Experimental Studies on Self-Oscillation of a Swirl Coaxial Injector

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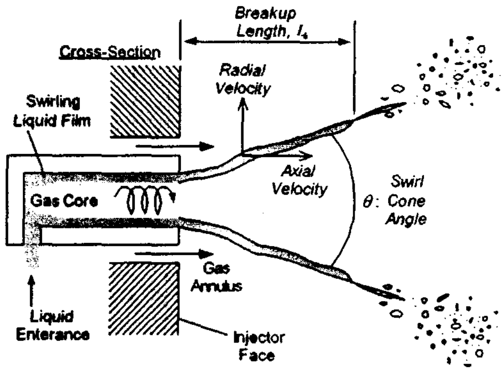
Abstract

The spray and acoustic characteristics by the self-oscillation of a swirl coaxial injector were experimentally studied. The self-oscillation of a swirl coaxial injector is defined as pressure and flowrate oscillations by a time-delayed feedback between liquid and gas phase and has strong influences on atomization and mixing processes. Hence the occurrence and effect of the self-oscillation are measured using shadow photography technique, acoustic test and PDPA. The occurrence of self-oscillation largely depends on the injection conditions, such as pressure drop of liquid phase and relative momentum ratio. From the experimental results, self-oscillation occurs when the momentum of gas phase is enough large and the smaller the pressure drop of liquid phase is, the better self-oscillation occurs at the same momentum ratio. The self-oscillation is also affected by injector geometries, increasing the recess length results in the expansion of self-oscillation region and the increase of sound pressure level. The self-oscillation of a swirl coaxial injector accompanies a high intensity scream and this scream may provide harmful disturbances to combustion processes. Self-oscillation leads to strong changes in the drop size distribution and smoothly varies the slope of radial SMD distribution.

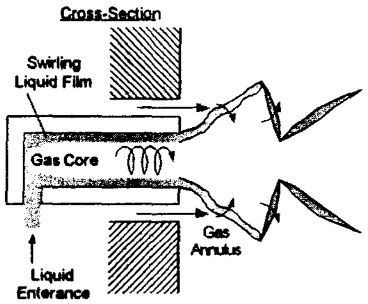
Introduction

Coaxial injectors are widely used in liquid rocket engines, even though both design and manufacturing processes are more difficult than any other injector 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 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 injected with specific spray angle, which corresponds to the ratio of axial and circumferential velocity as shown in Fig. 1(a). 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-oscillation by a time-delayed feedback between liquid and gas phases tends to occur with painful scream as shown in Fig. 1(b).



(a) Breakup mechanism of swirl coaxial injector



(b) Schematics of self-oscillation

Fig. 1. Spray patterns of a swirl coaxial injector

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-oscillations in gas-liquid coaxial injectors were first discovered in the mid-1970s for LOX/hydrogen systems when tested under reduced rating conditions.[2] Bazarov[3] 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-oscillation 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 propellant.

Zhou et al.[4] experimental and theoretically studied the flowrate and acoustics characteristics of gas-liquid swirl coaxial injectors and concluded that increasing the recess ratio of injector obviously reduced the screaming zone and the acoustic radiation pressure of scream.

Experimental

The swirl coaxial injectors used in the experiments consist of three parts as shown in Fig. 1: an inner oxidizer injector, an outer fuel injector and a casing. Four cases of LOX post recess from 0 to $1.5d_0$ were used to study the effect of the recess length on the self-oscillation of a swirl coaxial injector. For all cases, the inner and outer orifice diameter of an oxidizer injector was each 2.5mm and 4mm. The inner orifice diameter of a fuel injector was 7mm. The annular gap width, through which gas N_2 was discharged, was 1.5mm and is larger than conventional size, such as SSME.

