JASMAC
Conference of the Japan Society of Microgravity Application

OR3-3

小型超音速飛行実験機燃料タンク向け加圧ガス巻きこみ抑制技術の開発

Development of Pressurized Gas Entrainment Suppression Technology for Small-scale Supersonic Flight Experiment Aircraft Fuel Tanks

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1. Introduction

The Aerospace Plane Research Center in Muroran Institute of Technology is development the small-scale supersonic flight experiment aircraft as a flying test bed for a technical demonstration in high-speed flight environment. In the small-scale supersonic flight experiment aircraft, the liquid supplying system for bioethanol (BE) and liquid oxygen (LOX) by nitrogen pressurant has been studied. However, sloshing is expected to occur in these liquid fuel tanks by the acceleration during flight. Sloshing may adversely affect the aircraft attitude control and propulsion systems due to the presence of pressurized gas in the fuel supply.

The purpose of this paper is to research, develop and evaluate the performance of a propellant management device (PMD) and a sloshing suppression device to solve the problem of pressurized gas entrainment in aircraft fuel tanks.

2. The Propellant Management Device (PMD)

Figure 1 shows a structure of the PMD. The PMD has four nozzles mounted at the top and bottom and a cylindrical metal wire mesh nozzle attached to the tip of the nozzle. The PMD is installed at the fuel supply port inside the fuel tank to suppress gas entrainment. The mechanism by which the PMD suppresses gas entrainment is described here. As shown in **Figure 1**, when the porous screen surface gets wet, a liquid film is formed by the surface tension of the liquid, which inhibits the entry of bubbles that attempt to pass through the porous screen, allowing only the liquid to pass through, thus realizing gas-liquid separation. The bubble point pressure (P_{BP}) is defined as the pressure at which the liquid film on the porous screen surface is broken and the vapor passes through the porous screen to the liquid side. The P_{BP} is given by Equation (1):

$$P_{BP} = \frac{4\sigma\cos\theta}{D_p} \tag{1}$$

where σ is the surface tension of the liquid, θ is the contact angle of the liquid on the screen, and D_p is the pore diameter of the screen. As shown in Equation (2), if the difference in static pressure between the vapor and liquid phases in the porous screen is greater than P_{BP}, the liquid film on the surface of the porous screen is broken and bubbles pass through the porous screen:

$$P_{BP} < P_V - P_L \tag{2}$$

where P_V is the static pressure of the vapor phase, and P_L is the static pressure of the liquid phase. $P_V - P_L$ is equal to the total pressure drop (ΔP_{total}) across the PMD system:

$$P_V - P_L = \Delta P_{total} \tag{3}$$

ΔP_{total} can be expressed as a sum of constituent parts:

$$\Delta P_{total} = \Delta p_{sn} + \Delta p_{st} + \Delta p_{bt} + \rho_L g h_{UL} \tag{4}$$

where Δp_{sn} is the porous screen passage loss, Δp_{st} is the pressure loss of the straight part, Δp_{bt} is the pressure loss of the bend part and $\rho_L g h_{UL}$ is the head difference. Equations (2) and (3) show that babbles cannot pass through the porous screen unless the ΔP_{total} of the PMD exceeds P_{BP}. Equation (5) shows that gas-liquid separation can be achieved during transfer if the ΔP_{total} of the PMD does not exceed P_{BP}:

