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Experimental Study of Acoustic Damping Induced by Gas-Liquid Scheme Injectors in a Combustion Chamber

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In a liquid rocket engine, acoustic damping induced by gas-liquid scheme injectors is studied experimentally for combustion stability by adopting linear acoustic test. In the previous work, it has been found that gas-liquid scheme injector can play a significant role in acoustic damping or absorption when it is tuned finely. Based on this finding, acoustic-damping characteristics of multi-injectors are intensively investigated. From the experimental data, it is found that acoustic oscillations are almost damped out by multi-injectors when they have the tuning length proposed in the previous study. The length corresponds to a half wavelength of the first longitudinal overtone mode traveling inside the injector with the acoustic frequency intended for damping in the chamber. But, new injector-coupled acoustic modes show up in the chamber with the injectors of the tuning length although the target mode is nearly damped out. And, appreciable frequency shift is always observed except for the case of the worst tuned injector. Accordingly, it is proposed that the tuning length is adjusted to have the shorter length than a half wavelength when these phenomena are considered.

Key Words : Acoustic Damping, Gas-Liquid Scheme Injector, Combustion Stability, Linear Acoustic Test, Injector-Coupled Acoustic Mode

1. Introduction

Acoustic instability or high-frequency combustion instability is the phenomenon of amplification of pressure oscillations through in-phase heat addition/extraction from combustion (Harrje and Reardon, 1972). It can lead to undesired intense pressure fluctuations as well as excessive heat transfer to the combustor wall in combustion systems such as solid and liquid propellant rocket engines, ramjets, turbojet thrust augmentors, utility boilers, and furnaces (McManus et al., 1993). Accordingly, it has long gained significant interest in propulsion and power systems. Although it has caused common problems in these combustors, it has been reported that it occurs most severely in liquid rocket engines due to their high energy density. Thermal damage on injector faceplate and combustor wall, severe mechanical vibration of rocket body, and unpredictable malfunction of engines, etc. are usual problems caused by acoustic instability. To understand this phenomenon, there have been conducted lots of studies (Harrje and Reardon, 1972 ; Culick and Yang, 1995 ; Oefelein and Yang, 1993 ; Ducruix et al., 2003), but it is still being pursued and there is still no definite or conclusive proof concerning its mechanism.

There have been widely adopted two methods in the control of acoustic instability, classified into passive and active controls (Culick and Yang, 1995 ; Laudien et al., 1995). Passive control is to attenuate or suppress acoustic oscillation using combustion stabilization devices such as baffles, acoustic resonators, and acoustic liners. For ex-

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ample, acoustic resonator can damp out or absorb pressure wave oscillating in the chamber using well-tuned cavity (Keller, 1974; Laudien et al., 1995). However, the devices are installed additionally and inevitably to suppress undesirable acoustic oscillations if they should be. And thus, engine-performance degradation and complexity in engine manufacture can be caused by the installation of these devices.

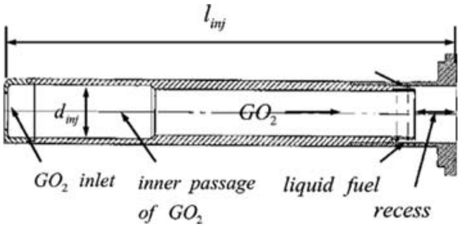
On the other hand, in liquid rocket engines, injectors are mounted necessarily to the faceplate for propellants injection. The previous work (Kim and Sohn, 2006) reported that the gas-liquid scheme injector could play a significant role in acoustic damping like acoustic resonators in addition to the original function of propellants injection. For this, acoustic behaviors in the chamber with a single injector were investigated experimentally by adopting linear acoustic test. From the experimental work, it has been found that the gas-liquid scheme injector should be designed as a half-wave resonator for maximum acoustic damping in addition to the original function of propellants injection. For simplicity, only a single injector was considered in the previous work and acoustic-tuning condition of the gas-liquid scheme injector was proposed. But, hundreds of injectors are practically mounted to the faceplate in the chamber and they may induce peculiar acoustic responses affecting the tuning condition.

