1. INTRODUCTION

Swirl injectors are widely used in liquid rocket engines, gas turbine engines, diesel engines, industrial furnaces and so forth. Even though design procedure of a swirl injector is more difficult than that of an impinging jet injector, swirl injectors have many advantages, such as atomization quality, wide operation range with stability and uniform mixing efficiency [1]. Spraying mechanism of a swirl injector is that liquid sheet is injected with the tangential velocity due to tangential entries, so liquid sheet is discharged with specific spray angle which corresponds to the ratio of axial and tangential velocity and the air core is formed. In a swirl injector, the empty air core is generated around the centerline of the orifice, so discharge coefficient is small. Because of the tangential velocity, thin liquid sheet is formed, disintegrated into ligament and droplets by hydraulic instability. A gas/liquid swirl coaxial injector has an annular gas stream which is injected through the annular gap between inner and outer injector. The annular gas stream strikes on liquid sheet with high velocity and disturbs it. The breakup mechanism of a gas/liquid swirl coaxial spray is not mainly due to hydraulic instability of liquid sheet, but momentum transfer of kinetic energy of high speed gas stream.

At the exit of an inner injector, liquid is injected with specific spray angle and this expansion of the swirling liquid sheet prevents annular gas stream from flowing out, while gas phase flow relatively presses the swirl liquid sheet. Because swirling liquid sheet is an inertia element, self-pulsation by a time-delayed feedback between liquid and gas phases tends to occur with painful scream. When self-pulsation phenomena occur, a strong spray oscillation and painful scream are detected.

Although many studies on the characteristics of a swirl coaxial injector have been performed during past decades, most of the studies were related to the atomization quality and spatial distribution of spray. Relatively few efforts were put on the acoustic characteristics of a swirl coaxial injector. Self-pulsation in gas/liquid coaxial injectors was first discovered in the mid-1970s for LOX/hydrogen systems when tested under reduced rating conditions [3]. Bazarov [4] performed several experimental studies on the influences of operating conditions and design parameters. According to his results, the LOX post recess length is shown to be one of the most important parameters in determining the self-pulsation characteristics. Zhou et al. studied the acoustic and flow rate characteristics of gas/liquid swirl coaxial injectors experimentally and theoretically [5, 6]. They concluded that increasing the recess ratio reduces the screaming zone and the acoustic radiation pressure of scream, and largely affects the flow rate variation.

In present study, the spray characteristics of swirl coaxial injectors are studied. And also the acoustic characteristics of self-pulsation will be investigated. Liquid
and gas velocity are chosen as injection parameters, and recess length is chosen as geometric parameters.

2. EXPERIMENTAL METHODS

Gas/liquid swirl coaxial injectors were designed and manufactured into three parts, inner injectors, outer injectors and injector case in order to change each part with ease as shown in Fig. 2. The simulants of oxidizer and fuel are water and nitrogen gas, respectively. Water is discharged with swirl motion through the inner injector. GN2 is discharged through the annular gap between the inner and outer injector. The flow rate of water is 14.81 ~ 27.15 g/s and the flow rate of GN2 is 1.15~7.29 g/s controlled using mass flow controller (Brooks Co.).

![Swirl coaxial injector](image)

**Fig. 2 Swirl coaxial injector**

The orifice diameter of the inner oxidizer injector is 2.5 mm and outer diameter is 4 mm. The inner diameter of outer fuel injector is 7 mm. For investigating the effect of recess length, inner oxidizer injector is recessed for 1.25, 2.5, 3.75 mm which correspond to 0.5, 1.0, 1.5 d_o respectively. The experimental conditions are summarized in Table 1.