$$P_{BP} > \Delta P_{total} \tag{5}$$

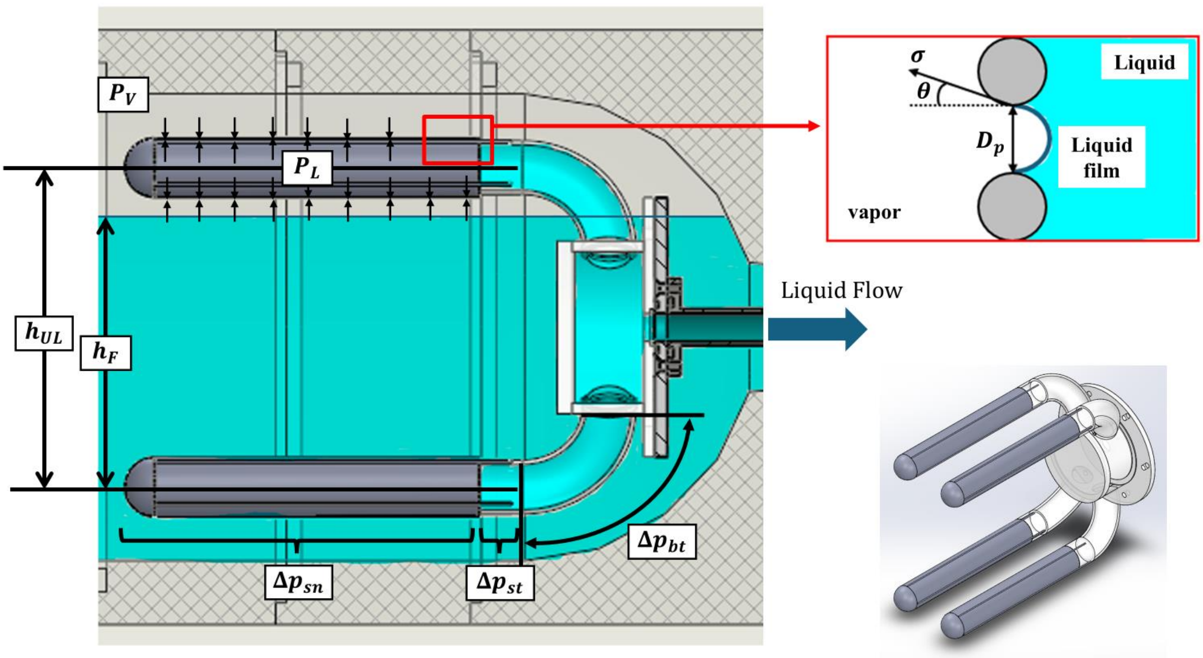

Figure 1. Structure of the Propellant Management Device (PMD).

In this study, the PMD with a mesh length of 150 mm was used, which was found in a previous study to be capable of realizing liquid discharge while achieving gas-liquid separation.[1)]

3. The Sloshing Suppression Device

Figure 2 shows a structure of the sloshing suppression device. By using a cylindrical geometry as the structure of the suppression mechanism, damping due to viscous stress increases outside the cylindrical geometry due to the increased contact area between the liquid fuel and the solid wall. Inside the cylindrical geometry, the ring baffle concept, which is a common method of suppressing transverse sloshing[2), is applied to suppress it. Sloshing can be controlled both inside and outside the cylindrical shape, reducing sloshing throughout the tank. The use of metal mesh on the cylindrical side walls prevents sloshing while preventing liquid accumulation inside the mechanism. This is because the surface tension of the liquid forms a liquid film on the metal mesh, which can be regarded as a pseudo solid wall.