In this regard, the present study is concentrated on acoustic-damping characteristics caused by multi-injectors. For this, acoustic behaviors in the chamber with multi-injectors are investigated experimentally by adopting linear acoustic test. The injector has the same type as one adopted in the previous work (Kim and Sohn, 2006) and acoustic damping of the 1st tangential (1T) mode is emphasized.

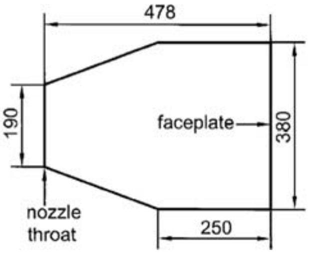
2. Experimental Methods

2.1 Combustion chamber and injector

The geometries of the injector and the sample chamber to be analyzed are shown in Fig. 1, which are the same as those adopted in the previous work (Kim and Sohn, 2006). The chamber domain ranges from the injector faceplate to nozzle throat including injector itself. The nozzle expansion part downstream of the throat is not considered since the part does not affect the acoustic field within the chamber. The sample chamber has the typical geometry of a liquid rocket combustion chamber. The diameters of the chamber and the nozzle throat, D_{ch} and D_{th}, are 380 and 190 mm, respectively. The lengths from the faceplate to nozzle entrance and the throat, L_e and L_{th}, are 250 and 478 mm, respectively and a half contraction angle in the conical section is 30°. Although the inner passage of the gas-liquid scheme injector can frequently have tapered or stepped shapes as shown in Fig. 1(a), the straight passage is assumed here for simplicity and clarity of acoustic investigation. Besides, it is assumed that the injector has no recess for the same purpose. Accordingly, it has completely cylindrical shape. Furthermore, injectors may generate and modify flow oscillations in them (Bazarov and Yang, 1998), but it is not considered here. The injector diameter, d_{inj} is variable within the range of 7 to 27 mm and the injector length, l_{inj} is adjustable for acoustic tuning in this study.



(a) Coaxial gas-liquid scheme injector



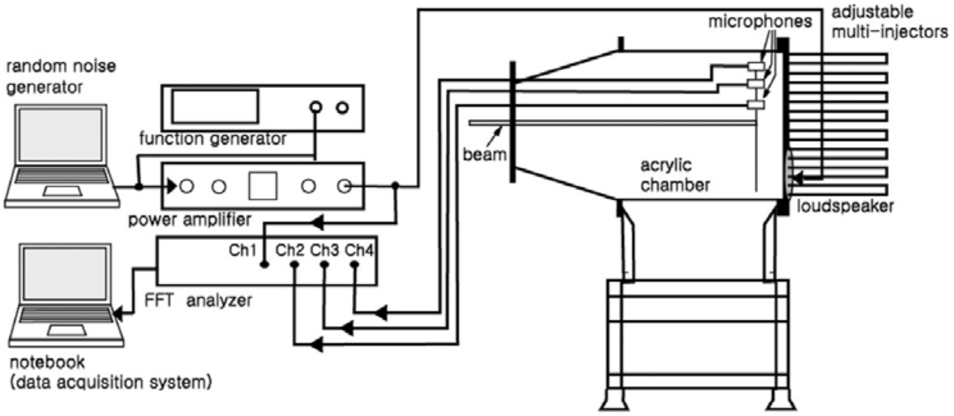
(b) Actual combustion chamber

Fig. 1 Schematic diagrams of the coaxial gas-liquid scheme injector and the actual combustion chamber (unit: mm)

