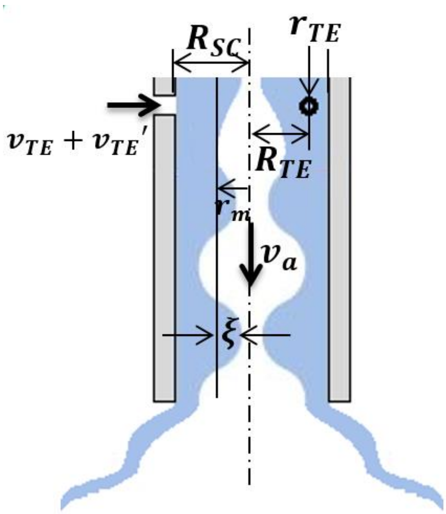


Figure 3.7 Schematic of surface wave propagation inside the swirl chamber

By substituting A for its definition, the amplitude can be expressed as

$$\bar{\Omega} = \frac{k_1}{R_{SC}\sqrt{2\{1 - k_2(\mu R_{SC})^2\}}} \frac{v'_{TE}}{v_{TE}}, \tag{3.4}$$

where the constants k_1 and k_2 are defined as

$$k_1 = \frac{n r_{TE}^2}{R_{TE}}, \qquad k_2 = \frac{R_{TE}^2}{n^2 r_{TE}^4}. \tag{3.5}$$

As we are interested in the effect of the swirl chamber diameter on the amplitude of surface wave, tendency of the discharge coefficient μ along the swirl chamber diameter should be figured out.

Fig 3.8 shows discharge coefficient at varying swirl chamber diameter. As it shows, discharge coefficient gradually decreases as the swirl chamber diameter

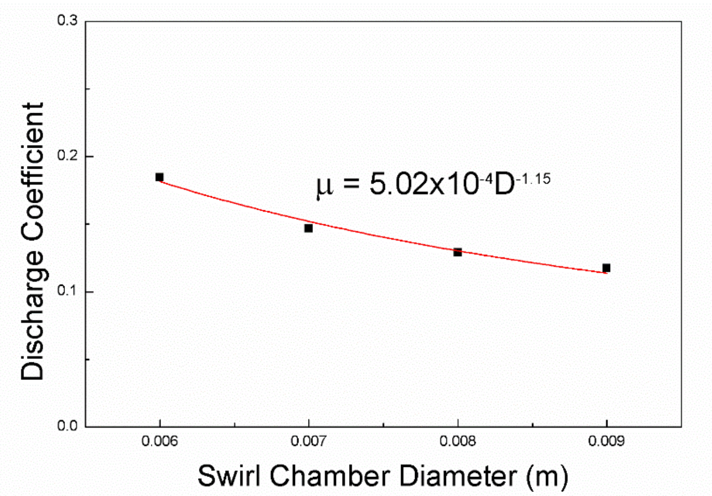


Figure 3.8 Swirl chamber diameter effect on the discharge coefficient

becomes larger. Applying this effect to equation (4), now we reach the conclusion that as the swirl chamber diameter increases, initial amplitude of surface wave decreases, concerning fluctuation magnitude of liquid film thickness reduced.

3.3.3 Comprehensive dynamic response of open-type swirl injector

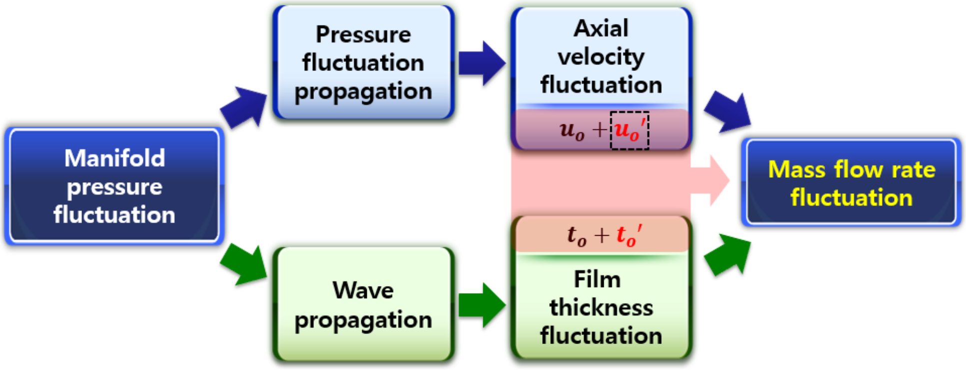


Figure 3.9 Simple process of mass flow rate fluctuation being generated

Mass flow rate pulsation is one of the most decisive factor in the stability of LRE, because it generates combustion instability directly when fuel and oxidizer burn in the combustion chamber. The simple mechanism is illustrated in Fig 3.9. When pressure fluctuation occurs, it propagates directly to the orifice, making axial velocity of the spray oscillate. Meanwhile, it creates surface wave inside the swirl chamber, which propagates till the end of the swirl chamber, generating liquid film thickness fluctuation. These two kinds of fluctuation combine together and finally generate mass flow fluctuation.