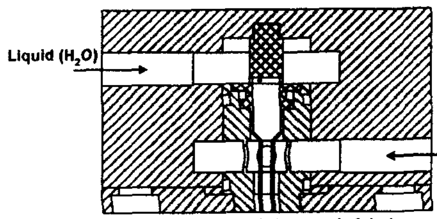


Fig. 2. Schematics of a swirl coaxial injector

Shadow photography technique was used to grasp spray patterns of swirl coaxial injectors. Water and gas N_2 were used as the simulants of LOX and fuel of gas phase listed in Table 1. The flowrate of water was 12.2 to 26.9g/s, which corresponds to the injection pressure range of 0.1 to 0.5MPa as shown in Fig. 3. The flowrate of gas N_2 was 2.7 to 8.1g/s and controlled using mass flow controller (Brooks Co.). A swirl coaxial injector was mounted on a test rig and water was injected vertically downstream into atmospheric environment.

SMD of the droplets was measured with PDPA(Phase Doppler Particle Analyzer). As a light source, an Ar-ion laser (514nm, SpectraPhysics) was utilized. The frequency of a laser beam was modulated 40 mm with Brag Cell. The scattered signal from droplets was detected by a receiver at 30-deg-off axis for forward scattering mode. The number of samples at each location was set to be typically 10,000, except for the center and peripheral region of cone spray where data rate drops abruptly. It has been known that measurement with a phase Doppler particle analyzer is very sensitive to user-controlled settings, particularly photomultiplier tube (PMT) voltage and laser power. So, the authors had maintained the consistency in the settings in the test and controlled laser power to avoid saturation of PMT at all measuring locations.

Mechanical patternator was used to measure mass distribution of swirl coaxial injectors. It consists of four primary modules such as pressurization, pressure regulation of simulants, collection cells and measuring devices of mass cylinders. Spray is collected through flat 180(15X 12) lattice cells the side length of which are 10mm uniformly in lows and columns. 180 transparent rubber tubes are connected with the lattice cells and measuring devices respectively.

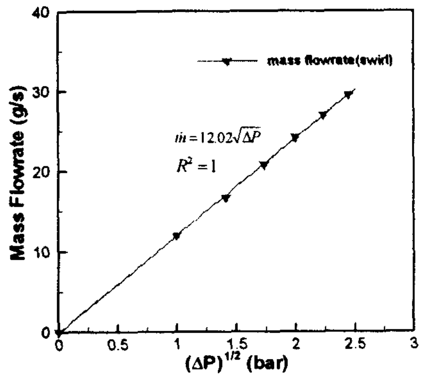


Fig. 3. Mass flow rate of liquid oxidizer

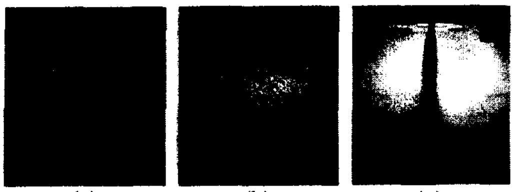
Table 1. Experimental conditions

	Oxidizer	Fuel
Simulant	Water	Gas N2
Pressure drop	0.1 – 0.5MPa	0.6 – 1.6 MPa
Mass flowrate	12.2 – 26.9g/s	2.7 – 8.1g/s
Momentum ratio	0.1, 0.5, 1.0, 1.9, 2.9	

Results and Discussion

Spray Patterns with Self-Oscillation

The breakup mechanism of a swirl coaxial spray is divided into two aspects: the breakup of swirling liquid itself and the atomization assisted by the gas flow of high velocity. First, the breakup of a swirling liquid proceeds with the thinning of the liquid film, the initial formation of the perforation in the liquid sheet, fragment into circular ligament and the breakup into fine drops. Second, high momentum gas flow has alternative effects on the atomization of a swirl coaxial spray. The gas flow of high velocity directly strikes on the liquid sheet and thus strips the droplets from it or disturbs it. On the other hand, pressing the liquid sheet into the center can make negative effects on atomization, such as collision and coalescence between the droplets.