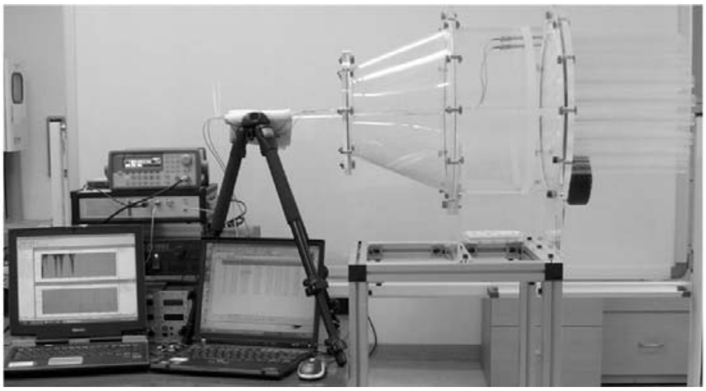
In this test, the chamber wall and the faceplate have the rigid wall made of acrylic material. Injector is also made of acrylic material. In the same manner as the previous work (Kim and Sohn, 2006), dry acoustic tests are conducted here for cold-volume condition without mean flow. That is, the medium is assumed to be a quiescent air of which density, ρ_{ch} and sound speed, c_{ch} are 1.2 kg/m^3 and 343 m/s at 20℃, respectively.

2.2 Acoustic-test apparatus and test procedures

Schematic diagram and photograph of the acoustic-test apparatus are shown in Fig. 2. The combustion chamber is installed in the horizontal position and operates at atmospheric pressure. The same test procedures as in the previous work (Kim and Sohn, 2006) are adopted here. For acoustic excitation, random-noise signal is generated by notebook computer, sent to amplifier, and finally sent to the loudspeaker. It is also sent to FFT (Fast Fourier Transform) spectrum analyzer through input-signal channel (Ch1). The loudspeaker imposes acoustic excitation into the chamber. The present test is linear acoustic test, i.e., the amplitude of acoustic pressure excited in the chamber is small and within a linear range. The acoustic-pressure signals or responses from the chamber are monitored by acoustic amplitude, which is measured by several microphones. The microphones are mounted by the horizontal beam and installed radially as shown in Fig. 2. The mounting beam can rotate and move longitudinally to measure the spatial distribution of the acoustic amplitude. The signals measured by the microphones are sent to the spectrum analyzer, through which FRF (Frequency Response Func-



(a) schematic diagram of test apparatus



(b) photograph of test apparatus

Fig. 2 Acoustic-test apparatus with multi-injectors

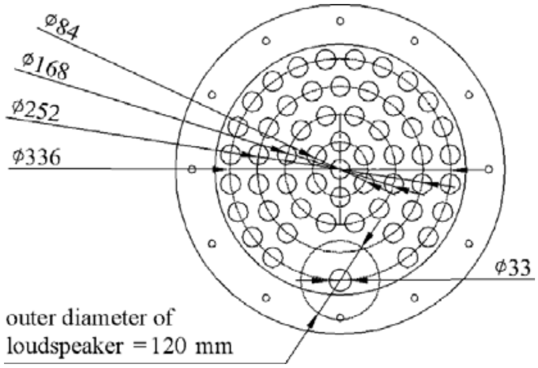


Fig. 3 Configuration of injectors mounted to the faceplate ($d_{inj}=27$ mm)

tion) is obtained. From FRF data, the acoustic resonance, the resonant frequencies, and the acoustic modes are identified. The details on the acoustic test can be found elsewhere (Laudien et al., 1995 ; Ko et al., 2004 ; Kim and Sohn, 2006).

First, the acoustic-pressure signals are measured in the chamber with one or two injectors, of which diameter varies from 7 to 20 mm. That is, they are measured in the chamber with the injectors as a function of the length of the injectors with several diameters in order to investigate the effect of injector diameter. Next, the chamber with 54 injectors is tested. Figure 3 shows the configuration of injectors mounted to the faceplate. To quantify the diameter and the number of injectors, the normalized parameter of open-area ratio, σ_A is introduced, which is defined as the ratio of open area, made by injectors, to faceplate area.

