Experimental Study on the Pulsation of a Liquid Jet Issued from a Coaxial Injector

M. Shirota[*1], K. Kitami[1], T. Kon[1], T.Inamura[1], Y. Nunome[2], H. Tamura[2]
[1]Faculty of Science and Technology,
Hirosaki University,
Hirosaki, Aomori 036-8561, Japan
[2]Engine System Research and Development Group,
Japan Aerospace Exploration Agency,
Kakuda, Miyagi 981-1525, Japan

Abstract
The mechanism of the onset of pulsation of liquid jet issued from a coaxial injector was experimentally studied. A two-dimensional transparent injector element model was used to observe the pulsation of the liquid jet. In order to prevent a liquid injection post from pulsation, which may cause the liquid jet pulsation, the injector with only one-side gas flow channel was used. Pressure variation in a recessed region and the sound caused by the liquid jet disintegration were also analyzed in order to clarify the condition for the transition of jet disintegration pattern. At a certain momentum flux ratio of liquid and gas, liquid jet disintegration pattern changes from fiber to pulsating jet. This transition causes a rapid increase in recess pressure as well as the change in the characteristic frequency of jet disintegration sound. The critical liquid and gas momentum flux over which the liquid jet starts pulsating were obtained for several gas flow rate. We clarified the critical momentum flux ratio lies between 2 to 3. The characteristic frequency of jet disintegration sound is found to be smaller than the resonance frequency of the liquid injection post. This confirms that the pulsation of liquid jet is not caused by mechanical pulsation of injection post but by hydrodynamic instability at the jet surface.

Introduction

Coaxial injectors are widely used in a rocket engine. Liquid oxigen jet issued form a central injection post of the injector is exposed to a high-speed hydrogen gas flowing around the liquid oxigen jet. Shear forces between these two propellants causes hydrodynamic instability of liquid jet surface and the liquid oxygen is highly atomized.

Recessing the central liquid injection post of a coaxial injector improves the atomization and mixing of the propellants, and thus combusiton efficiency[1]. However too-long recess length may lead to high-frequency pulsating combustion and sometimes damages the rocket or payloads.

The breakup patterns of the liquid jet from a non-recessed injector were classified by Chigier et al.[2] by using liquid Reynolds number and gas Weber number. They showed that the jet disintegration pattern changes from fiber to pulsating type with the increase in gas Weber number.

With a recessed injectior model, Nunome et al.[3] experimentaly clarified the critical Reynolds number and Weber number, over which the jet disintegration mode changes from fiber to super-pulsation disintegration. They used a two dimensional injector model with two-side gas flow channel, in which the liquid injection post can mechanically pulsate. In a certain range of liquid Reynolds number and gas Weber number, they observed the pulsation of both liquid jet and liquid injection post. The pulsation frequency was found to correspond to the resonance frequency of the liquid injection post. Therefore the mechanism for the onset of pulsation is not yet fully understood.

In the present study, in order to prevent the injection post from pulsation, an injector model with only one-side gas flow channel is used. The liquid jet disintegration, even in the recessed region, was observed using this transparent two-dimensional injection model. The gas pressure in the recessed region was also measured in order to detect the change in disintegration pattern of liquid jet. The sound caused by the liquid jet disintegration was also sampled in order to compare the characteristic frequency of liquid jet pulsation with the resonance frequency of the liquid post pulsation.

Experimental setup and method

Figure 1 shows the schematic diagram of the experimental setup. In experiments, water and air were used as substitution fluids for liquid oxygen and hydrogen gas respectively. Pressurized water stored in a water tank was transfered to a injection model through a ultrasound flow meter. The water flow rate was controlled by adjusting