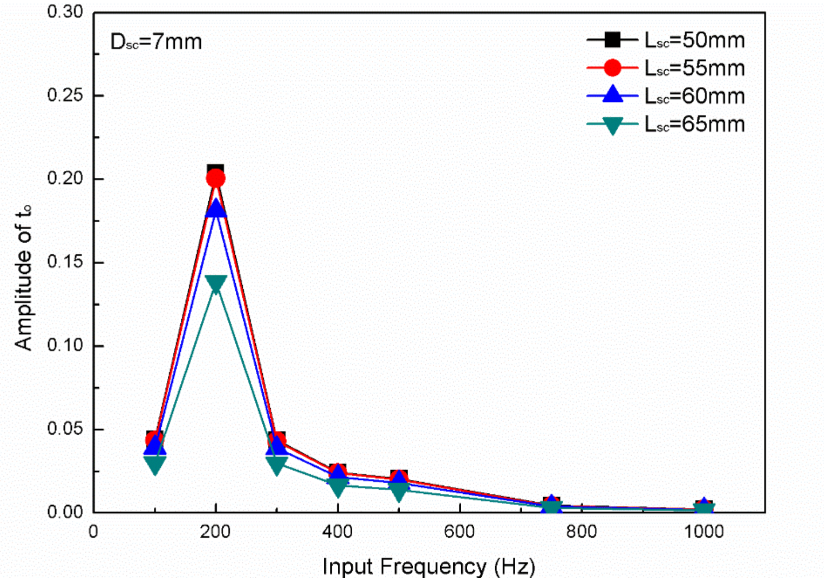
As it appears in previous chapters 3.3.1 and 3.3.2, pressure fluctuation occurs very little at the end of the orifice, while film thickness fluctuation occurs much more. It represents that in case of open type swirl injectors which are in the range of this experiment, wave propagation is the main reason that causes mass flow rate fluctuation, rather than propagation of pressure fluctuation itself.

3.4 Effect of Pulsation Frequency

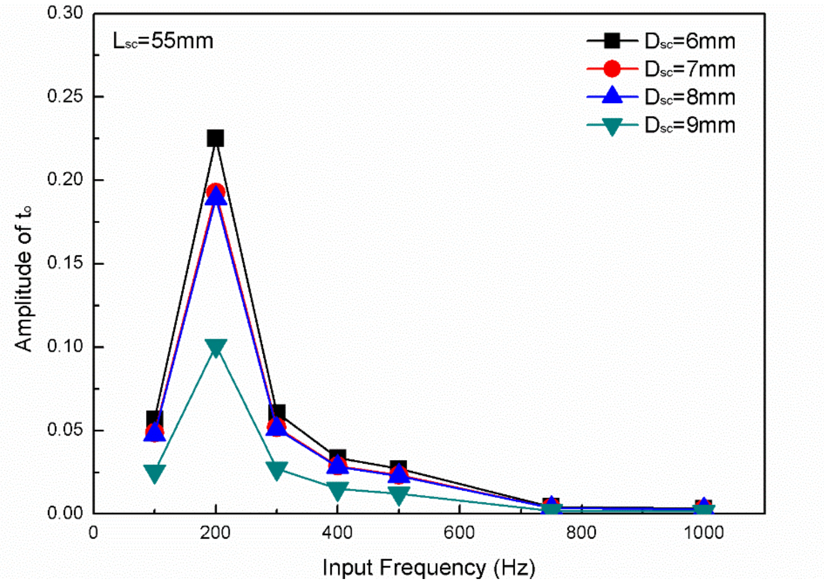
Let us now consider the relationship between pulsation frequency and fluctuation magnitude. Though considering mass flow rate fluctuation is proper to figure out dynamic characteristics along the pulsation frequency, based on the results of previous chapters, because orifice pressure fluctuation values showed extremely small amount, it is reasonable to use fluctuation of liquid film thickness only, instead of using magnitude of total mass flow rate fluctuation. Fig 3.10 shows the results.

The amplitude of liquid film thickness oscillation increase with oscillation frequency at the initial part of the frequency range, forming the maximum peak at the frequency of 200Hz. Then the amplitude of oscillation reduces drastically with oscillation frequency rise to 1000Hz. Every injector used in this study has such trend without exception, even though there are gaps of amplitude between them. Fig 3.10 (a) shows the result of fluctuation amplitude being decreased with increasing L_{SC}, while Fig 3.10 (b) shows the effect of D_{SC}, the amplitude is getting smaller as diameter becomes larger. These tendencies tie in exactly with what we already see in previous chapters 3.3.1 and 3.3.2.