3. Results and Discussions

3.1 Review on injector's role as a half-wave resonator

The optimum length of the injector for maximum acoustic damping was derived as (Kim and Sohn, 2006)

$$l_{inj}=\frac{c_{inj}}{2f_0}-\Delta l \tag{1}$$

where l_{inj} and c_{inj} denote the injector length and sound speed of the fluid inside the injector, respectively, and Δl length or mass correction factor. This equation expresses theoretically the optimum length of the injector canceling the acoustic oscillation coming from the chamber with the frequency of f_0. From the previous work (Kim and Sohn, 2006), the injector, which Eq. (1) is true for, is called a half-wave resonator and it is known that 1T mode resonant at $f_{1T}=558$ Hz has the largest amplitude in the adopted chamber. Accordingly, it is intended to be damped by the injector tuning in the present study.

3.2 Acoustic damping induced by the injectors with several diameters

Three diameters, $d_{inj}=7$, 14, 20 mm are selected and their open-area ratios are 0.03, 0.14, and 0.28%, respectively. The acoustic-pressure responses were obtained in the chamber with each single injector and can be found in Fig. 11 of the previous work (Kim and Sohn, 2006). To quantify the damping capability of the injector, damping factors, η, (Laudien et al., 1995) were introduced and calculated as a function of injector length, l_{inj}. High damping factor indicates weak resonance. Irrespective of injector diameter, damping factor had the maximum near the injector length of 300 mm or so, which corresponds to a half wavelength, $(1/2)\lambda$ of the first longitudinal overtone mode traveling in the present injector with the frequency of 558 Hz. Accordingly, it was found that the present gas-liquid scheme injector could function as a half-wave resonator. With larger diameters of $d_{inj}=14$ and 20 mm, mode split was observed as reported in the previous work (Kim and Sohn, 2006) and thus, damping factors of upper and lower splitted modes were shown. It has been found that damping factor tends to increase with open-area ratio despite of the occurrence of mode split and large damping factors are maintained over the wide range of l_{inj} as open-area ratio increases.

In the present study, first, acoustic-pressure responses are obtained in the chamber with two injectors of $d_{inj}=14$ mm and a single injector of $d_{inj}=20$ mm to investigate effects of the number of injectors on damping capacity. They are mounted near the chamber wall at the opposite side to the loudspeaker. These two cases has the identical open-area ratio of 0.28%, but different injector diameter from each other. When the injector has the optimum length of 300 mm near $(1/2)\lambda$, the measured acoustic responses are shown in Fig. 4. Based on the acoustic responses, the damping factors are calculated as a function of l_{inj} and shown in Fig. 5. As predicted, mode split is observed in both cases, and lower and upper peaks are clearly demonstrated in Fig. 4. In case of two injectors of $d_{inj}=14$ mm, the amplitude of acoustic oscillation and the sharpness of the peaks are relatively lower than the case of a single injector of $d_{inj}=$ 20 mm. The sharpness or resonance is quantified by damping factor as aforementioned. Accordingly, we can predict that with open-area ratio fixed, multi-injectors with smaller diameter will damp out acoustic oscillation more effectively. This point is clarified in Fig. 5. As shown in the figure, two injectors of $d_{inj}=14$ mm damp out the acoustic oscillation more effectively in both aspects of damping factor and the width of damping range in injector length. That is, two injectors of $d_{inj}=14$ mm produce higher damping factor over the wider range of l_{inj} compared with a single injector of $d_{inj}=20$ mm.

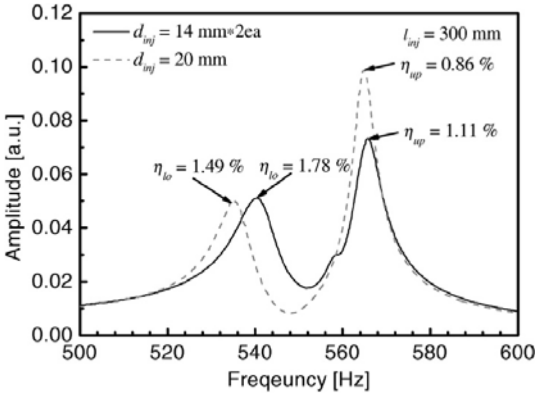


Fig. 4 Acoustic-pressure responses near f_{1T} in the chamber with two injectors of $d_{inj}=14$ mm and a single injector of $d_{inj}=20$ mm ($l_{inj}=$ 300 mm)