* Corresponding author: mshirota@cc.hirosaki-u.ac.jp

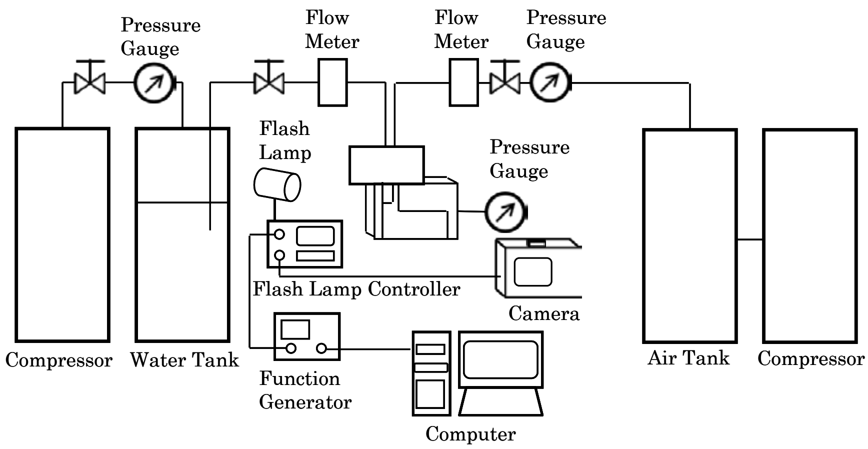

Figure 1. Schematic diagram of the experimental setup.

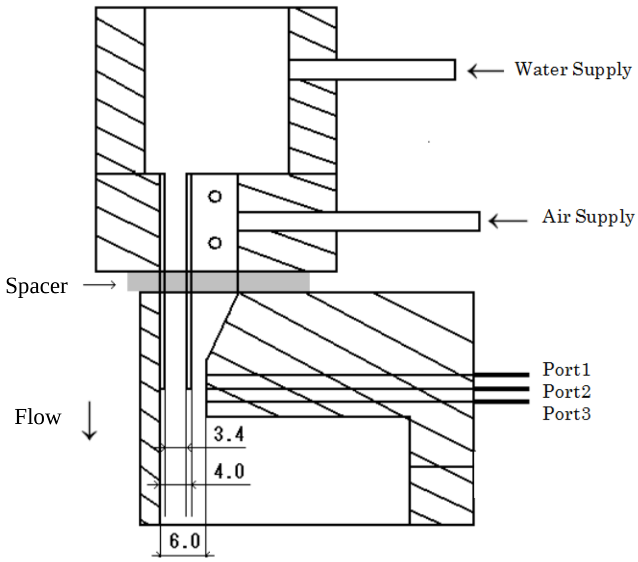

Figure 2. Schematic diagram of injector model.

a needle valve connected to the flow meter. Air was pressurized and transfered to the injection model through a rotameter as well. In Fig. 2 the schematic diagram of the injector model was shown. The injector model consists of acrylic body and a stainless steel liquid injection post. As noted in the previous section, in order to prevent the liquid injection post from pulsation, this injector model has only one gas flow channel at one-side of liquid injection post. The rectangular cross sectional area of a liquid injection post is 4.0×4.0 mm^2 with 0.3 mm thickness while the one for the gas flow is 2.0×4.0 mm^2. Recess depth can be varied by inserting a spacer. Recess pressure was measured using pressure transducer through pressure port 1, 2 and 3 in the injector model (see Fig. 2). The disintegration pattern of the liquid jet was captured using a digital still camera with strobe flash backlighting. The data of pressure and liquid flow rate and synchronizing signal of strobe flash were simultaneously stored in a data acquisition device at the sampling rate of 50 Hz. The sound caused by the liquid jet disintegration was also measured at the sampling rate of 44.1 kHz using a microphone attached to the injector model. The sound data were analyzed with spectrogram method, in which the time variation of power spectrum is calculated.

Experiments are conducted under the atmospheric pressure. In an experiment, air mass flow rate was kept constant, while the water injection rate was gradually decreased; the gas pressure in the water tank decreased due to the transfer of water to the injector, which correspondingly results in the gradual decrease in water flow rate. The recess depth was set at RN = 0, 0.5, 1.0 or 1.5, where $RN = L/d$ with L the dimensional recess depth and d the inner width of liquid injection post (d = 3.4 mm). In this paper, only the case of RN = 1.5 will be considered.