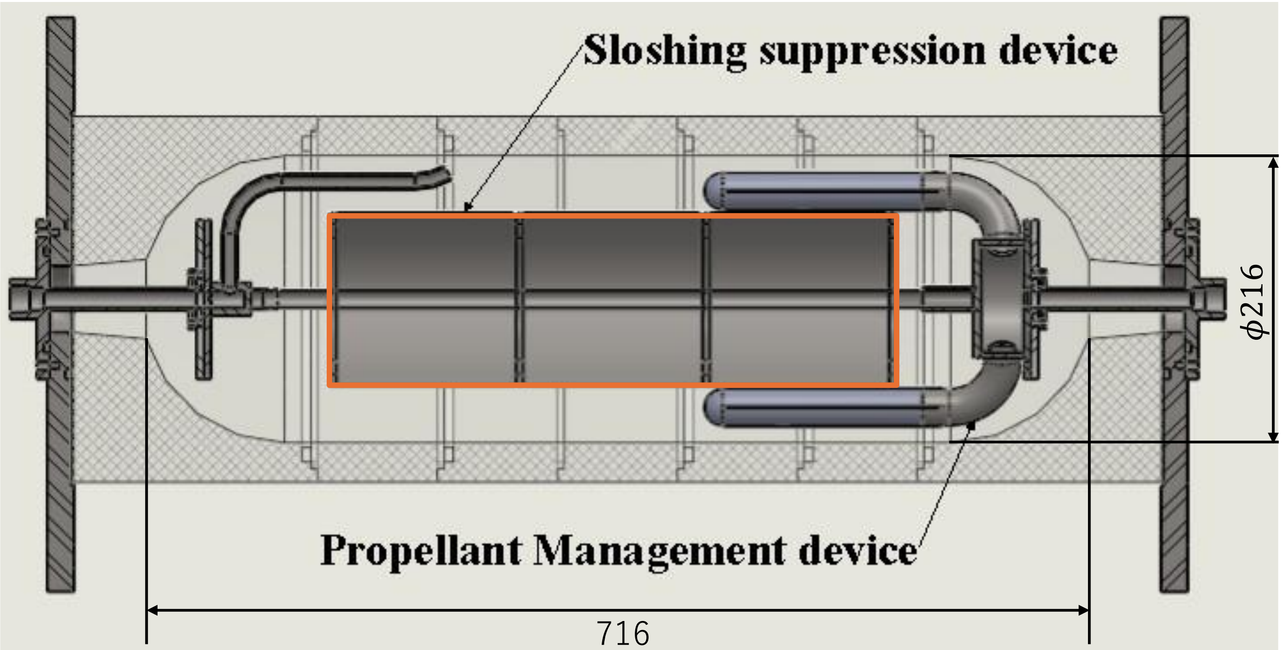

Figure 2. Structure of the Sloshing Suppression Device.

4. Experimental Method

4.1. Liquid discharge test under static conditions

The test tank was placed horizontally and the flow behavior inside the tank and PMD was observed under static conditions with downward gravitational acceleration. **Figure 3** shows a drawing of the test tank. The tank was made of transparent polycarbonate resin to visualize the internal flow behavior, and the inner wall of the tank was formed by overlapping rectangular blocks hollowed out of hemispheres and cylinders. The PMD was installed on the liquid outlet side and a gas supply nozzle on the pressurized gas supply side.

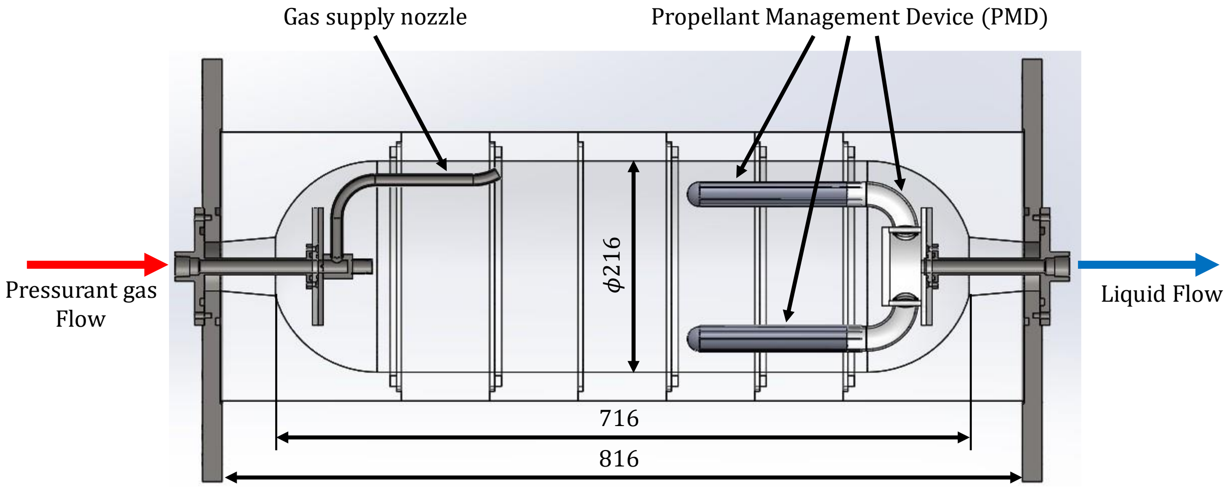

Figure 3. Test tank and inner structure.