This result gives crucial information designing open type swirl injector. In the range of this study, open type swirl injector shows distinct weak point at certain frequency of disturbance. It also provides information how to deal with the amplitude of fluctuation by changing injector geometry.



(a) Orifice pressure



(b) Orifice pressure

Figure 3.10 Effect of pulsation frequency on the amplitude of film thickness

Chapter 4 CONCLUSION

Dynamic characteristics of open type swirl injectors with varying geometry were investigated in this study. Hydrodynamic mechanical pulsator was used to generate pressure fluctuation as it emulates the pressure pulsation in the feed system of real LRE. A conductance measurement method was used to measure instantaneous liquid film thickness. Swirl chamber length and diameter were varied by 4 kinds each, to figure out geometrical effects on the injector dynamics.

Simple static characteristics were examined first. As manifold pressure is getting higher, mass flow rate grows up and liquid film thickness falls down. Under the variation of geometry, swirl chamber length variation influences very little to the mass flow rate while swirl chamber diameter variation affects more. The steady characteristics of the liquid film thickness was also compared with the empirical equations of previous researches, which shows clear distinction followed by geometrical difference.

Fluctuation of orifice pressure and liquid film thickness were measured as response of manifold pressure oscillation. For all 7 kinds of injector used in this study, fluctuation magnitude of orifice pressure has extremely small value regardless of the input fluctuation magnitude. On the other hand, magnitude of liquid film thickness fluctuation is linearly proportional to the input magnitude. This results indicate that mass flow rate fluctuation is mainly caused by wave propagation rather than transmission of pressure oscillation itself. Under the geometry variation, the slope between input and output magnitude is getting lower as the swirl chamber length becomes longer as well as the swirl chamber diameter becomes larger. It suggests that the injector with larger swirl chamber diameter and longer swirl chamber length is dynamically more stable.

Frequency effect on the output fluctuation magnitude was investigated. The magnitude drastically increases at the initial part of the frequency range and then gradually reduces to 1000Hz, making clear peak at 200Hz. This result implies that open type swirl injector may have weak point, which is especially vulnerable at certain frequency. These characteristics should be considered when designing the open type swirl injector, geometrical variation provides some hint to control the magnitude of fluctuation.

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초 록

연소 불안정 현상은 연소 현상을 이용한 모든 종류의 기관에서 발생할 수 있는데, 특히 액체 로켓과 같이 고온 고압에서 작동하는 추진기관의 경우 연소불안정 현상은 곧 엔진의 파괴로 이어진다. 연소 불안정은 연소기 내에서 방출되는 열과 압력파가 상호작용하며 발생하는데, 이 때 발생하는 압력파는 인젝터로 유입되는 연료 또는 산화제에 압력섭동을 일으킨다. 이러한 연소 불안정 현상을 억제하는 방식으로 Baffle이나 Acoustic Cavity와 같은 부가적인 장치들이 사용되어왔으나, 그로 인하여 엔진의 무게가 증가하고 효율이 감소하는 불이익을 감수해야만 했다. 만약 연료를 분사하는 인젝터가 외부에서 가해지는 압력 섭동에 대하여 스스로 damper와 같은 역할을 수행할 수 있다면 적은 비용으로 고성능, 고효율의 액체로켓엔진 제작이 가능할 것이고, 이러한 배경에서 인젝터 동특성에 대한 연구가 필요하다.

연구를 위해 인위적인 압력섭동을 발생시킬 수 있는 회전원판형 진동발생기를 제작하였고, 액막두께를 측정하기 위한 전극장치를 제작하여 오리피스 끝에 장착하였다. 인젝터의 형상 변화에 따른 영향을 알아보기 위하여 스월챔버의 길이와 지름에 변화를 주어 총 7개의 오픈형 스월 인젝터가 제작되었다.

인젝터에 대한 간단한 정특성 연구가 먼저 수행되었다. 매니폴드 압력에 따른 유량과 액막두께의 변화를 측정하였으며, 측정된 액막두께와 기존 연구자들의 실험식을 비교하였고, 그 차이에 대한 분석을 수행하였다.

동특성 연구에서는 오픈형 스월 인젝터로 유입되는 작동유체(물)에

압력 섭동을 발생시켜, 그에 따른 출력 변수들의 응답 특성을 실험적으로 측정하였다. 출력 변수로는 오리피스 끝에서의 액막두께와 압력이 설정되었는데, 매니폴드에 입력된 압력섭동에 대하여 각각의 출력변수들이 보이는 반응을 측정하였다. 또한 스월 챔버의 길이 변화와 지름 변화가 각각 인젝터의 응답특성에 미치는 영향과 그 원인을 분석하였다.

주요어: 액체로켓엔진, 동특성, 오픈형 스월 인젝터, 연소불안정, 펄세이터
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