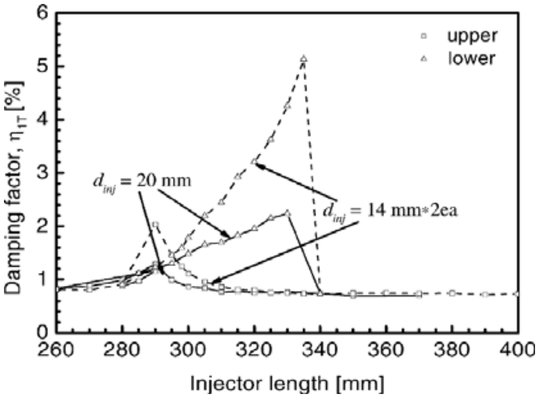


Fig. 5 Damping factors as a function of injector length in the chamber with two injectors of $d_{inj}=14$ mm and a single injector of $d_{inj}=20$ mm

Half-wave resonator has the same damping mechanism as that of quarter-wave resonator (Harrje and Reardon, 1972 ; Laudien et al., 1995) ; it can damp out or absorb acoustic oscillation through wave cancellation. That is, the incident acoustic wave from chamber into resonator is cancelled out by the out-of-phase acoustic wave generated inside the resonator. To enhance wave cancellation, high-amplitude pressure fluctuation should be generated inside the resonator (Park and Sohn, 2005a). As aforementioned, acoustic-damping capability of the injector becomes higher as its diameter increases. But, the increase in diameter is accompanied by the increase in peripheral surface area of the injector, which the wave contacts inside the injector. The acoustic energy of pressure fluctuation inside the injector is absorbed or dissipated at the peripheral surface of the injector. Accordingly, the increase in the surface area mitigates the pressure fluctuation generated inside the injector, leading to degradation of wave-cancellation effect. This indicates that the injector with doubled cross-sectional area does not have twice as much damping capability as two injectors with the base area have. To verify this point, with the aid of linear acoustic analysis (Park and Sohn, 2005a ; 2005b), damping factors are calculated and shown in Fig. 6 as a function of l_{inj} with two values of boundary absorption coefficient, β of 0.002 and 0.005. Injector diameter is set to be 14 mm. Higher β indicates more absorption or dissipation of acoustic energy at the injector wall. With mal-tuned injectors, of which length is far away from the optimum tuning length, damping factors are higher at higher β

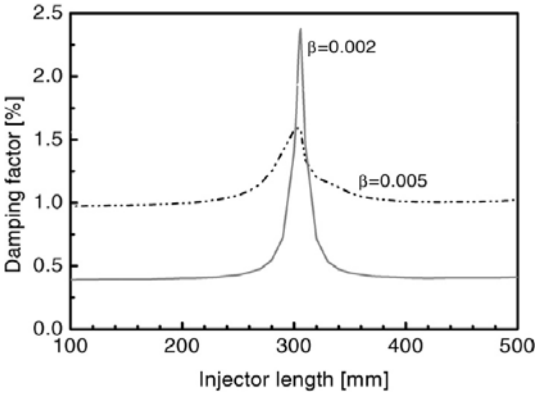


Fig. 6 Damping factors as a function of injector length with boundary absorption coefficients of 0.002 and 0.005 ($d_{inj}=14$ mm)

compared with the case at lower β. But, with the optimally tuned injector, damping factor is higher at lower β. This point verifies the results shown in Figs. 4 and 5.

Eventually, with respect to acoustic damping produced by half-wave resonator, a single injector with large diameter is less effective than numerous injectors with small diameter. This is the reason why two injectors of $d_{inj}=14$ mm have higher damping capability than a single injector of $d_{inj}=20$ mm although they have the identical open-area ratio of 0.28%.

3.3 Characteristics of acoustic damping induced by multi-injectors

Since actual rocket combustors usually have hundreds of injectors on its faceplate, acoustic damping induced by numerous injectors is investigated in the chamber with 51 injectors, of which diameter is 27 mm. Its open-area ratio amounts to 25.7%.

