SELF-PULSATION CHARACTERISTICS OF A SWIRL COAXIAL INJECTOR WITH VARIOUS INJECTION AND GEOMETRIC CONDITIONS

Ji-Hyuk Im*, Dongjun Kim*, Youngbin Yoon** and V. Bazarov***

Abstract

The spray and acoustic characteristics of a gas/liquid swirl coaxial injector are studied experimentally. The self-pulsation is defined as a pressure and flow rate oscillations by a time-delayed feedback between liquid and gas phase. Self-pulsation has strong influences on atomization and mixing processes and accompanies painful screams. So, the spray and acoustic characteristics are investigated. Spray patterns are observed by shadow photography technique in order to determine the onset of self-pulsation. And self-pulsation boundary with injection conditions and recess length is get. To measure the frequency of the spray oscillation, oscillation of the laser intensity which passesthrough spray is analyzed by Fast Fourier Transform. For acoustic tests, a PULSE System was used. Acoustic characteristics of a swirl coaxial injector are investigated according to the injection conditions, such as the pressure drop of the liquid and gas phase, and injector geometries, such as recess length and gap size between the inner and outer injector. From the experimental results, the increase of recess length leads to the rapid increase of the sound pressure level. And as the pressure drop of the liquid phase increases, the frequency of the self-pulsation shifts to the higher frequency. The frequency of spray oscillationis the same as that of the acoustic fields by self-pulsation.

Key Words : Swirl Coaxial Injector, Self-Pulsation, Combustion Instability, Acoustics.

Nomenclature

d_o	orifice diameter
ρ_l	liquid density
ρ_g	gas density
V_l	liquid injection velocity
V_g	gas injection velocity

1. Introduction

Coaxial injectors are widely used in liquid rocket engines, even though both design and manufacturing processes are more difficult than any other injectors such as impinging jet injector[1]. Coaxial injectors are divided into shear coaxial injector and swirl coaxial injector according to the spraying mechanism of liquid phase. The breakup of a shear coaxial injector is achieved due to the transfer of kinetic energy by gas stream of high speed on the liquid jet. Compared to the impinging jet injector, a shear coaxial injector has an operational stability, but low mixing efficiency.

To make up this disadvantage, a swirl coaxial injector, using screw or tangential entry to make a thin liquid sheet, was adopted and shows enhanced mixing and atomization characteristics. Due to the high circumferential velocity, an air core is formed around the centerline inside the injector to balance the static pressure of a working fluid and the environment pressure. At the exit of an inner injector, the liquid is

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injected with specific spray angle, which corresponds to the ratio of axial and circumferential velocity. This expansion of the swirling liquid sheet prevents annular gas phase 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 as shown in Fig. 1.

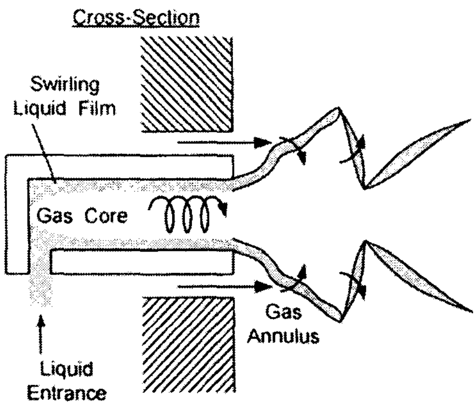

Fig. 1 Schematic of self-pulsation

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 these 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 the most important parameter in determining the self-pulsation characteristics. The LOX post recess in swirl coaxial injectors is the configuration that the exit surface of an inner LOX injector is located at a certain length on the inward side from the exit surface of an outer injector, and it is known that recess can augment mixing efficiency and affect flame stabilization through internal mixing of propellants.

In present study, the spray characteristics such as spray pattern and spray periodicity will be studied. And also acoustic characteristics of self-pulsation will be investigated. Liquid and gas velocity are chosen as injection parameters, and recess length and gap size between inner and outer injector are chosen as geometric parameters.

2. Experimental Apparatus

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.).