![Schematic of a swirl coaxial injector](image)

**Fig. 3 Schematic of a swirl coaxial injector**

<table>
<thead>
<tr>
<th>Oxidizer</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulant</td>
<td>Water</td>
</tr>
<tr>
<td>Pressure drop (MPa)</td>
<td>0.1 ~ 0.5</td>
</tr>
<tr>
<td>Mass flowrate (g/s)</td>
<td>14.8 ~ 27.2</td>
</tr>
<tr>
<td>Recess Length (mm)</td>
<td>0, 1.25, 2.5, 3.75</td>
</tr>
</tbody>
</table>

**Table 1 Experimental conditions**

Shadow photography technique was used to grasp spray patterns of swirl coaxial injectors. Also, using shadow photography technique, the onset of self-pulsation can be detected.

In order to understand spray oscillations of self-pulsation, He-Ne laser and photo detector system is used. Laser signal which passes through self-pulsation spray is measured by photo detector and analyzed by FFT (Fast Fourier Transform). For acoustic tests, PULSE System (B&K Corp., 3560C Type) is used to measure the frequency of acoustic fields.

3. EXPERIMENTAL RESULTS

3.1 Spray Patterns

When self-pulsation occurs, it has great influences on spray patterns compared with stationary spray. As mentioned before, self-pulsation accompanies very strong screams and periodic spray oscillation is observed (Fig. 1). Using shadow photography technique the onset of self-pulsation can be determined.

![Spray patterns with the gas velocity](image)

**Fig. 4 Spray patterns with the gas velocity**

![Wavelength of spray oscillation with the gas velocity](image)

**Fig. 5 Wavelength of spray oscillation with the gas velocity**

Figure 4 shows spray patterns according to the gas velocity. At fixed liquid velocity (5.92 m/s), increase of gas velocity leads to strong self-pulsation. Self-pulsation becomes severe as the interaction between liquid and gas phase increases. Due to the increase of the gas velocity, gas phase momentum becomes stronger, interaction becomes severe and gas phase disturbs liquid phase more easily. The wavelength of spray oscillation is marked in Fig. 5. If the wavelength of spray periodicity is defined as the length
between the dense part and another dense part in spray, qualitatively the wavelengths of the spray oscillation for all cases are almost the same. The frequency is inversely proportional to the wavelength. So, this means that the frequencies of spray oscillation by self-pulsation are not changed much as the gas velocity increases.

Spray patterns according to liquid velocity is shown in Fig. 6. At fixed gas velocity (166.64 m/s), increase of the liquid velocity suppresses self-pulsation. At low liquid velocity, self-pulsation phenomena occur, but when the liquid velocity becomes 10.20 m/s, self-pulsation does not occur. Liquid phase momentum increases with the liquid velocity, so liquid phase can resist the disturbances of gas phase. The wavelength of spray oscillation is shown in Fig. 7. The wavelength of spray oscillation by self-pulsation becomes shorter as the liquid velocity increases. Frequency which is inversely proportional to wavelength increases qualitatively.

![Fig. 6 Spray patterns with the liquid velocity](image)

It is known that recess augments mixing efficiency through the internal mixing of propellants and stabilizes flame due to the recirculation zone after injector post tip but enhances the self-pulsation phenomena [7]. Spray patterns are captured according to recess length in Fig. 8. Self-pulsation is not observed in the case of short recess length (0 \( d_o \), 0.5 \( d_o \)), but as recess length increases, self-pulsation is detected. If the orifice of the inner injector is recessed, liquid and gas phase are interacted with each other in confined volume by the outer injector wall. So, the interaction compared with that in the case of no recess becomes more severe. Due to the severe interaction, self-pulsation phenomena happen more easily.

![Fig. 8 Spray patterns with recess length](image)

### 3.2 Acoustic Characteristics

In general, self-pulsation accompanies painful scream with strong spray oscillation. Zhou et al. [5] and Huang et al. [6] reported that acoustic fields can cause combustion instability by providing disturbances to combustion fields. But Bazarov [3] reported that acoustic frequency by self-pulsation is different from that of combustion chamber, so acoustic field cannot provide any disturbances to combustion instability.

