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小型超音速飛行実験機燃料タンク向け推薬捕捉機構の開発

Development of a propellant capture device for Small-scale Supersonic Flight Experiment Aircraft Fuel Tanks

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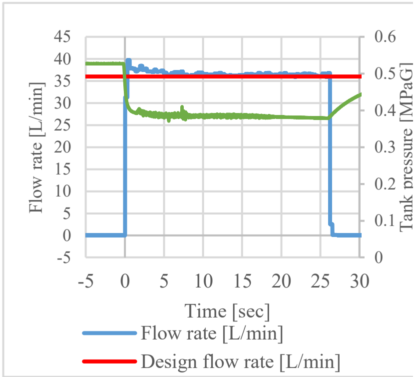
Abstract: The Aerospace Research Center at Muroran Institute of Technology is developing a small supersonic flight test aircraft that uses bioethanol (BE) and liquid oxygen (LOX) as fuel. The fuel is supplied in liquid form under pressure using nitrogen gas. The center is currently engaged in the development of a propellant capture mechanism, which is intended to serve as a means of suppressing gas entrainment. This entrainment is caused by sloshing that occurs as a result of acceleration in the fuel tank. The resolution of this issue entailed the execution of liquid discharge experiments, which incorporated the propellant capture mechanism and sloshing suppression mechanism within a water environment. Consequently, stable liquid discharge was achieved at the design flow rate.



Keywords: Small-scale Supersonic Flight Experiment Aircraft, Propellant management device, Sloshing suppression device

1. Structure & style of the sections

1.1. The Propellant Management Device (PMD)

Figure 1 shows the 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 training. 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}:

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

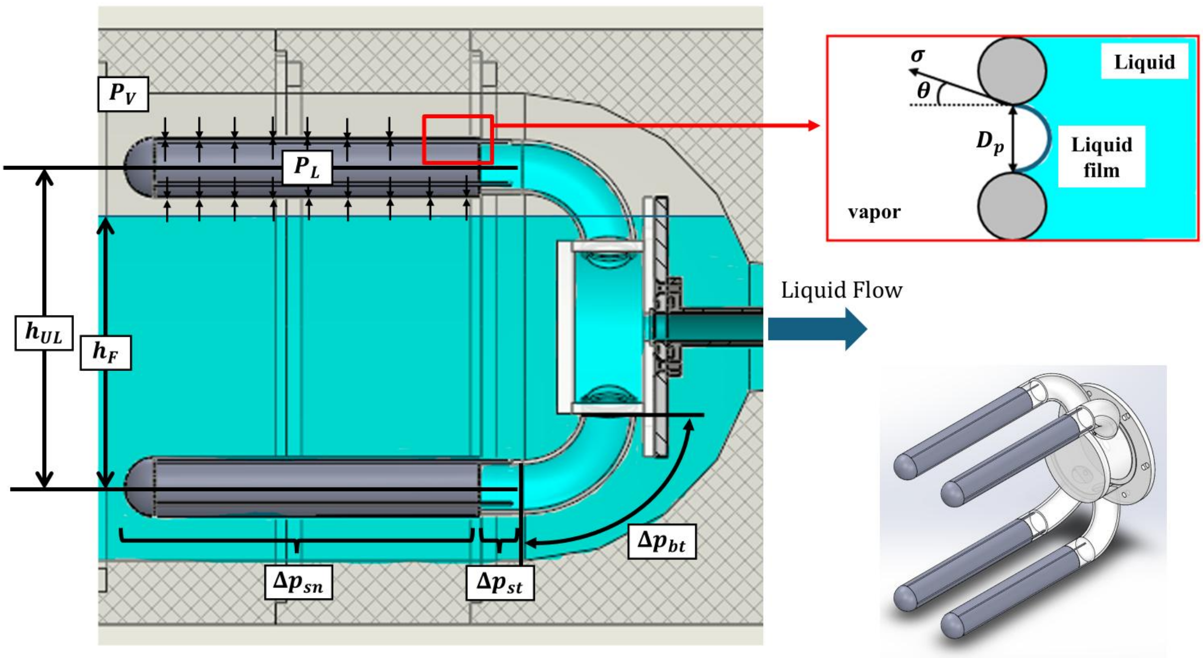


Figure 1. Structure of the Propellant Management Device (PMD).