(a) (b) (c)

Fig. 4. Spray Patterns according to Momentum Ratio (a) Without gas (b) Low momentum ratio (J = 0.1) (c) High momentum ratio (J = 1.9)

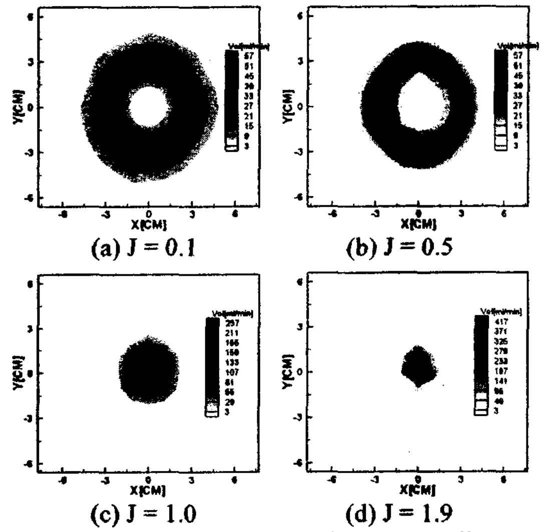


Fig. 5. Swirling liquid distributions perpendicular to injected direction

Figure 4 shows the spray patterns of a swirl coaxial injector according to the momentum ratio by shadow photography technique. It is known that the characteristics of a coaxial spray is determined by the momentum ratio between liquid and gas phase, because the atomization of a coaxial spray is not due to the instability of liquid itself, but mainly to the transfer of kinetic energy by gas flow. A swirling spray without gas flow is a hollow-cone shape as shown in Fig. 4(a) and the breakup of liquid sheet is accelerated by annular gas flow as shown in Fig. 4(b). But in the case of low momentum ratio, a swirl coaxial spray still remains in a hollow-cone shape. As the momentum ratio increases as shown in Fig. 4(c), the spray width becomes narrow and thus spray distribution perpendicular to the injected direction varies into a solid-cone shape like a shear coaxial spray. These tendencies of spray shapes with the momentum ratio are reconfirmed in Fig. 5, in which spray distributions measured by a mechanical patternator are represented.

Spray patterns of swirl coaxial injector according to the momentum ratio and the pressure drop of liquid phase are shown in Fig. 6 and Fig. 7. Figure 6 is the case without recess and Fig. 7 is the case with recess length of $1.0d_0$. At the low pressure drop of liquid phase and high momentum ratio, periodic spray distributions, which are the results of self-oscillation, are observed. Therefore, it can be determined whether self-oscillation occurs or not from the figures. These unwanted oscillations of spray distribution can cause unstable combustion with time and harmful pressure oscillation in the combustion chamber. In the case of self-oscillation, however, spray width becomes wide and spatial spray distributions perpendicular to the injected direction are even compared with the case of no self-oscillation. Consequently, it can be said that the spray distribution by self-oscillation has both positive and negative effects.

According to the Fig. 6, the case without recess, it can be inferred that self-oscillation depends on the injection conditions, such as pressure drop of liquid phase and relative momentum ratio. As mentioned above, self-oscillation is defined as the pressure and flowrate oscillation by a time-delayed feedback between liquid and gas phase, and occurs when the momentum of gas phase is enough large. Though the periodicity of spray by self-oscillation is observed in the case of ΔP_L = 0.1MPa and J > 0.5, not in the case of ΔP_L = 0.3MPa. As increasing the pressure drop of liquid phase, the flowrate and velocity increase and thus swirling liquid sheet is disturbed less due to the large momentum or inertia.

Figure 7 shows the spray patterns of swirl coaxial injectors with recess length of $1.0d_0$. The gas flow is confined in the recess region by both the expansion of liquid sheet and outer injector wall, therefore the pressure and flowrate oscillations in the liquid and gas feed lines may become severe. These tendencies will become intensified when recess length increases, because interaction region between liquid and gas phase is closer to the propellants feed lines. When the pressure drop of liquid phase is ΔP_L = 0.1MPa, the periodic oscillations were detected even though very low momentum ratio(J > 0.1). When the pressure drop of liquid phase is ΔP_L = 0.3MPa, however, the onset of self-oscillation occurs at the J = 0.5. Similar to the case without recess, the smaller the pressure drop of liquid phase is, the earlier self-oscillation occurs at the same momentum ratio.