To understand the effects of acoustic field by self-pulsation, acoustic tests are performed using PULSE System (B&K Corp., 3560C Type). Acoustic characteristics according to the gas velocity are shown in Fig. 9. Liquid velocity is fixed at 5.92 m/s. When self-pulsation occurs, a sharp and narrow increase of sound pressure level is detected. And at all gas velocity cases, characteristic acoustic frequencies slightly increase with the gas velocity, but there are no clear trends with recess length.

![Fig. 9 Acoustic frequency with the gas velocity](image)

Characteristic acoustic frequencies according to the liquid velocity at constant gas velocity 166.64 m/s are shown in Fig. 10. As the liquid velocity increases, characteristic acoustic frequency increases, but the slope of the curve is larger than that of Fig. 9. So, acoustic frequency is mainly dependent on the liquid velocity. Like Fig. 9, there are no clear trends with recess length. For all
conditions, characteristic acoustic frequencies are in the range of 2-4 kHz. This coincides with 1T mode of combustion instability in liquid rocket engines. Zhou et al[5]. suggested that this acoustic field may cause harmful disturbances to combustion instability. On the other hand, Bazarov[3] reported that acoustic field by self-pulsation is not related with combustion instability because frequency range of self-pulsation is different from that of combustion instability. So, more systematic study of acoustic characteristics is needed in future.

3.3 Spray Oscillation Characteristics

A strong spray and flow rate oscillation can be observed in instantaneous images when self-pulsation phenomena happen(Fig. 1). In section 3.1, we estimated the frequency of spray oscillation qualitatively. If fuel and oxidizer are injected periodically, this leads to periodic heat release by combustion and there can be periodic pressure oscillation in combustion chamber. Therefore, if pressure oscillation by self-pulsation matches with acoustic fields of combustion instability, strong spray oscillation can enhance the combustion instability.

Self-pulsation spray has dense and sparse parts periodically. If laser beam passes through self-pulsation spray, there will be much attenuation in dense spray and less attenuation in sparse spray. So, by analyzing the intensity of laser beam which passes through the self-pulsation spray, the periodicity of spray oscillation can be quantified.

He-Ne laser and photo detector are used to measure the frequency of spray oscillation. Laser beam passes through the centerline of self-pulsation spray and attenuated laser beam is received by photo detector. The intensity signal is transmitted to oscilloscope and signal is analyzed by FFT(Fast Fourier Transform) utilizing PC. Experimental conditions are the same as before.

Figure 12 shows characteristic frequencies of acoustic and spray oscillation with recess 1.0 d₀. Frequencies of spray oscillation are the same as those of acoustic tests. This means that acoustic fields by self-pulsation are directly connected to flow fields and by measuring either one of them the other can be estimated and predicted. Characteristic spray frequency is also slightly dependent on the gas velocity and mainly on the liquid velocity.
self-pulsation in the frequency range of 2-4 kHz. If mass flow rate of oxidizer and fuel oscillates with the same frequency range of 1T mode of combustion instability, these effects can generate the oscillation of pressure fields and enhance the combustion instability.

3.4 Normalized Self-Pulsation Frequency

In a swirl injector, a thin liquid sheet emanates from the nozzle in the form of a hollow cone. As the swirling liquid film travels downstream, its thickness decreases and unstable waves are observed at the liquid film surface. The amplitude of unstable waves increases due to the hydraulic and aerodynamic instability. When the amplitude of an unstable wave reaches a critical value, the liquid sheet disintegrates into a ligament. And a dominant frequency is defined as the frequency of waves which has the highest growth rate. This dominant wave with highest growth rate plays a critical role in breakup of liquid sheet[8].

In this study a dominant frequency is investigated experimentally and theoretically. To measure the dominant frequency of liquid sheet wave experimentally, laser system is utilized as shown in Fig. 11. Due to the unstable wave, there exist thick and thin sheet periodically. Laser beam will be more attenuated at thick liquid sheet and less attenuated at thin liquid sheet, so the intensity of laser beam which passes through liquid sheet will be changed periodically. After FFT analysis, maximum peak can be obtained and frequency of dominant wave can be measured. In order to reduce the effects of location where laser beam passes, four points are selected. Two points are located at the centerline, one is very close to the exit of orifice and the other is located 8 mm downstream. The other two points are located at the edge of liquid sheet. From the results, effects of locations can be neglected, so all experiments are performed at 8 mm downstream of the injector exit.