Figure 4 shows the test system. The test tank is connected to a gas supply line, a test liquid supply line, and a liquid discharge line. The pressurized gas is supplied from the gas tank to the test tank via a regulator and solenoid valve, and the test liquid is discharged from the test tank to the drain tank via an ultrasonic flow meter. The test liquid is supplied to the test tank by vacuum filling. Other measurement items were the pressure inside the tank, and the flow behavior inside the tank was observed with a video camera. Pure water was used as the test liquid. The tank pressure was regulated using Bang-Bang control, in which the solenoid valve is opened to supply pressurized gas when the pressure falls below a set lower limit pressure, and the solenoid valve is shut off to stop the supply of pressurized gas when the pressure rises above the upper limit pressure. The experimental conditions for this experiment are shown in **Table 1**.

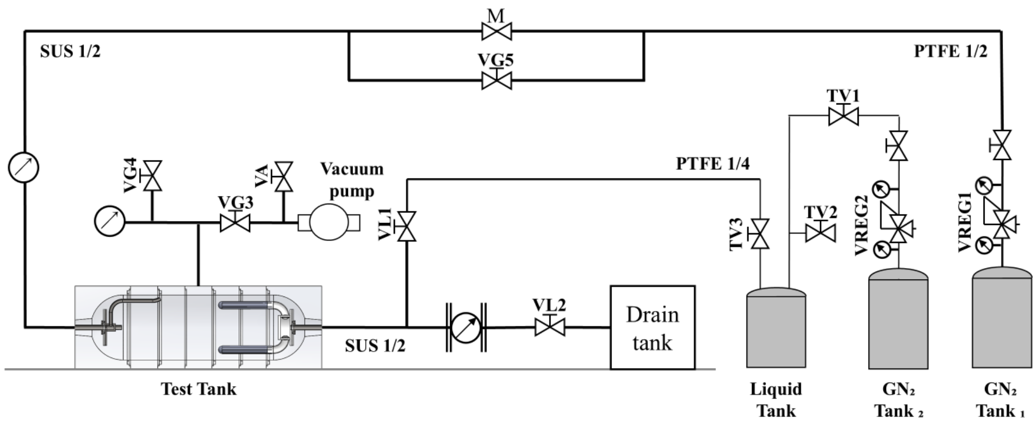

Figure 4. Test system of liquid discharge test under static conditions.

Table 1. The experimental conditions for liquid discharge test under static conditions.

Item	Set value
Test Liquid	Pure water
Pressurized gas	nitrogen
Initial pressure	0.41 [MPaG]
Supply pressure	0.65 [MPaG]
Upper limit pressure	0.32 [MPaG]
Lower limit pressure	0.31 [MPaG]

4.2. Liquid discharge test under acceleration conditions

The test tank was placed horizontally and a running test was conducted using the High-Speed Test Track at the Shiraoi Engine Test Field of Muroran Institute of Technology to observe the flow behavior in the tank and inside the PMD during liquid discharge under acceleration conditions. The PMD was placed on the liquid outlet side and the gas supply nozzle was placed on the pressurized gas supply side, and the test tank was run in the opposite direction of the liquid outlet.

Figure 5 shows the test system. The test tank is connected to a gas supply line, a test liquid supply line, and a liquid discharge line. The pressurized gas is supplied from the gas tank to the test tank via a regulator, and the test liquid is discharged from the test tank to the outside via an ultrasonic flow meter. The test liquid is supplied to the test tank by vacuum filling. Other measurement items were tank pressure and temperature, and the flow behavior inside the tank was observed with a video camera. Pure water was used as the test liquid. The experimental conditions for this experiment are shown in **Table 2**.