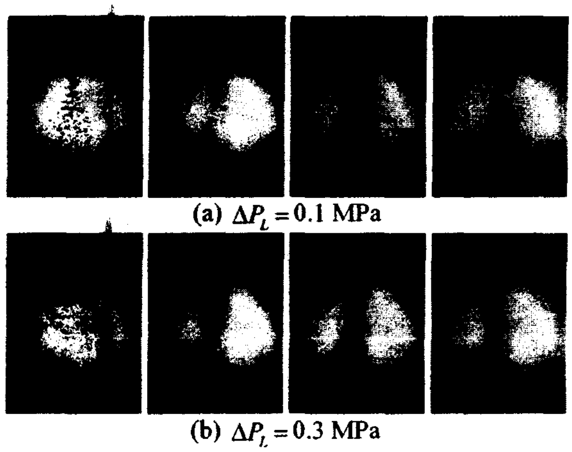
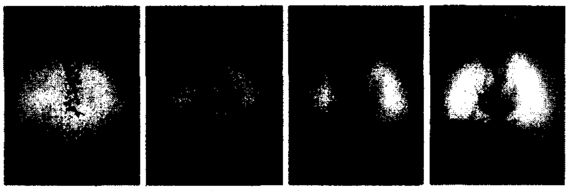
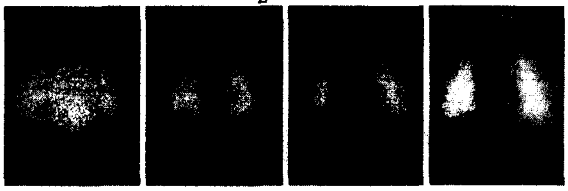


Fig. 6. Spray patterns without recess



(a) $\Delta P_L = 0.1$ MPa



(b) $\Delta P_L = 0.3$ MPa

Fig. 7. Spray patterns with recess length = $1.0d_0$

Acoustic Characteristics

In general, the self-oscillation of a swirl coaxial injector accompanies high intensity scream. According to the results of Bazarov[3], the sound intensity in the test chamber with opened windows was close to the painful level around 132dB.

For acoustic tests, a PULSE system(3560C type, B&K) was used. It has two generator modules, four input modules and two output modules.

Frequency spectrum of the scream with injection conditions is given in Fig. 8. The pressure drop of liquid phase is fixed at 0.2MPa and momentum ratio increases in turns from above raising the pressure drop of gas phase. As shown in Fig. 8, the onset of self-oscillation can be determined by acoustics tests together with shadow photography technology. It is found that self-oscillation, with a sharp and narrow increase of sound pressure level, starts from J = 1.0 and its frequency is measured around 2.3kHz in all cases. It is necessary to remark that the self-pulsation sound pressure level of J = 1.0 is higher than that of J = 1.9 or J = 2.9. The sufficient momentum of gas phase is needed for the oscillation, but further increase of the momentum of gas phase, on the contrary, has an effect of damping the oscillation. Zhou et al.[4] also indicated that further increasing the pressure drop of gas phase, the scream may disappear or transfer from one frequency to another.

Figure 9 shows the frequency spectrum measured by acoustics tests with variations of recess length. In all cases, the pressure drop of liquid phase is 0.2MPa and momentum ratio is 0.5. Although self-oscillation was not observed in the case without recess as shown in Fig. 8, a sharp peak around 2.3kHz is measured in all cases with recess at this injection condition. Also, the increases of recess lengths lead to a rapid increase of the self-pulsation sound pressure level and thus the sound pressure level of recess = $1.5d_0$ is more than that of recess = $0.5d_0$ by 5 times. As the sound pressure level gets higher with the increase of recess length, a frequency peak of harmonic mode around 4.6kHz takes place. Consequently, as the recess length increases, the onset of self-oscillation occurs at low momentum ratio and sound pressure level by it increases. The total sound pressure level of recess = $1.5d_0$ was about 124.8dB.