Also, a dominant frequency can be calculated using linear stability analysis[8]. From linear stability analysis, linearized disturbance equations are derived, the displacement disturbances are assumed as Eq. (1) and dynamic and kinematic boundary conditions are applied.

$$\eta(x, \theta, t) = \hat{\eta} \exp[i(kx + n\theta - \omega t)]$$

Where $k$ and $n$ is the wave number and $\omega$ is the growth rate of the disturbance. $n$ is the azimuthal wave number and for axisymmetric mode, $n$ is 0. The unstable wave which has the maximum growth rate, $\omega$, for varying $k$ is the dominant wave and its frequency can be calculated from maximum growth rate.

Dominant frequencies of liquid sheet waves are shown in Fig. 13. There are lots of errors between measured and calculated frequencies at low liquid velocity. The reasons these errors exist are that the accuracy of film thickness is not known because liquid film thickness is calculated by the results of Rizk and Lefebvre[9] and spray cone is not fully developed at low liquid velocity. From Rizk and Lefebvre[9], liquid film thickness can be calculated as Eq. (2).

$$t = 3.66 \left[ \frac{d_t F N \mu_l}{(\Delta P_l \rho_l)^{0.25}} \right]^{0.25}$$

Eq. (2) itself has many uncertainties and at low liquid velocity spray cone angle is difficult to define due to undeveloped spray cone. But at high liquid velocity where liquid cone is fully developed, two data are approximately matched. Compared with the order of magnitudes of frequencies, measured frequency of liquid sheet wave is assumed to represent the true value and experimental data are compared and confirmed by linear stability analysis.

To find out the relation between the dominant frequency of liquid sheet wave and self-pulsation frequency, the other effects must be the same. The dominant frequency of liquid sheet wave does not include the annular gas effects, so direct comparison to self-pulsation frequency which has the gas effects is not possible. Self-pulsation frequency is slightly dependent on the gas velocity. So, for direct comparison, whether the gas effects must be added to the
dominant frequency of liquid sheet wave or the gas effects must be excluded from self-pulsation frequency. But, both options are not possible experimentally. The dominant frequency of liquid sheet wave cannot be measured with the gas velocity and self-pulsation does not occur without the annular gas stream. So, assumption is necessary and introduced. The assumption is that self-pulsation frequency is linearly proportional to the gas velocity and gas effects can be eliminated by extrapolating to zero gas velocity. After extrapolation to zero gas velocity in all cases, normalized self-pulsation frequency is defined as Eq. (3).

\[ NSF = \frac{f_{\text{pulsation}}}{f_{\text{wave}}} \]  

Where, NSF is normalized self-pulsation frequency, \( f_{\text{pulsation}} \) is self-pulsation frequency without gas effects and \( f_{\text{wave}} \) is the dominant frequency of liquid sheet wave.

The normalized self-pulsation frequency with liquid velocity and recess length is shown in Fig. 14. At all velocity and recess length conditions, NSF is around the unity. From Fig. 14, it seems that there exists a direct connection between self-pulsation and liquid sheet wave. Self-pulsation frequency without gas effects and the dominant frequency of liquid sheet wave have the same value. The dominant wave of liquid sheet interacts with high speed annular gas and at certain gas velocity which is large enough to generate self-pulsation, so that one period of the dominant wave is torn out and spray oscillation is observed. Therefore, it seems that self-pulsation occurs due to the unstable wave of liquid sheet and its frequency is the same with the dominant frequency of the unstable waves. But, there are lots of errors between the experimentally measured frequencies and calculated frequency of liquid sheet estimated by linear stability analysis and the assumption that self-pulsation frequency is linearly proportional to the gas velocity and gas effects can be eliminated by extrapolating to zero gas velocity is not validated, so further study is necessary.