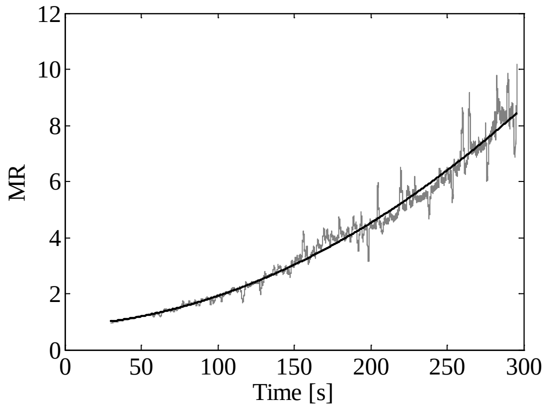

Figure 3. Typical example of time history of momentum flux ratio MR.

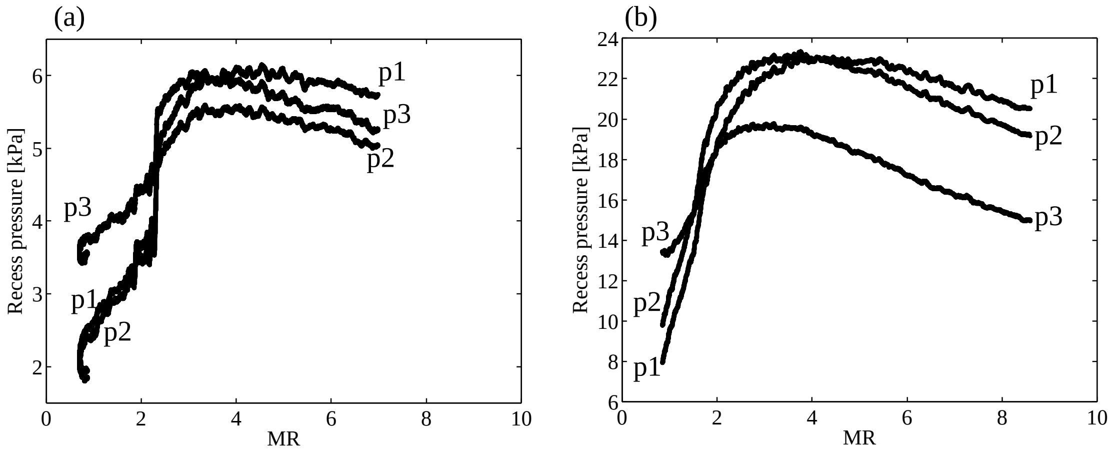

Figure 4. Change in recess pressure as a function of MR. (a) Mg = 0.0014 kg/s, (b) Mg = 0.0020 kg/s.

Results and discussion

The liquid Reynolds number and gas Weber number for the flow concerned in this study is of the order of 10^4 and 10^3 respectively. The inertial force therefore dominates the viscous and surface tension force for both liquid and gas flows. We thus uses momentum flux ratio *MR* for the measure of gas-liquid interaction;

$$MR \equiv \frac{\rho_g U_g^2}{\rho_l U_l^2} \tag{1}$$

Here ρ and U denotes density and velocity, and the suffix g and l represents gas and liquid respectively. In an experiment, gas momentum flux was kept almost constant, while liquid momentum flux decreased gradually. This corresponds to the gradual increase in *MR*, typical example of which is shown in figure 3. The original *MR* data contains electrical noises and is not suitable for the analysis. Therefore by fitting a quadratic function, a monotonic relation between time and *MR* was obtained (solid line in Fig. 3). With this function, the time variation of pressure and sound data were rearranged as a function of *MR*.

Figure 4 shows two different types of recess pressure change as a function of *MR*. In case (a), the gas mass flow rate was about 0.0014 kg/s, corresponding gas injection velocity was about 130 m/s. In this case of relatively low gas flow rate, a step-wise increase in recess pressure was found at $MR \approx 2.3$. Further increase in *MR* leads to the decrease in recess pressure.