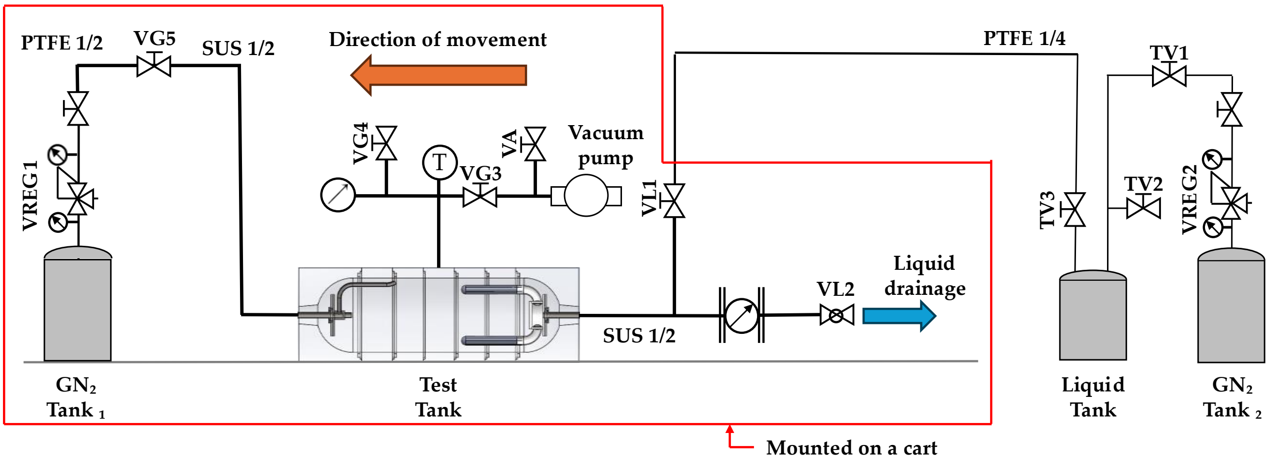

Figure 5. Test system of liquid discharge test under acceleration conditions.

Table 2. The experimental conditions for liquid discharge test under acceleration conditions.

Item	Set value
Test Liquid	Pure water
Pressurized gas	nitrogen
Initial pressure	0.47 [MPaG]
Supply pressure	0.47 [MPaG]

5. Experimental result and discussion

5.1. Liquid discharge test under static conditions

Figure 6 shows the results of this experiment. In this experiment, the flow rate of 38 [L/min], which exceeded the design flow rate of 36 [L/min], was successfully discharged without gas entrainment. **Figure 7** and **Figure 8** show some of the images taken during the experiment. **Figure 7** shows that no gas entrainment occurred when the lower nozzle was in contact with the liquid and the upper nozzle was fully exposed. **Figure 8** shows that no gas entrainment occurred even when the upper half of the lower nozzle was exposed. These results indicate that the PMD with a mesh length of 150 mm meets the required performance under static conditions.