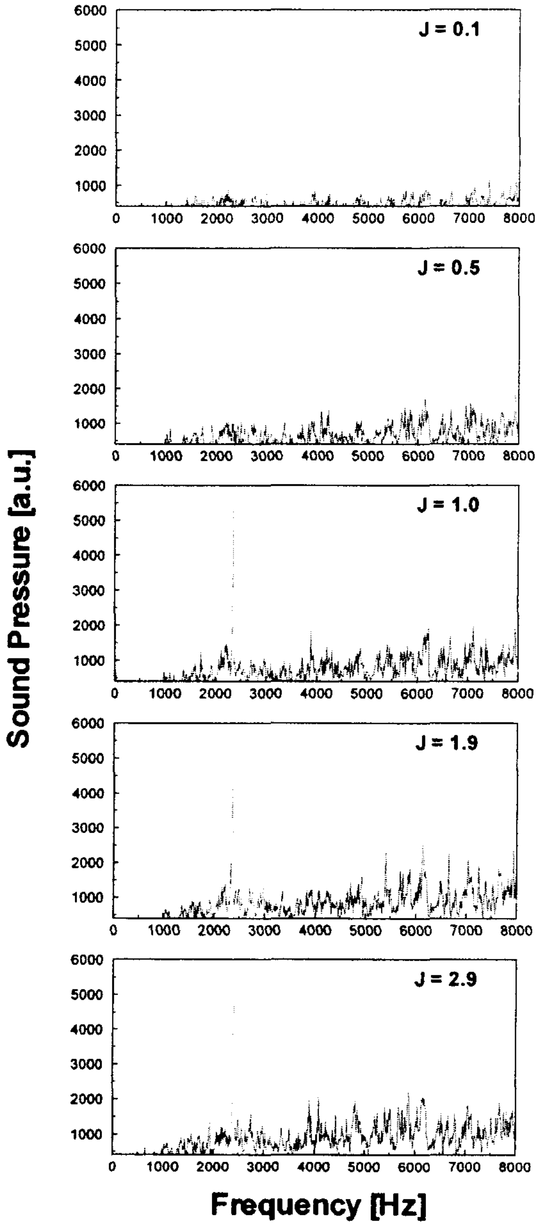


Fig. 8. Frequency spectrum with injection conditions at $\Delta P_L = 0.2$MPa

Typically, the first tangential (1T) mode, whose frequency is in the range of 2 – 4kHz, was the troublesome oscillation in the combustion instability of liquid rocket engines.[5] Thereby this scream around 2.3kHz by self-oscillation may provide harmful disturbances to combustion processes. Huang et al.[6] also concluded that the mechanism to drive the injector self-oscillation is related to some combustion instability observed in a lot of prior fire tests on liquid rocket engines. While Bazarov[3] concluded that acoustic characteristics by self-oscillation can't directly affect the combustion instability, because the frequency around 5.5kHz by self-oscillation is far from the combustion chamber acoustic characteristics. Therefore, a more systematic studies will be needed on the relation between self-oscillation phenomenon and combustion instability.