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)]

1.2. Sloshing suppression device

Figure 2 shows the structure of the Sloshing suppression mechanism**.** A cylindrical sloshing suppression device is installed in the tank's center to prevent sloshing. This increases the contact area between the liquid fuel and the solid wall, leading to enhanced viscous stress damping. Inside the cylinder, sloshing is suppressed using ring baffles, a common method for reducing lateral sloshing[2)]. Thus, sloshing is suppressed from both the inside and outside of the cylinder, reducing sloshing throughout the entire tank.

Metal mesh is used on the walls of the sloshing suppression device to suppress sloshing and prevent liquid fuel from remaining inside the mechanism. This is because the metal mesh allows liquid to pass through, and the surface tension of the liquid forms a liquid film on the metal mesh, which can be regarded as a pseudo-solid wall.

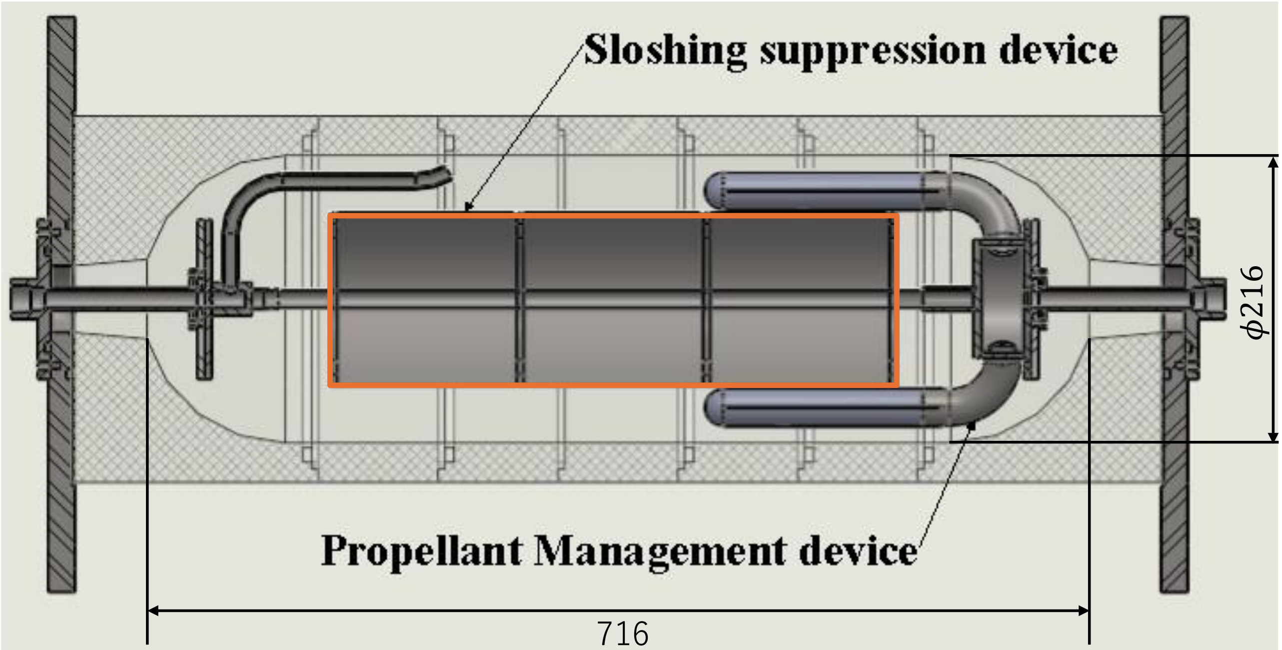


Figure 2. Sloshing suppression device.

2. Experimental Method

2.1. Liquid discharge test under static conditions

PMD is attached to a full-scale transparent polycarbonate resin tank, and liquid discharge experiments are conducted using a high-speed orbital experiment device. **Figure 3** shows a drawing of the test tank. This allows for the evaluation of the gas entrainment suppression performance of the propellant capture mechanism under acceleration conditions. Pure water is utilized as the liquid medium, while GN2 is employed as the pressurized gas under constant experimental conditions.