Acoustic-pressure responses are measured as a function of the excitation frequency with the variable l_{inj} and shown in Fig. 7. The injector length ranges from 0 to λ. As shown in this figure, both acoustic frequency and amplitude are varied appreciably depending on the length of the injectors. These characteristics are quite different from those of a single injector (Kim and Sohn, 2006). Acoustic response at $l_{inj}=302\text{ mm}=(1/2)\lambda$, i.e., a half wavelength, has three peaks at frequencies

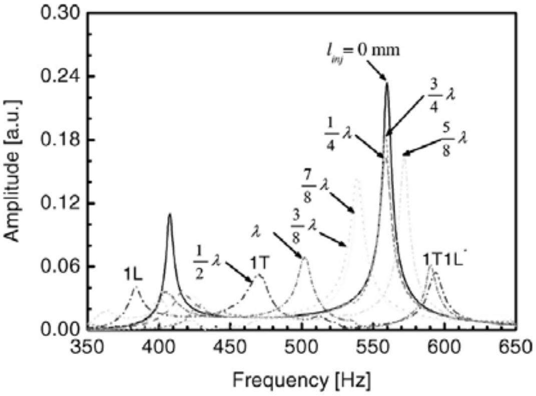
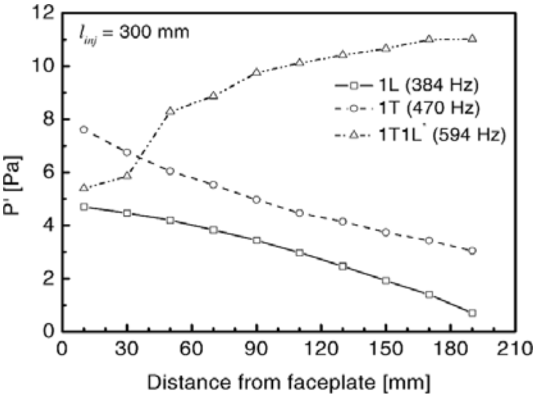


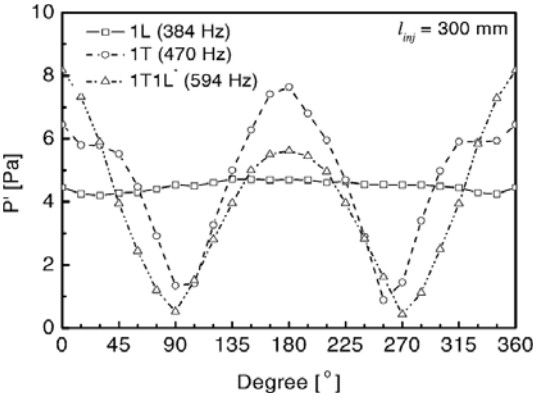
Fig. 7 Acoustic-pressure responses in chamber with multi-injectors

of 384, 470, and 594 Hz, of which amplitudes are appreciably small compared with ones at $l_{inj}=0$ mm. These acoustic responses indicate sufficient damping or absorption of acoustic waves and especially, complete damping-out of acoustic wave oscillating at $f=558$ Hz.

To identify three peaks resonant at the specific frequencies shown in Fig. 7, spatial distribution of acoustic fluctuation should be found. For this purpose, sinusoidal acoustic excitation with a specific frequency is generated by function generator and it is imposed into the chamber by the loudspeaker. The respective acoustic response to the sinusoidal excitation with 384, 470, and 594 Hz is plotted in Fig. 8. From the longitudinal and tangential distributions of each fluctuation, the first longitudinal (1L) and the first tangential (1T) modes can be easily identified based on the basic knowledge of acoustics (Zucrow and Hoffman, 1977). But, the third peak with 594 Hz shows up newly here and it has not been observed in the chamber with a single injector. In Fig. 8, the acoustic fluctuation resonant at 594 Hz shows quite peculiar behavior. From its tangential distribution, it has the character of 1T mode. And, its longitudinal distribution is close to a part of the combined mode of 1T and 1L in the full domain including the chamber and the injectors. That is, it is predicted that two pressure nodes are formed at the injector inlet and the nozzle throat. For this reason, as shown in Fig. 8(a), pressure-fluctuation amplitude continues to increase as it approaches the nozzle throat. This peculiar mode is distinct from the original 1T1L mode formed only in the chamber domain and here, it is denoted by 1T1L*, which is called injector-coupled 1T1L mode. From the spatial distribution of 1T1L* mode, we can find that the novel mode results from acoustic coupling between chamber and multi-injectors. The mode has never been observed in the chamber with a single injector. Strictly speaking, the coupling shows up more evidently as the open-area ratio increases. This is that the one end of injectors on the matching surface with the chamber tends to act as the interior volume rather than the interior boundary as σ_A increases. Accordingly, pressure node is not formed clearly any more at the end and clear distinction between chamber and injectors disappears at high σ_A.