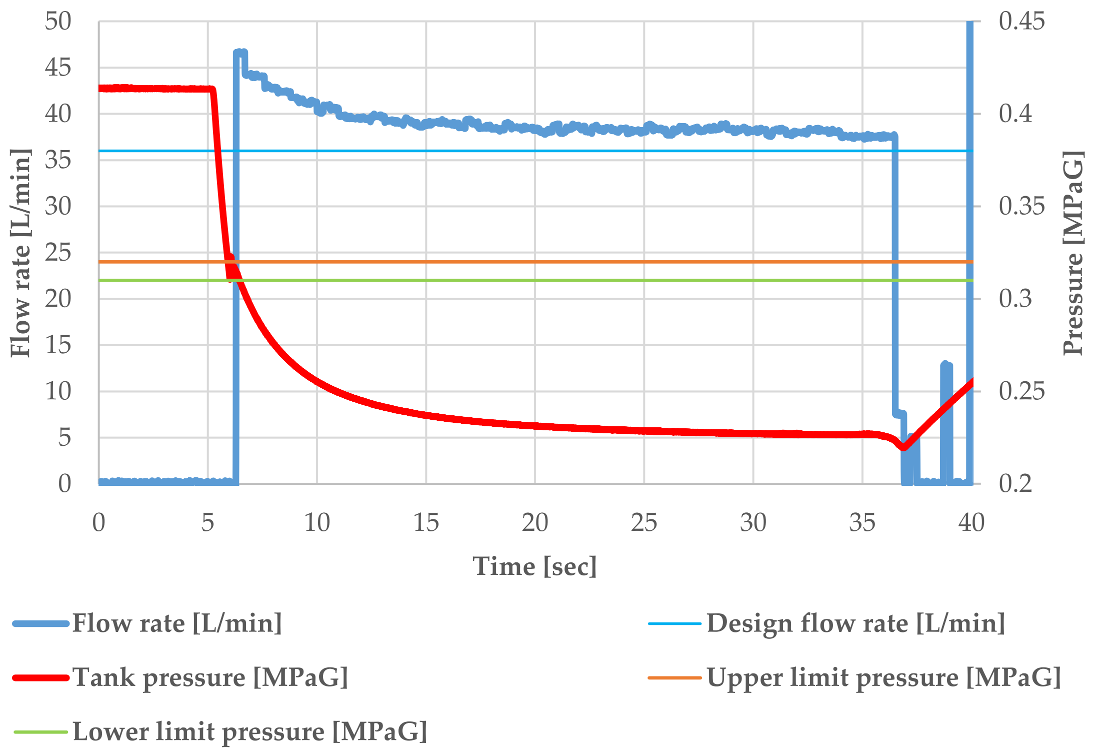

Figure 6. Results of liquid discharge test under static conditions.

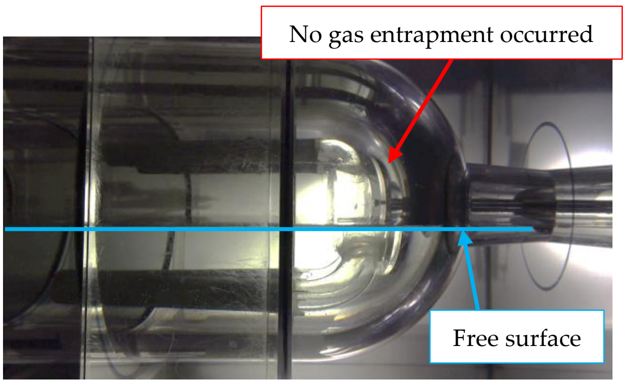

Figure 7. Image 17 second after the start of discharge.

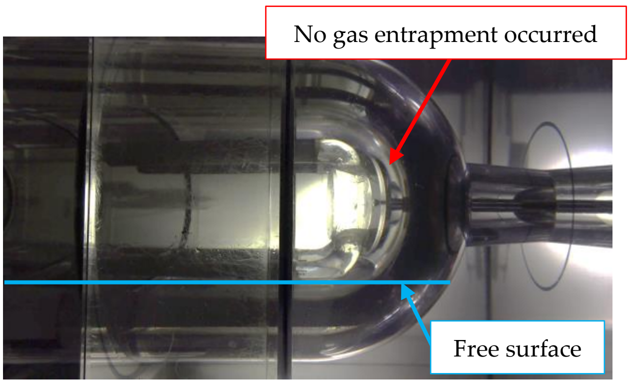

Figure 8. Image 28 second after the start of discharge.

5.2. Liquid discharge test under acceleration conditions

Figure 9 and **Figure 10** show the results of this experiment and the acceleration history. In this experiment, under an acceleration environment where 1.5G was added during acceleration and about 2G during deceleration, the propellant was successfully discharged at about 38[L/min], which was higher than the design flow rate of 36[L/min], without gas entrainment for about 11 seconds after the start of running, but gas entrainment occurred thereafter and stable propellant supply was not realized. **Figure 11** and **Figure 12** show some of the images taken during the experiment. **Figure 11** shows that no gas entrainment occurred when the upper nozzle was fully exposed with the gas phase, and the lower nozzle was submerged. **Figure 12** shows that gas entrainment occurred when the lower nozzle was fully exposed. The reason for the failure of stable propellant supply was that the lower nozzle was completely exposed during deceleration and no propellant could not be supplied to the PMD, and the strong liquid slosh force acting on the base of the PMD nozzle during sloshing caused structural failure of the adhesive, which allowed pressurized gas to enter through the gap at the failure point. The structural failure of the adhesion zone can be easily addressed by changing the material of the PMD to a higher-strength material, but it is difficult to address the problem of the lower nozzle being completely exposed during deceleration by changing the PMD alone. Therefore, it is necessary to construct a highly reliable system by increasing the contact time between the PMD and the propellant using a sloshing suppression device.