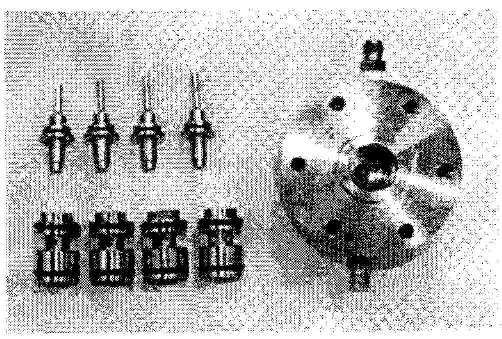

Fig. 2 Swirl coaxial injector design

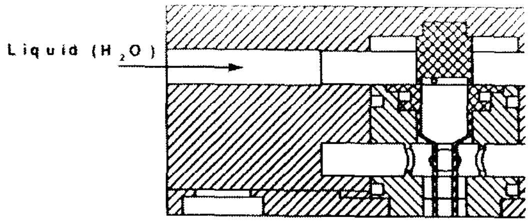

Fig. 3 Schematic of a swirl coaxial injector

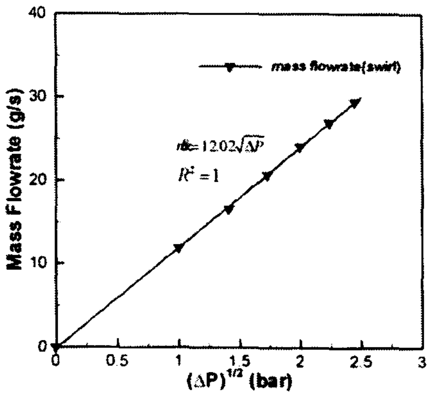

Fig. 4 Operating conditions

Before the experiments, the mass flow rate of liquid phase is measured, and experiments are performed in the region in which linear relation between pressure and mass flow rate is preserved. 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 and gap size, 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. 4 outer injectors are manufactured for gap size. The experimental conditions are summarized in Table 1.

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 characteristics of self-pulsation, laser measurement technique is used. For acoustic tests, PULSE System(B&K Corp., 3560C Type) is used to measure the frequency of acoustic field. Frequency of spray periodicity is measured with He-Ne laser, photo-detector and oscilloscope and signal is analyzed by FFT(Fast Fourier Transform).

Table 1 Experimental conditions

	Oxidizer	Fuel
Simulant	Water	Nitrogen Gas
Pressure drop (MPa)	0.1 ~ 0.5	0.6 ~ 1.6
Mass flow rate (g/s)	14.8 ~ 27.2	1.2 ~ 7.3
Recess length (mm)	0, 1.25, 2.5, 3.75	
Gap size (mm)	0.5, 1.0, 1.5, 2.0	

3. Spray Patterns

When self-pulsation occurs, it has great influences on spray characteristics. The periodic spray and flow rate oscillation are detected from the shadow photography technique. So, the onset of self-pulsation can be determined using shadow photography technique.

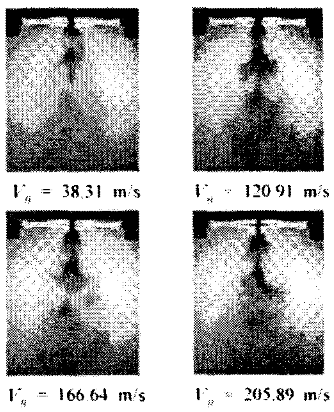

Fig. 5 Spray patterns with gas velocity

Figure 5 shows spray patterns according to gas velocity. At fixed liquid velocity(5.92 m/s), increase of gas velocity leads to strong self-pulsation. Due to the increase of gas velocity, gas phase momentum becomes stronger and disturbs liquid phase more easily. From Fig. 6, spray periodicity can be observed. 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 periodicity 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 even if gas velocity is changed.

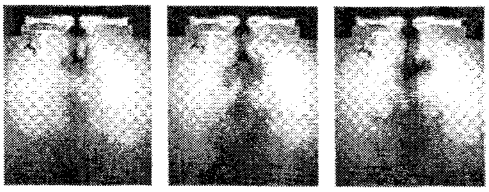

Fig. 6 Wavelength of spray oscillation with gas velocity

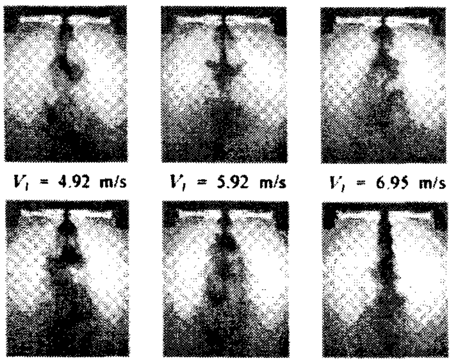

Fig. 7 Spray patterns with liquid velocity

Spray patterns according to liquid velocity is shown in Fig. 7. At fixed gas velocity(166.64 m/s), increase of liquid velocity suppresses the self-pulsation. The self-pulsation phenomena occur at low liquid velocity condition, but when liquid velocity becomes 10.20 m/s, self-pulsation does not occur. Liquid phase momentum increases with liquid velocity, so liquid phase can resist the disturbances of gas phase. Increased liquid phase momentum suppresses self-pulsation. From Fig. 8, periodic spray oscillation is observed. The wavelength of spray oscillation by self-pulsation becomes shorter as liquid velocity increases. Frequency which is inversely proportional to wavelength increases qualitatively.