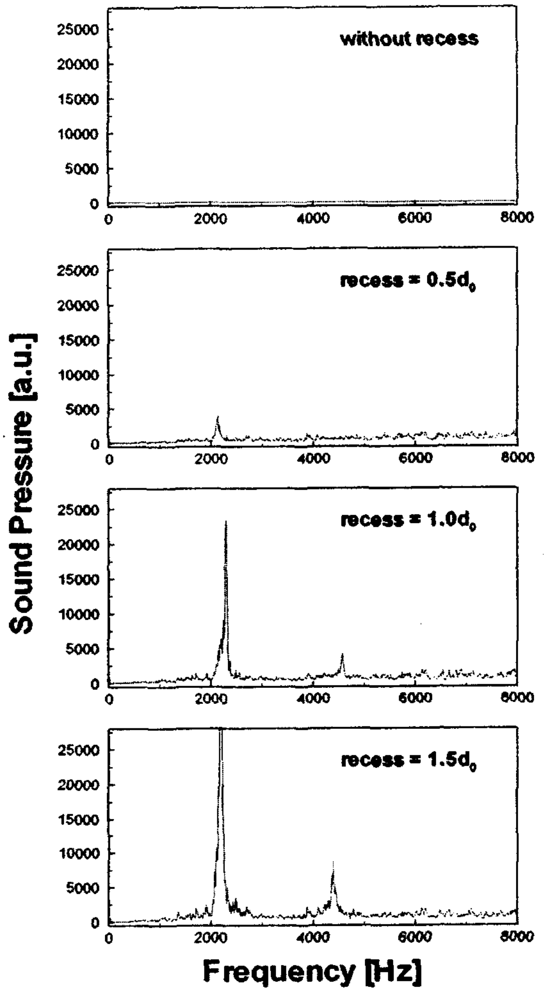


Fig. 9. Frequency spectrum with recess lengths

Self-Oscillation Boundary

As looking into previous sections, the occurrence of self-oscillation depends on the injection conditions and injector geometries. Injection conditions affecting self-oscillation include the pressure drop and velocity of liquid and gas phases, mass flowrate, relative momentum ratio, properties of test fluids, ambient pressure, and so on. In this study, the pressure drop of liquid phase and relative momentum ratio are considered, the former corresponds to the inertial element against the oscillation and the latter disturbing and damping element. While injector geometries affecting self-oscillation include recess length, annular gap width, 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-oscillation according to ΔP_L and J is plotted in Fig. 10. The increase of recess length quickens the occurrence of self-oscillation at the same injection condition, so that each region is classified by symbols and lines. The circle shape symbol(●) indicates the start of self-oscillation from the case without recess, the square shape symbol(■) from recess = 0.5d$_0$, delta shape symbol(▲) from recess = 1.0d$_0$ and diamond shape symbol(◆) from recess = 1.5d$_0$. And × symbol represent that self-oscillation do not occur in the experiment with current injector geometries. If the pressure drop of liquid phase increases to some extent, the momentum of liquid phase is enough to resist against the disturbances of gas flow so that self-oscillation disappears. As the recess length increases, self-pulsation boundary sifts to the right.

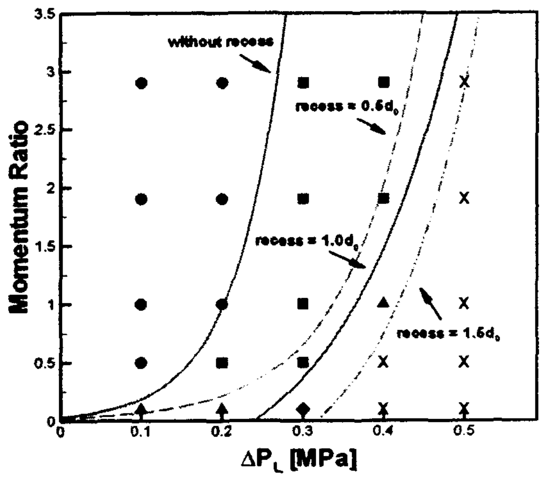


Fig. 10. Self-oscillation boundary with injection conditions for various recess lengths

Atomization Characteristics

Self-oscillation induces the pressure and flowrate oscillations in the liquid and gas feed lines. Although unstable combustion can happen and it is difficult to predict the combustion performance due to the unwanted oscillation and the periodic spray distribution, self-oscillation dose not always have negative influences if high amplitude combustion pressure oscillations are not happened. The wider spray width and uniform spray distribution in radial direction are positive influences like Fig. 6 and Fig. 7. To examine the effect of self-oscillation on the atomization characteristics, mean drop size was measured with injection conditions and injector geometries.

Figure 11 shows the SMD distributions with the pressure drop of liquid phase and it is the case without recess and of J = 1.0. The SMD distribution of a swirl coaxial spray with annular gas flow features the shape having maximum in the centerline, which is similar to a shear coaxial spray. Self-oscillation leads to strong changes in the drop size distribution and two distinct tendencies of SMD profile are observed. At J = 1.0, self-oscillation occurs till ΔP_L = 0.3MPa and disappears from ΔP_L = 0.4MPa. The mean drop size with self-oscillation is smaller around the centerline but larger around the outer edge than that without self-oscillation. Therefore, self-oscillation influences on the atomization characteristics and smoothly varies the slope of radial SMD distribution.

Figure 12 shows the SMD distributions with the variation of recess length at the injection conditions of ΔP_L = 0.3MPa and J = 1.0. In this injection condition, the occurrence of self-oscillation starts from recess = $0.5d_0$ according to Fig. 10. Self-oscillation by recess makes little change of drop size in the centerline, but widens the width of atomized spray.