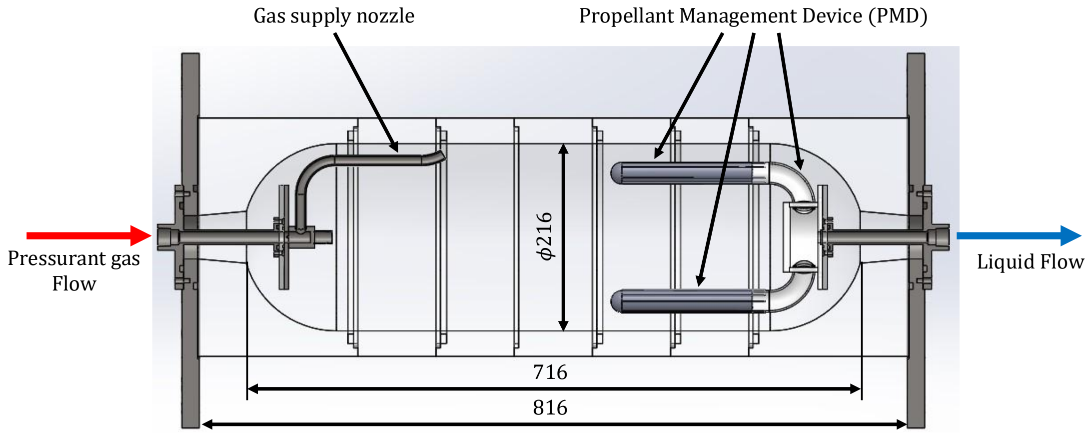


Figure 3. Test tank and inner structure.

Figure 4 shows the test system. The test tank is connected to the gas supply line, the test liquid supply line, and the 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. Prior to the introduction of liquid into the tank, the tank is subjected to a process of evacuation. This process is intended to remove air from the PMD. The tank is then filled with liquid under conditions of vacuum. The pressurization of the tank and subsequent discharge of the liquid is facilitated by the supply of GN2 from the cylinder. In order to ascertain whether gas entrainment occurs during liquid discharge, a camera is utilized to photograph the interior of the tank and the propellant capture mechanism from the lateral perspective.

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. The experimental conditions for this experiment are shown in **Table 1**

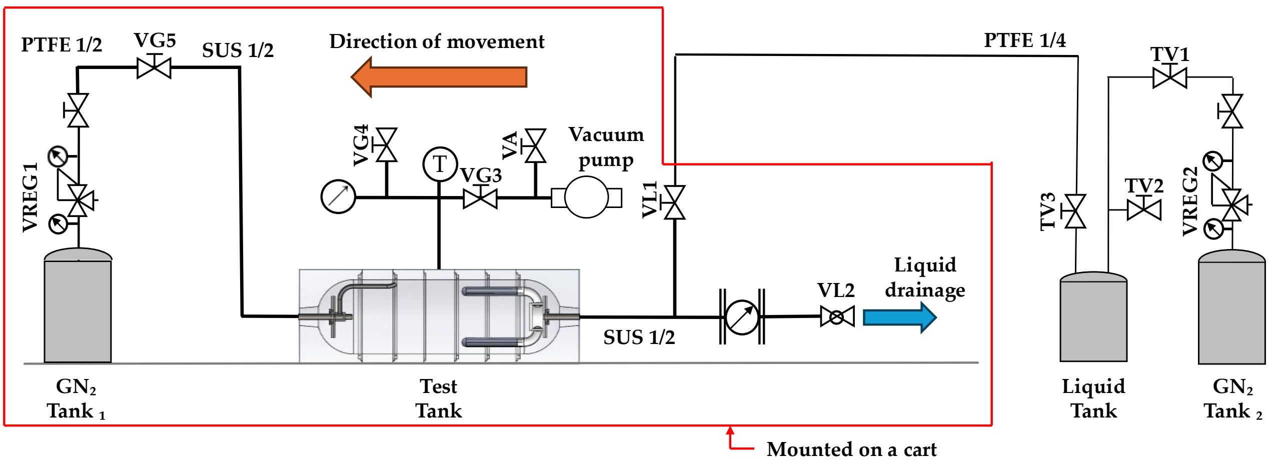


Figure 5. Test system of liquid discharge test under acceleration conditions.

Table 1. Experimental Conditions

Item	Set value
Test Liquid	Pure water
Pressurized gas	Nitrogen
Initial pressure	0.65 [MPaG]
Supply pressure	0.65[MPaG]

3. Experimental results and discussion

3.1. Liquid discharge test under acceleration conditions

Figure 6 shows the changes in discharge flow rate and tank pressure over time during the experiment, and **Figure 7** shows a graph recording the acceleration history. The graph displays the acceleration history. In this experiment, an acceleration of approximately 1.5G was applied during acceleration and approximately 2G during deceleration. With respect to liquid discharge, stable liquid discharge at a design flow rate of 36 L/min or more was achieved for approximately 12 seconds from the start. However, the presence of gas entrainment into the PMD was observed when the lower nozzle was exposed. The reduction in liquid inside the tank caused by liquid discharge and the resulting liquid movement has been shown to result in a reduction of liquid contact area with the mesh, thereby increasing the flow velocity through the mesh. Consequently, the flow loss escalates, leading to the dissolution of the liquid film that forms on the mesh surface and the subsequent entrainment of gas. Given the propellant capture mechanism's inability to fully impede gas entrainment, the necessity of a sloshing suppression mechanism has been demonstrated. Furthermore, damage was observed at the bonding points between the cylindrical section and the nozzle section of the propellant capture mechanism following the experiment. This finding underscores the necessity to augment the structural integrity of the propellant capture mechanism.