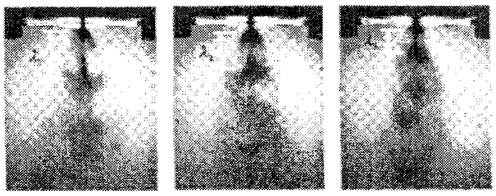

Fig. 8 Wavelength of spray oscillation with liquid velocity

It is known that recess augments mixing efficiency and stabilizes flame but enhances the self-pulsation phenomena[7]. Spray patterns are captured according to recess length and gap size in Fig. 9 and Fig. 10, respectively. 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. At the same operating conditions, self-pulsation is suppressed as gap size increases. When gap size is small, self-pulsation is observed, but when gap size is 2.0 mm, self-pulsation phenomena disappear. In the case of narrow gap size, gas phase which passes through the narrow area is blocked by liquid phase, so interaction becomes more severe. But increase of gap size provides wider area for gas phase to pass through and interaction between liquid and gas phase is decreased. This reduced interaction prevents self-pulsation phenomena.

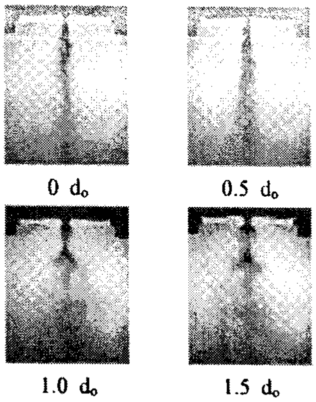

Fig. 9 Spray patterns with recess length

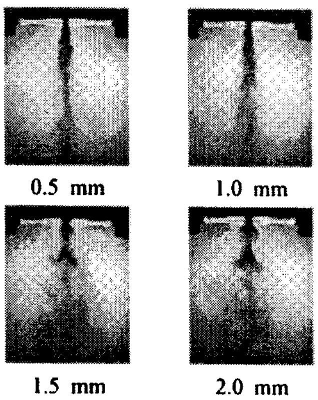

Fig. 10 Spray patterns with gap size

4. 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 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 effect of acoustic field by self-pulsation correctly, acoustic tests are performed using PULSE System(B&K Corp., 3560C Type).Acoustic characteristics according to gas velocity are shown in Fig. 11. Liquid velocity is fixed at 5.92 m/s. When self-pulsation occurs, a sharp and narrow increase of sound pressure level is detected. Performing acoustic tests, the onset of self-pulsation can be determined with shadow photography technique. Sound pressure level increases according to gas velocity. This means that self-pulsation becomes more severe and results from the acoustic tests are the same as those from spray patterns. And at all gas velocity cases, characteristic acoustic frequencies are constant around 2.5 kHz.

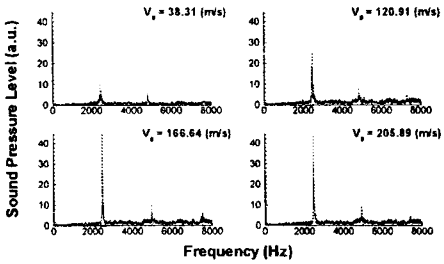

Fig. 11 Frequency spectrum with gas velocity

Fig. 12 shows frequency spectrum according to liquidvelocity at constant gas velocity, 166.64 m/s. As liquid velocity increases, sound pressure level increases, but further increase of liquid velocity reduces sound pressure level. As mentioned before, due to increase of liquid phase momentum, liquid phase can resist the disturbances of annular gas and self-pulsation is weakened. Characteristic acoustic frequency increases with liquid velocity. At low liquid velocity, characteristic acoustic frequency is 2.2 kHz, but at liquid velocity 10.20 m/s, characteristic acoustic frequency shifts to high frequency, 3.9 kHz. Frequency range with liquid velocity is from 2 kHz to 4 kHz, which corresponds to frequency range of 1T mode in combustion instability. 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 is needed in future.