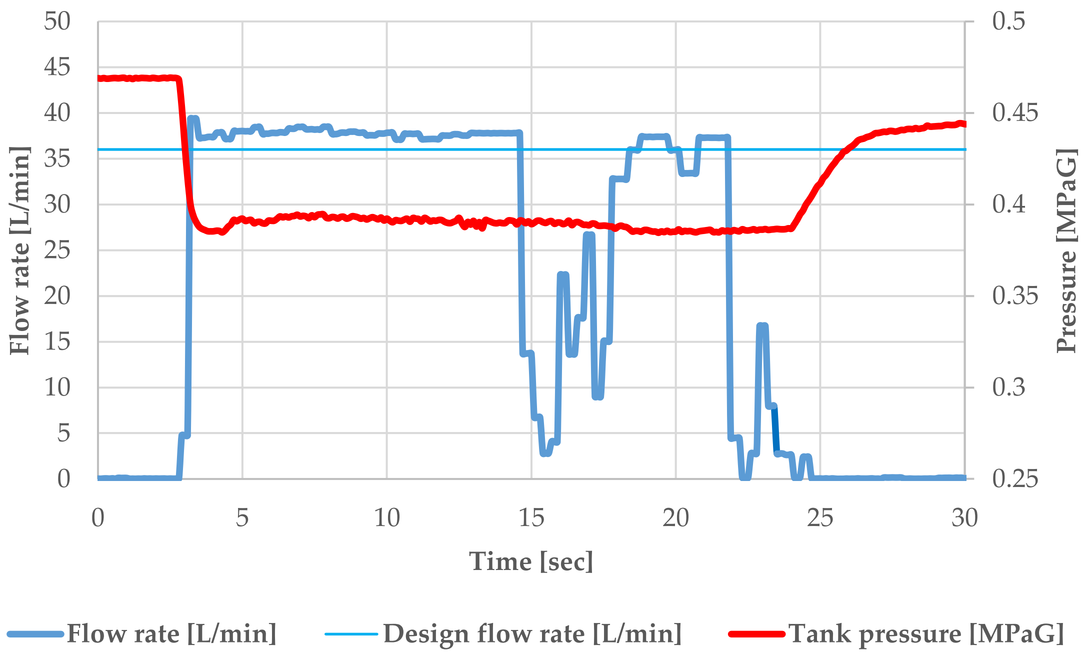

Figure 9. Results of liquid discharge test under acceleration conditions.