The photographs corresponding to Fig. 4 (a) are shown in Fig. 5 (a). It is found that before the step-wise increase in recess pressure, i.e. $MR < 2.3$, the disturbance on liquid jet surface is small. We defined this jet disintegration as "fiber type" following Chigier et al [2]. On the contrary, when $MR > 2.3$, the liquid jet starts pulsating. We defined this jet disintegration as "pulsating type". The pulsation of liquid jet promotes the formation of liga-

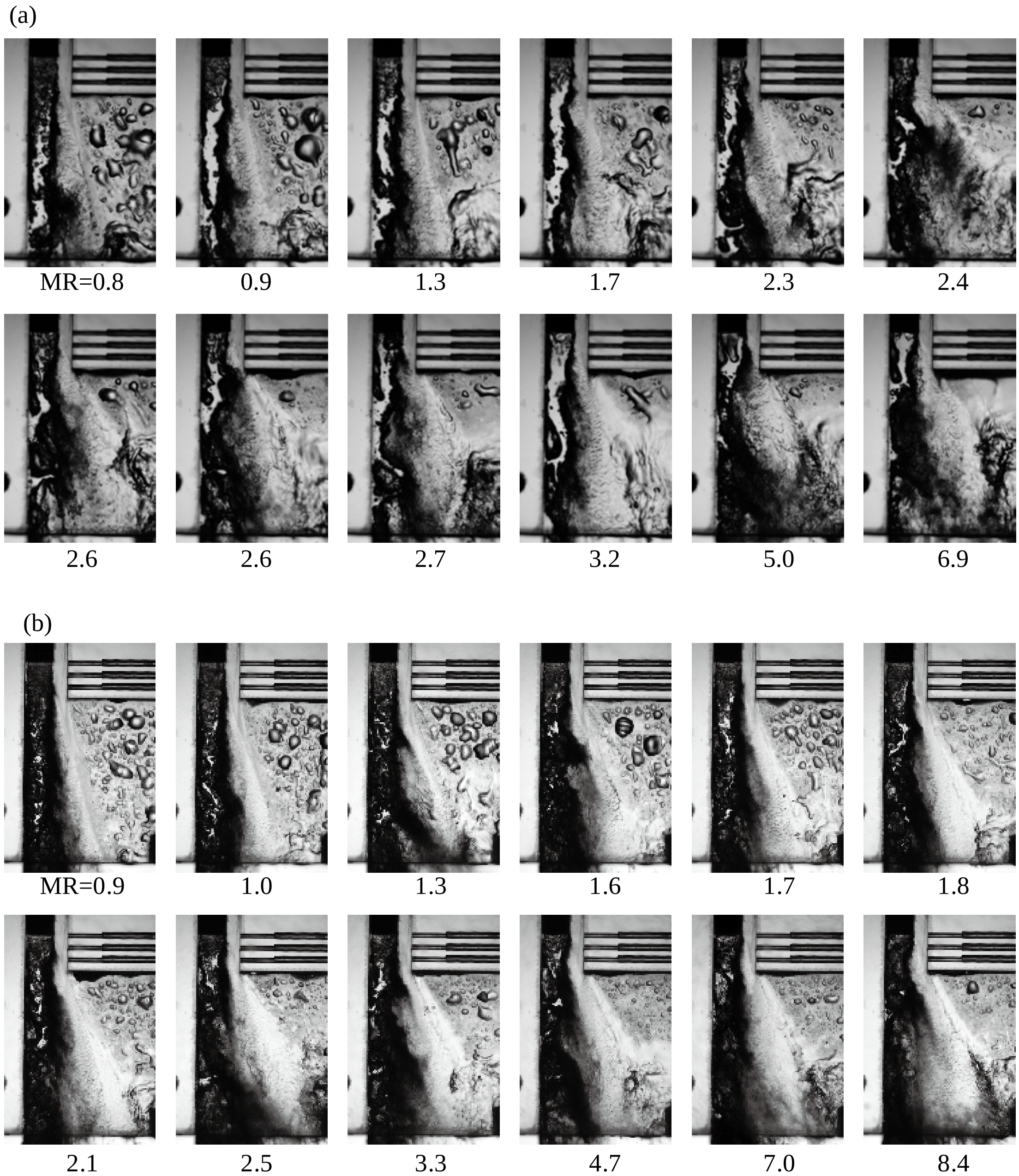

Figure 5. Photographs of liquid jet disintegration. (a) Mg = 0.0014 kg/s, (b) Mg = 0.0020 kg/s.