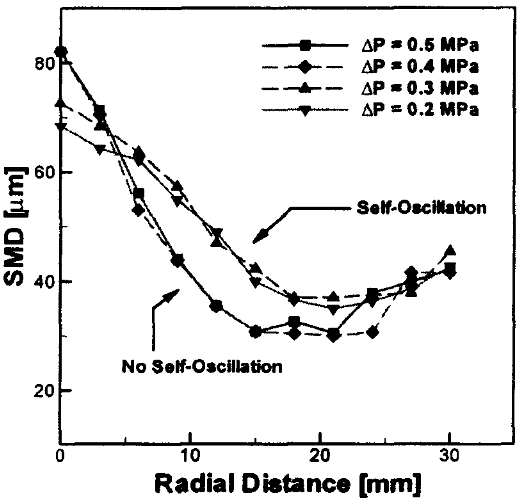


Fig. 11. Mean drop size with injection conditions

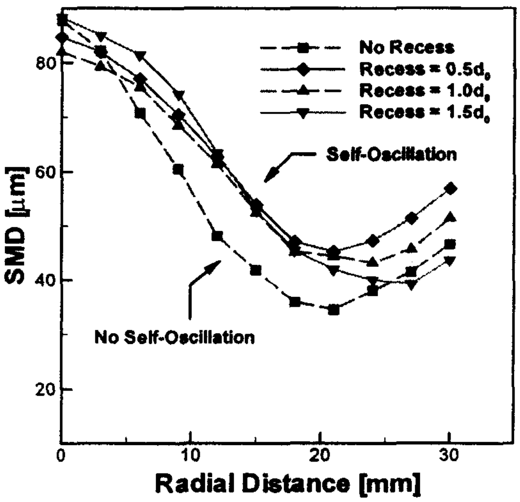


Fig. 12. Mean drop size with recess lengths

Conclusion

During the experiments of spray characteristics of a swirl coaxial injector, self-oscillation by the interaction between liquid and gas phase occurred with a strong pressure and flowrate oscillation. It is found that the occurrence of self-oscillation varied with injection conditions and injector geometries, so that detailed measurements using shadow photography technique, acoustic test and PDPA were performed. From the experimental results, the following conclusions can be drawn;

1. The smaller the pressure drop of liquid phase is, the better self-oscillation occurs at the same momentum ratio, because the reduced momentum of liquid phase is too small to resist the momentum of gas phase.
2. Self-oscillation occurs when the momentum of gas phase is enough large, but further increase of it lowers the sound pressure level of scream.
3. As the recess length increases, the onset of self-oscillation occurs at lower momentum ratio and sound pressure level by it increases. Because liquid and gas phases interact in a confined region, the pressure and flowrate oscillations may become severe.
4. In the case of self-oscillation, spray width becomes wider and radial spray distributions are even compared with the case of no self-oscillation.
5. The self-oscillation of a swirl coaxial injector accompanies a high intensity scream and its frequency is measured about 2.3kHz. This scream by self-oscillation may provide harmful disturbances to combustion processes.
6. Self-oscillation leads to strong changes in the drop size distribution and smoothly varies the slope of radial SMD distribution.

References

1) Bayvel, L. and Orzechowski, Z.: Liquid Atomization, *Taylor & Francis*, 1993.
2) Bazarov, V. and Lul'ka, L.A.: Self-Pulsation of Liquid Flow in Coaxial Air Stream, *Soviet Aeronautics*, Vol. 3, Pergamon, New York, 1978, pp. 14-18.
3) Bazarov, V.: Self-Pulsations in Coaxial Injectors with Central Swirl Liquid Stage, *AIAA 95-2358*, 1995.
4) Zhou, J., Hu, X., Huang, Y. and Wang, Z.: Flowrate and Acoustics characteristics of Coaxial Swirling Injector of Hydrogen/Oxygen Rocket Engine, *AIAA 96-3135*, 1996.
5) Culick, F. and Yang, V.: Overview of Combustion Instabilities in Liquid-Propellant Rocket Engines, *Progress in Astronautics and Aeronautics*, Volume 169, Chap. 1, 1995.
6) Huang, Y., Zhou, J., Hu, X. and Wang, Z.: Acoustic Model for the Self-Oscillation of Coaxial Swirl Injector, *AIAA 95-2358*, 1997.