### 3.5 Self-Pulsation Boundary

As looking into previous sections, the occurrence of self-pulsation depends on the injection conditions and injector geometries. Injection conditions affecting self-pulsation include velocity of liquid and gas phases, mass flow rate, relative momentum ratio, properties of test fluids, ambient pressure, and so on. In this study, the liquid and gas velocity are considered, the former corresponds to the inertial element against the self-pulsation and the latter disturbing element. While injector geometries affecting self-pulsation include recess length, annular gap size, size of air core, and so on. We consider only the recess length as injector geometry, which may create an intense interaction between liquid and gas phase in a confined region.

From the results of shadow photography and acoustic tests, the onset of self-pulsation according to liquid and gas momentum is plotted in Fig. 15. The increase of recess length quickens the occurrence of self-pulsation at the same injection condition, so that each region is classified by symbols and lines. The square shape symbol(■) indicates the start of self-pulsation from recess = 0.5 \( d_o \), the delta shape symbol(▲) from recess = 1.0 \( d_o \), the diamond shape symbol(◆) from recess = 1.5 \( d_o \) and (×) symbol represents that self-pulsation does not occur in the experiment with current injector geometries. If the liquid velocity increases to some extent, the momentum of liquid phase is enough to resist against the disturbances of gas flow so that self-pulsation disappears. As the recess length increases, self-pulsation region becomes wider. The wide range of operation conditions in LOX/H2 engines coincides with self-pulsation region. To avoid these unwanted unstable phenomena, study of self-pulsation is necessary.

### 4. CONCLUSIONS
First of all, spray patterns of self-pulsation in a gas/liquid swirl coaxial injector are investigated with injection and geometric conditions. The onset of self-pulsation is influenced by injection conditions and geometric conditions. Liquid phase momentum plays a role for damping self-pulsation and gas phase momentum and recess quickens the onset of self-pulsation and increases the strength of self-pulsation. As liquid momentum increases, liquid phase can resist the disturbances of gas phases. From the shadow photography technique, spray images are analyzed and the onset of self-pulsation is determined. From the results, self-pulsation boundary is obtained. Liquid phase momentum suppresses the self-pulsation and as recess length increases, self-pulsation boundary becomes wider.

Acoustic and spray characteristics are investigated. A sharp and narrow increase of sound pressure level is detected in the case of self-pulsation, so acoustic field is changed significantly. Characteristic acoustic frequency is measured and its range is between 2 kHz and 4 kHz. Acoustic frequency is dependent mainly on the liquid velocity. Also, frequency of spray oscillation is measured using laser system. By FFT analysis, frequency of spray oscillation is calculated. Spray frequency range is from 2 kHz and 4 kHz like acoustic tests. The characteristic frequency of spray oscillation is the same as that of acoustic tests.

Finally, the waves of liquid sheet are investigated using laser system and compared with the calculation of linear stability analysis. The frequency of major wave is measured experimentally and theoretically and those two results show a relatively good agreement at high liquid velocity. From frequencies of liquid sheet waves, characteristic frequencies of self-pulsation are normalized and normalized self-pulsation frequencies have the value of unity. Therefore, self-pulsation seems to be related to the liquid sheet and frequencies of self-pulsation are affected by the waves of liquid sheet.

5. NOMENCLATURE

- \( d_o \) orifice diameter [m]
- \( \rho_l \) liquid density [kg/m³]
- \( \rho_g \) gas density [kg/m³]
- \( V_l \) liquid injection velocity [m/s]
- \( V_g \) gas injection velocity [m/s]
- \( \eta \) amplitude of disturbance [m]
- \( t \) liquid film thickness [m]
- \( \Delta P_L \) liquid pressure drop [Pa]
- \( \mu_l \) liquid viscosity [kg/ms]
- \( FN \) flow number

6. REFERENCES