ments and small droplets from liquid jet shown as black region on the liquid jet surface. We thus conclude that the rise in gas pressure in recessed region is caused by the decrease in gas momentum that is transported to the droplets peeled off from the liquid jet surface.

The case of higher gas flow rate is shown in (b) of Figs. 4 and 5, where the gas mass flow rate is 0.0020 kg/s (corresponding gas injection velocity is about 250 m/s). In this case the recess pressure also increases but not in step-wise manner. The jet regime transition occurs at $MR \approx 1.8$ which almost corresponds to the MR where the rate of change in recess pressure has maximum value.

It is noteworthy from the typical example shown in Figs. 4 and 5 that the transition of flow regime from fiber to pulsating type occurs even when the pulsation of liquid injection post is suppressed. The liquid jet pulsation can occur only by hydrodynamic instability caused by high shear rate at liquid jet surface.

A close observation of photographs in Fig. 5 reveals that after the liquid jet starts pulsating the tip of the liquid injection post fully covered with ligaments and droplets shown as a black region; before the transition the width of the liquid jet at the exit of injection post is nearly equal to the inner width of the post, and the thickness of the injection post is recognized.

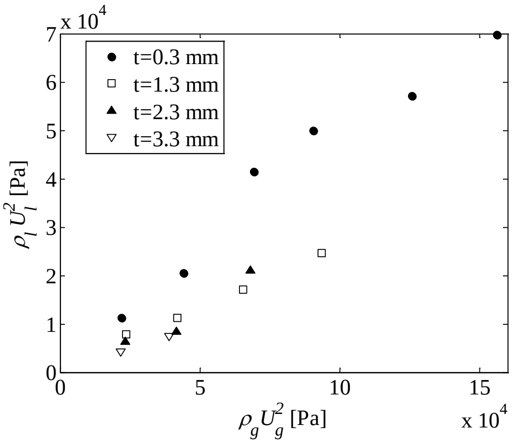

Figure 6. Momentum flux of gas and liquid at the transition of liquid jet disintegration.

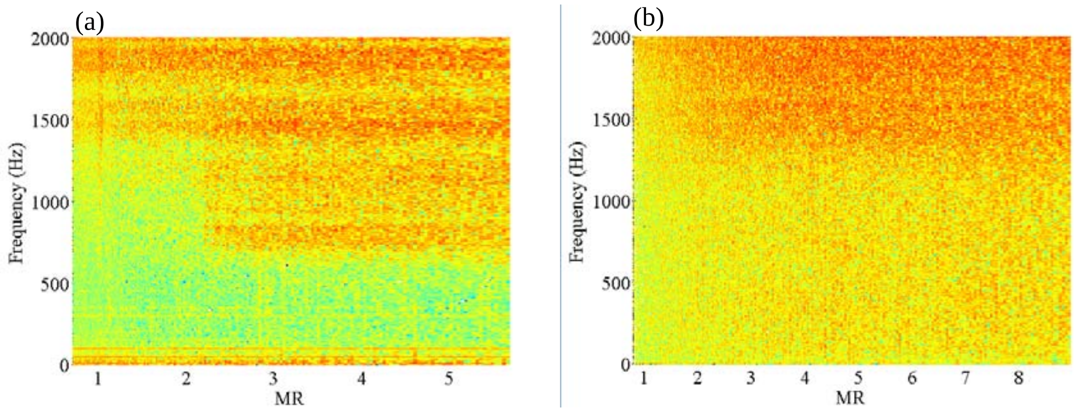

Figure 7. Spectrogram of the sound caused by the liquid jet disintegration.
(a) Mg = 0.0014 kg/s, (b) Mg = 0.0020 kg/s.