(a) Longitudinal distribution of acoustic-fluctuation



(b) Tangential distribution of acoustic-fluctuation

Fig. 8 Spatial distributions of acoustic fluctuation responding to each sinusoidal excitation

From Fig. 7, it is found that multi-injectors of $l_{inj}=\lambda$ also have good damping capability as well although they are a little less effective than multi-injectors of $l_{inj}=(1/2)\lambda$. On the other hand, we can find another interesting characteristics induced by multi-injectors of $l_{inj}=(1/4)\lambda$ and $(3/4)\lambda$. When the multi-injectors of the lengths are mounted, there is not observed any frequency shift of 1T mode, but only slight decrease in the amplitude as shown in Fig. 7. This indicates that multi-injectors of $l_{inj}=(1/4)\lambda$ and $(3/4)\lambda$ can not produce acoustic damping through wave cancellation and the slight decrease in the amplitude is caused only by acoustic-energy absorption at the boundary walls of the multi-injectors. That is, the lengths of $(1/4)\lambda$ and $(3/4)\lambda$ will be regarded as mal- or worst-tuning length.

These peculiar acoustic behaviors induced by multi-injectors may affect injector tuning. To find the tuning condition suitable to multi-injectors, the damping characteristics of multi-injectors concerning acoustic amplitude and frequency shift are examined. They are measured as a function of injector length and shown in Fig. 9. As injector length increases from 0 mm, f_{1T} increases slightly and then gradually decreases. As l_{inj} approaches a half wavelength, f_{1T} decreases rapidly. The amplitude also decreases rapidly near $l_{inj}=(1/2)\lambda$. As injector length increases further, 1T mode becomes weaker and weaker, and finally, it is completely damped out with the injector length over $l_{inj}=410$ mm. In the meantime, new mode of 1T1L* appears at higher frequency just before $l_{inj}=(1/2)\lambda$. It starts from $l_{inj}=270$ mm, at which f_{1T1L}^* is 625 Hz. As injector length increases from 270 mm, f_{1L1L}^* decreases, but the amplitude of 1T1L* mode continues to increase and reaches its maximum at $l_{inj}=430$ mm. As injector length increases further, both f_{1T1T}^* and the amplitude decrease, but another new mode of 1T2L* shows up and the same patterns are repeated.

In Fig. 10, damping factors of 1T, 1T1L*, and 1T2L* modes are shown as a function of injector length. In contrast to their frequencies and amplitudes shown in Fig. 9, their damping factors vary irregularly with injector length. But, as injector length increases, on the average, damping factor of 1T mode increases and then decreases at longer length over 315 mm. On the other hand, damping factor of 1T1L* mode decreases at the initial stage of its appearance and then, increases gradually. Damping factor of 1T2L* mode has similar pattern to that of 1T1L* modes.