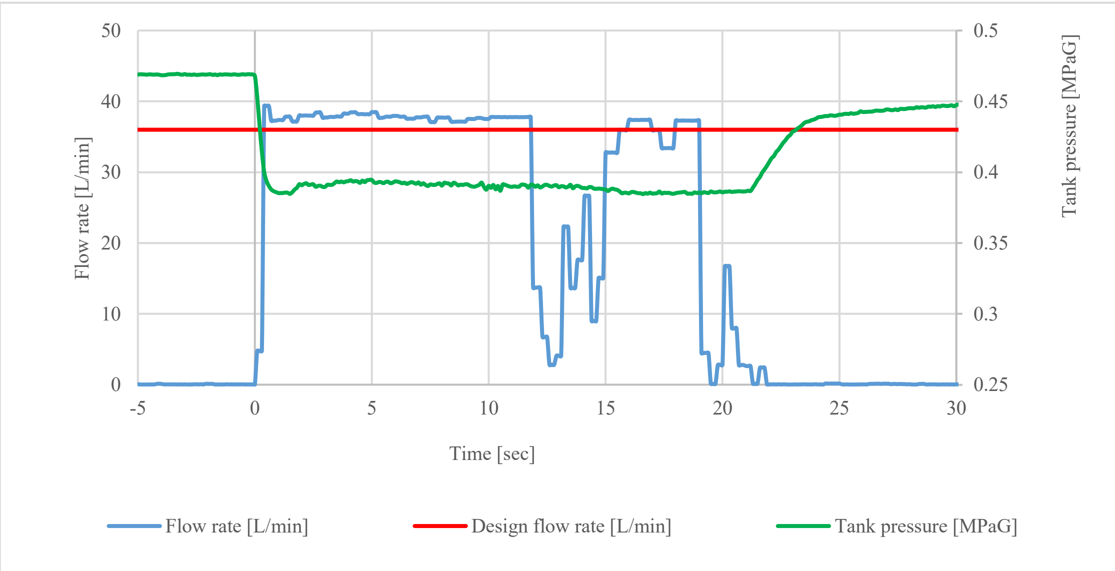


Figure 6. Results of liquid discharge test under PMD performance evaluation test.

3.2 Investigation of the effects of using metal PMD on a liquid discharge experiment

A new experiment was conducted to assess the structural strength of a metal PMD. This experiment was initiated in response to the damage observed to the PMD in the liquid discharge experiment. Furthermore, a liquid discharge experiment was conducted under static conditions to compare the performance of the PMD utilized in the experiment. **Table 2** shows a comparison of the experimental results, and **Figure 7** shows a comparison of the changes in flow rate over time. The findings indicated that there was no statistically significant change in the liquid discharge time when comparing the metal PMD with the conventional polycarbonate (PC) PMD, in which gas entrapment is easily observed. Additionally, given that the discharge flow rate of the metal PMD exceeds that of the previous PMD, it can be concluded that the impact of utilizing the metal PMD is minimal.

Table 2. Comparison of experimental results.

Measurement items＼PMD	Metal	PC
Discharge time[sec]	35.1	35.9
Flow rate[L/min]	37~40	36~38
Volume of liquid discharged[L]	22.0	22.3