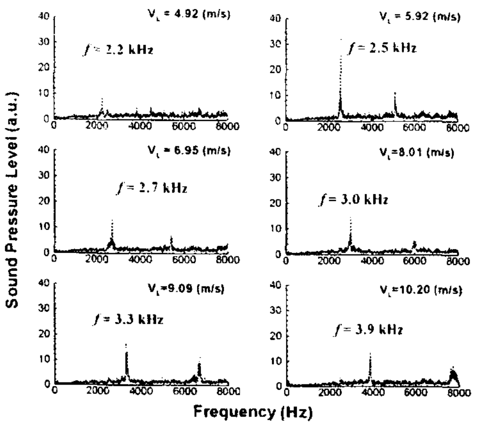

Fig. 12 Frequency spectrum with liquid velocity

Frequency spectrum according to recess length at constant injection condition is shown in Fig. 13. Sound pressure level increased abruptly with increase of recess length and self-pulsation becomes stronger. This tendency is confirmed by spray patterns. At constant injection condition, characteristic acoustic frequency is not changed with recess length. Fig. 13 is the result at liquid velocity 10.20 m/s and frequency is the same as that of Fig. 12 at V_l=10.20 m/s. From Fig. 11, 12 and 13, it seems that characteristic acoustic frequency is only dependent on liquid velocity.

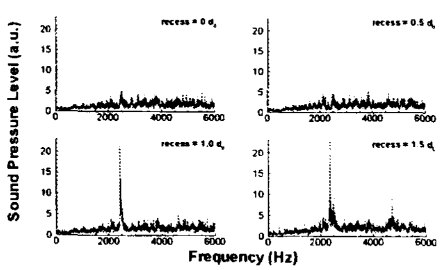

Fig. 13 Frequency spectrum with recess length

5. Periodicity of Spray Oscillation

A strong spray and flow rate oscillation can be observed in instantaneous images when self-pulsation phenomena happen. As mentioned before, we can estimate frequency of spray oscillation qualitatively and tendencies of spray oscillation according to injection conditions are similar to those of acoustic characteristics. So, correlation between spray and acoustic frequency may exist. If fuel and oxidizer is injected periodically, this leads to periodic heat release by combustion and there can be periodicity in pressure field. Therefore, if pressure oscillation by self-pulsation matches with pressure oscillation of combustion instability, strong spray oscillation can enhance the combustion instability. Self-pulsation spray has dense and sparse part 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 measured quantitatively.

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.

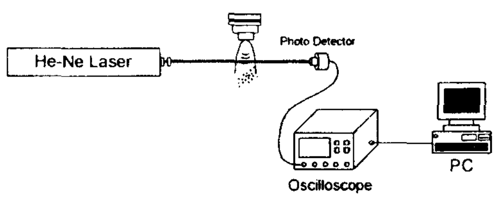

Fig. 14 Experimental setup

Figure 15 shows that frequency spectrum according to gas velocity at constant liquid velocity, 5.92 m/s. There are lots of noises at low gas velocity but as gas velocity increases, noise becomes small. At constant liquid velocity, spray frequency is almost the same at 2.5 kHz. This value is exactly the same in acoustic tests.