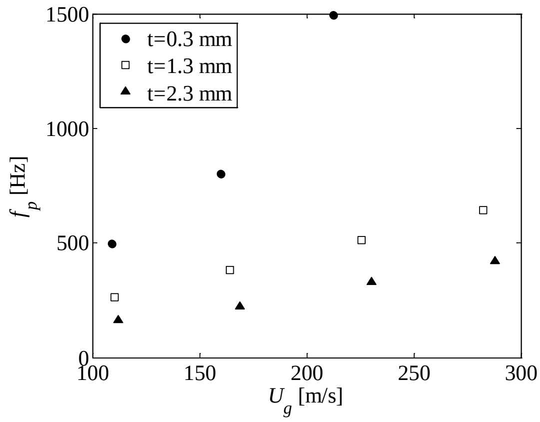

Figure 8. Peak frequency of the jet disintegration sound.

In order to investigate the effect of the tip thickness of liquid injection post, a different injection model was used. This model has wider gas flow channel, i.e., w = 5 mm, and an aluminum plate of thickness of 1, 2 or 3 mm was attached to the gas-side wall of the liquid injection post.

Pairs of critical gas and liquid momentum flux over which liquid jet starts pulsating are plotted in Fig. 7 for liquid injection post with different side-wall thickness. It is found from this figure that for t = 0.3 mm the pairs of the momentum fluxes lies along a line. In this case, the critical *MR* is about 2. The critical *MR* for t = 1.3, 2.3 and 3.3 mm have relatively high value of about 3.

In the previous study with two-side gas channel model, both the liquid injection post and liquid jet pulsated at the resonance frequency of the post, which is about 1500 Hz. In order to investigate the characteristic frequency of the liquid jet pulsation, the sound caused by liquid injection was analyzed by using spectrogram method. Typical spectrograms corresponding to cases (a) and (b) of Figs. 4 and 5 are shown in Figs. 7 (a) and (b). In case (a), the step-wise increase is also found in the sound intensity of less than 1000 Hz. On the contrary, as in the pressure change in Fig. 4, the gradual change in the sound intensity is found in case (b).

The peak frequency of the sound caused by liquid disintegration is shown in Fig. 8 as a function of gas speed at the exit of liquid injection post U_g. It is revealed that the peak frequency increases with the increase of U_g and the decrease of the side-wall thickness of liquid injection post t. All the frequencies plotted in this figure are below the resonance frequency (1500 Hz) of the liquid injection post. We thus confirm that without the pulsation of liquid post, the liquid jet pulsates at the lower frequency than the resonance frequency of the post due to hydrodynamic instability.

Conclusion

The mechanism of the onset of liquid jet pulsation in a coaxial injector was experimentally investigated. An injector model with one-side gas flow channel was used in order to prevent the liquid injection post from mechanical pulsation. By the observation of liquid jet disintegration pattern as well as the measurements of the gas pressure in the recessed region and the sound caused by liquid jet disintegration, we conclude that the liquid jet pulsation can be caused without the mechanical pulsation of liquid injection post but only with hydrodynamic instability at the gas-liquid interface of the jet. The critical momentum flux ratio of gas to liquid for the transition to “pulsating type” disintegration lies between 2 to 3. It is also clarified that the peak frequency of the jet disintegration sound increases with the increase of gas disintegration velocity and the decrease of the side-wall thickness of liquid injection post at exit.

Nomenclature

d	inner width of the liquid injection post [m]
L	recess length [m]
Mg	mass flow rate of gas [kg/s]
MR	momentum flux ratio of gas to liquid
ρ	density [kg·m^{-3}]
t	thickness of the liquid injection post at exit [m]
U	velocity [m/s]
w	width of gas channel [m]

Subscripts

g	gas
l	liquid

References

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