In Fig. 10, it is worthy of note that damping factor of 1T1L* mode is quite low near $l_{inj}=(1/2)\lambda$ despite of high damping factor of 1T mode. As aforementioned, the higher modes as from 1T1L* arise from acoustic coupling between chamber and multi-injectors, which indicates that acoustics inside the injector interacts with ones in the chamber and the injector is no longer original passive device. In the previous work (Kim and Sohn, 2006), the optimal tuning length of $(1/2)\lambda$ was suggested from the experiments with a single injector. But, in the chamber with multi-injectors, it should be modified with peculiar acoustic coupling considered because the new coupling mode shows up near the original tuning length, resulting in small damping factor. From Figs. 9 and 10, it is proposed that the best tuning length should be selected a bit less than a half wavelength and furthermore, it may not exceed a half wavelength so as to avoid strong resonance of the injector-coupled mode. Conclusively, although numerous injectors are mounted, the gas-liquid scheme injector still functions as a half-wave resonator, but a little shorter length than a half wavelength is recommended for acoustic tuning of multi-injectors.

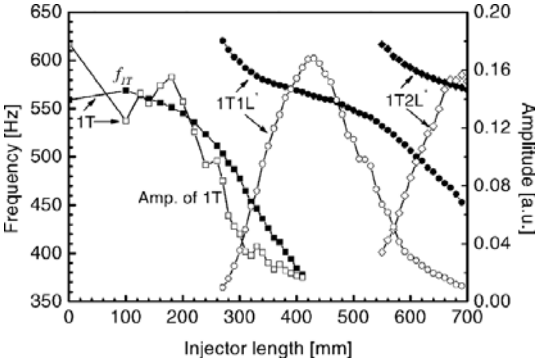


Fig. 9 Acoustic frequencies and amplitudes of 1T, 1T1L*, and 1T2L* modes as a function of injector length in chamber with multi-injectors

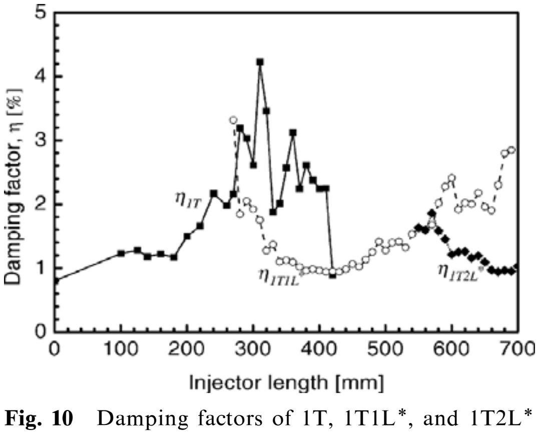


Fig. 10 Damping factors of 1T, 1T1L*, and 1T2L* modes as a function of injector length in chamber with multi-injectors

4. Concluding Remarks

Acoustic-pressure responses in the chamber with gas-liquid scheme injector have been investigated experimentally by adopting linear acoustic test. This experimental study is intended to make acoustic tuning of multi-injectors for acoustic damping in the chamber. From the previous experiments with a single injector, it is known that the present injector can function as a half-wave acoustic resonator. The first tangential mode has been selected a target mode to be damped in this study.

Acoustic behaviors induced by the injectors with several diameters have shown that numerous injectors with small diameter are more effective in acoustic damping than a single injector with large diameter. This is that the increase in the surface area of the injector mitigates the pressure fluctuation generated inside the injector, leading to degradation of wave-cancellation effect.

When numerous injectors are mounted to the chamber, open area on the faceplate will not be negligibly small any longer. As open-area ratio increases, peculiar characteristics, i.e., acoustic coupling between the chamber and injectors shows up. Acoustics inside injectors interacts with in-chamber acoustic field, and thereby, the injectors behave acoustically on a level with the chamber. As a result of acoustic coupling, new acoustic modes show up near the injector lengths of (1/2) λ, λ, and (3/2) λ, etc. They have been identified as the injector-coupled modes of 1T1L*, 1T2L*, and higher formed in the full domain including injector part. And thereby, acoustic-damping capability of the tuned injector can be appreciably degraded. With the coupling considered, the tuning length should be modified to be a bit less than a half wavelength to avoid the strong injector-coupled mode. When the injectors are tuned finely or properly, acoustic stability would be improved considerably and further, fine tuning of the injectors could make the classical combustion-stabilization devices such as baffle and resonators unnecessary.

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