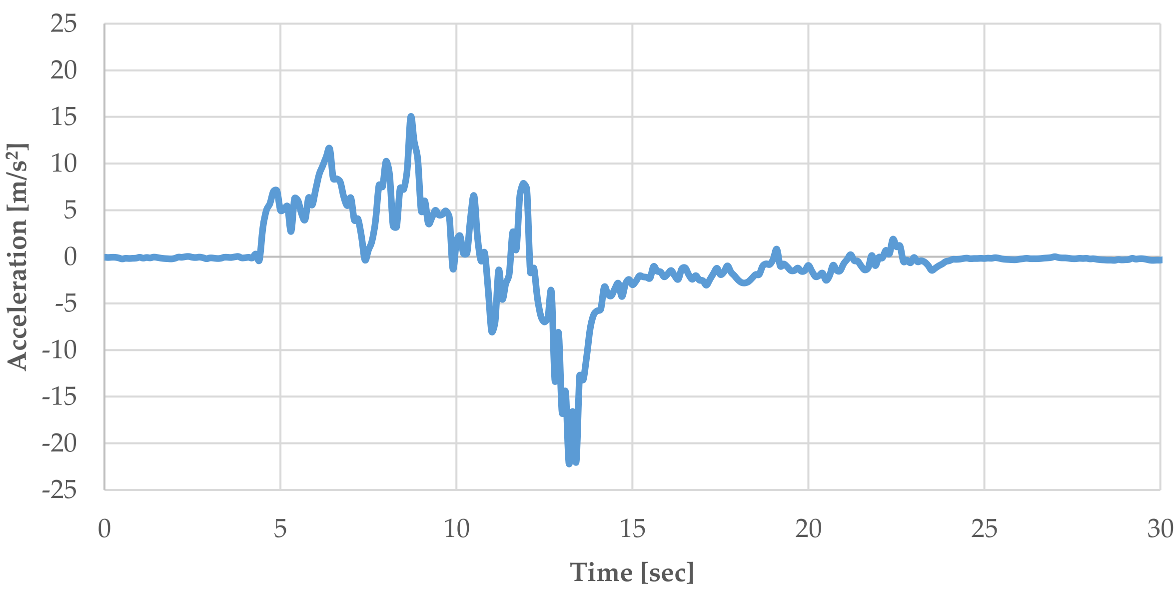

Figure 10. The acceleration history of liquid discharge test under acceleration conditions.

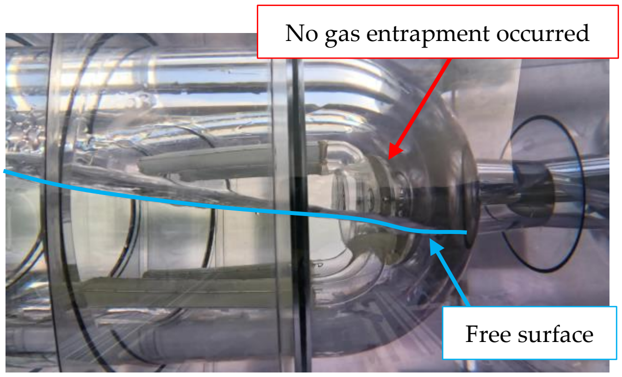

Figure 11. Image after 7 second of running.

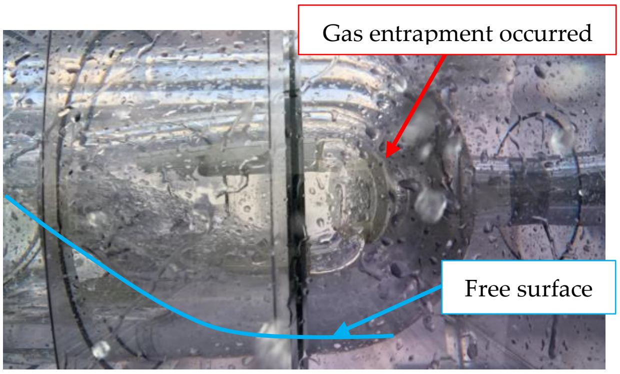

Figure 12. Image after 11 second of running.

6. Conclusion

In this study, a propellant management device and a sloshing suppression device were developed to solve the problem of pressurized gas entrainment in the fuel tank of the small-scale supersonic flight experiment aircraft. To evaluate the performance of the PMD, liquid discharge tests were conducted under static and acceleration conditions. The PMD was able to meet the required performance under static conditions, but not under acceleration conditions. The reasons for the failure to meet the required performance were that the lower nozzle was completely exposed during deceleration and could not supply propellant to the PMD, and that the strong slosh force of the liquid acting on the base of the PMD nozzle during sloshing caused structural failure of the adhesive, which allowed pressurized gas to enter through the gap at the failure point. The structural failure of the adhesion zone could be easily addressed by changing the material of the PMD to a higher strength material, but it was considered difficult to address the problem of the lower nozzle being completely exposed during deceleration by changing only the PMD. We designed and fabricated a sloshing suppression device using a cylindrical structure.

In the future, in order to evaluate the performance of the sloshing suppression device, we will conduct a running test using the High-Speed Test Track at the Shiraoi Engine Test Field of Muroran Institute of Technology to observe the flow behavior in the tank, and evaluate the effect of the shape. After that, a running test will be conducted with a combination of propellant management device and sloshing suppression device to investigate the discharge characteristics.

References

1) Takuya WADA, Miu MANABE, Aoki ANADA, Daisuke NAKATA, Masaharu UCHIUMI and Ryoji IMAI, Study on Propellant Management Device for Small-scale Supersonic Flight Experiment Vehicle (Improvement and Evaluation Test), Int. J. Microgravity Sci. App., submitting.
2) Keiji KOMATSU, Sloshing Liquid level fluctuations and tank vibrations, 1st ed., Morikita Publishing Co., Ltd. (2015)