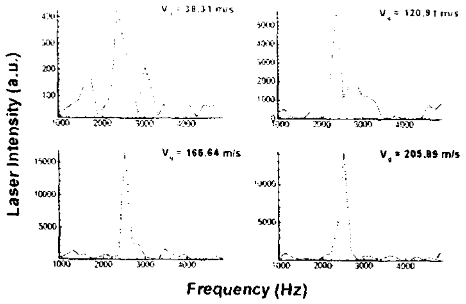

Fig. 15 Frequency spectrum with gas velocity

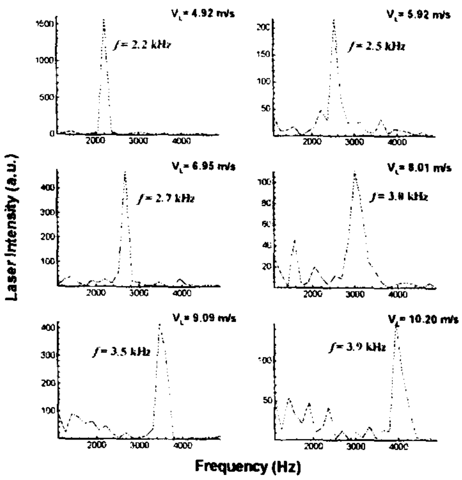

Fig. 16 Frequency spectrum with liquid velocity

Frequency spectrum according to liquid velocity is shown in Fig. 16 at constant gas velocity, 166.64 m/s. Spray frequency of self-pulsation increases with liquid velocity. Frequency is 2.2 kHz at 4.92 m/s and 3.9 kHz at 10.20 m/s. The values of frequency at each condition are the same in acoustic tests. From Fig. 15 & 16, we can conclude that frequency of spray oscillation is only dependent on liquid velocity like acoustic tests. So, from acoustic tests, not only frequency of scream can be measured but also frequency of spray oscillation can be found. Not only scream has frequency range of 2-4 kHz, but also spray oscillates at frequency range of 2-4 kHz. It is the same range of 1T mode of combustion instability. If spray is injected at frequency range of 2-4 kHz, heat release will oscillate at the same frequency range. If this heat release oscillation induces pressure oscillation in combustion chamber in liquid rocket engines, combustion instability can be enhanced by self-pulsation. Therefore, self-pulsation can provide harmful disturbances to combustion instability in acoustic aspects and also flow rate oscillation can be connected to combustion instability.

Peak frequency variation according to liquid and gas velocity get from acoustic tests and spray oscillation is shown Fig. 17 and 18. Acoustic and spray frequency are matched with each other. And Fig. 17 and 18 shows that frequency is only dependent on liquid velocity and by performing only either one of the tests the other results can be expected.

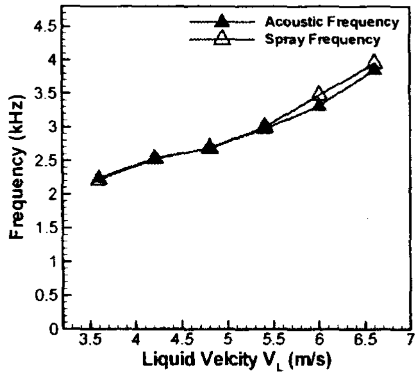

Fig. 17 Peak frequency variation with gas velocity

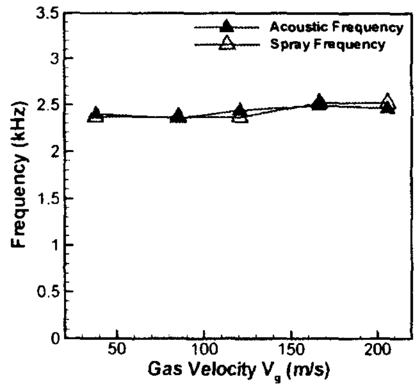

Fig. 18 Peak frequency variation with liquid velocity

6. 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, 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.

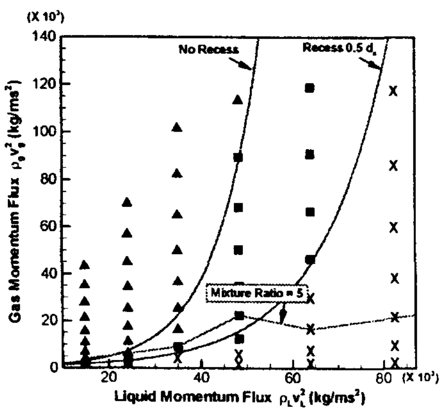

Fig. 19 Self-pulsation boundary with injection and recess length

From the results of shadow photography and acoustic tests, the onset of self-pulsation according to liquid and gas momentum is plotted in Fig. 19. 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 delta shape symbol(▲) indicates the start of self-pulsation from the case without recess, the square shape symbol(■) from recess = $0.5d_0$. And (×) symbol represents that self-pulsation does not occur in the experiment with current injector geometries. If 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(mixture ratio, 5) coincides with self-pulsation region. To avoid these unwanted unstable phenomena, study of self-pulsation is necessary.

7. Conclusions

First of all, spray patterns of self-pulsation in 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. Also, self-pulsation is suppressed as gap size increases due to reduced interaction between liquid and gas phase. From the shadow photography technique, spray images are analyzed and the onset of self-pulsation is determined. From the results, self-pulsation boundary is get. Liquid phase momentum suppresses the self-pulsation and as recess length increases, self-pulsation boundary shifts to the right.

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 only on liquid velocity. Also, frequency of spray periodicity 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.

Acknowledgments

This study was supported by National Research Laboratory program (M1-0104-00-0058). The authors wish to acknowledge this financial support.

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