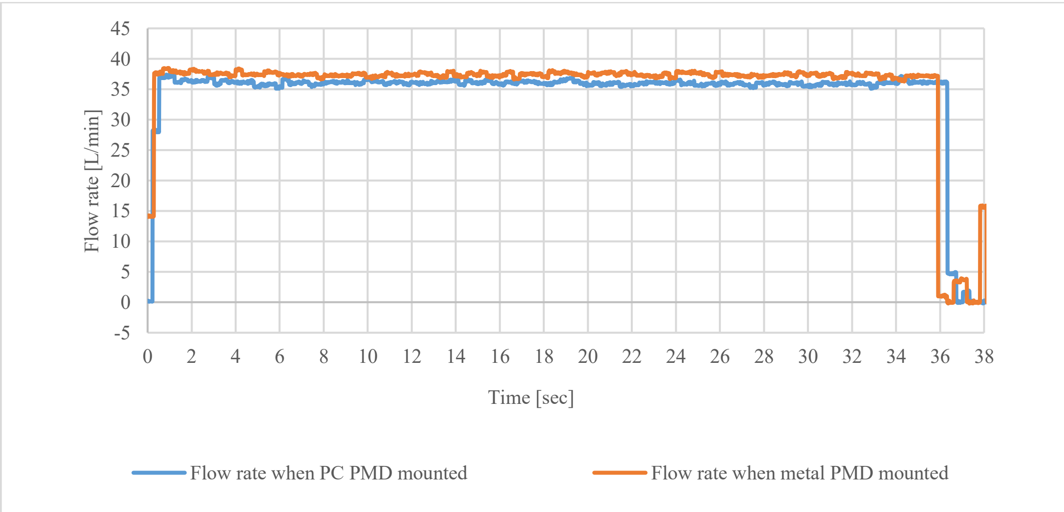


Figure 7. Comparison of time variation of flow rates.

4. The present study will investigate the effects of installing a sloshing suppression device

An investigation was conducted into alterations in liquid discharge characteristics in the context of the implementation of a sloshing suppression mechanism. The outcomes obtained when the sloshing suppression mechanism was installed within the tank were then compared with the results in 3. **Table 3** presents a comparison of the experimental results, and **Figure 8** shows a comparison of the changes in flow rate over time. At this time, the volume of the sloshing suppression mechanism was approximately 0.3 L. The graph shows that there is no significant difference between the items with and without the sloshing suppression mechanism installed.

Table 3. Comparison of experimental results.

Measurement items＼Device	With	Without
Discharge time[sec]	35.1	35.9
Flow rate[L/min]	37~40	36~38
Volume of liquid dischareged[L]	22.0	22.3

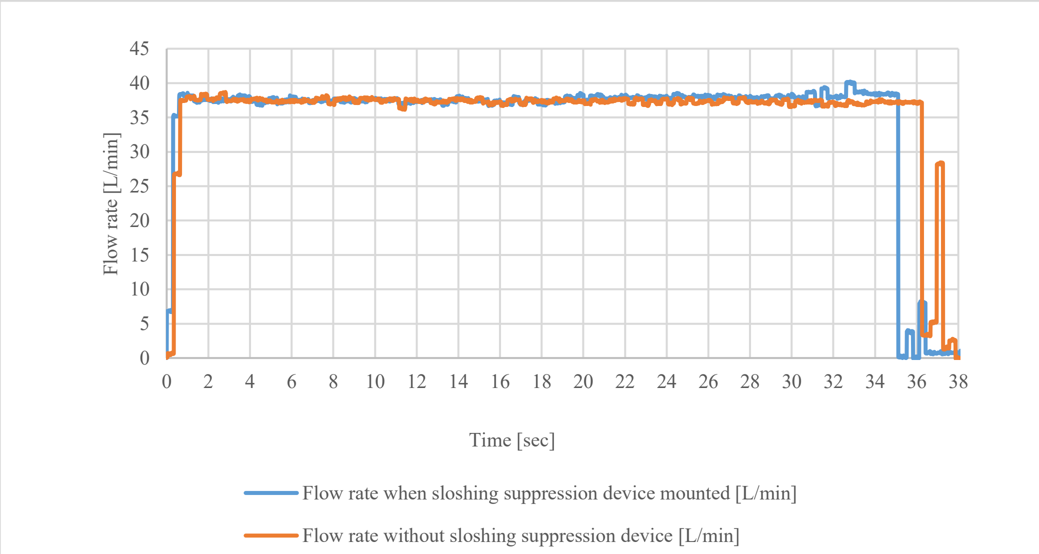


Figure 8. Comparison of time variation of flow rates.

5. The present study will investigate the effects of installing a sloshing suppression device

Table 4 shows the experimental conditions and results of this experiment, **Figure 9** shows a graph recording the changes in discharge flow rate and tank pressure over time during the experiment, and **Figure 10** shows a graph recording the acceleration history. In this experiment, accelerations of approximately 2G during acceleration and approximately 1.5G during deceleration were applied Regarding liquid discharge, stable liquid discharge at the design flow rate of 36 L/min was achieved throughout the entire duration from the initiation of the process to its conclusion. Furthermore, the behavior of the liquid within the tank, as influenced by the sloshing suppression mechanism, was confirmed to result in a flat liquid surface during acceleration. In contrast, the other

Table 4. Experimental Conditions and Results.

Item	Set value
Test Liquid	Pure water
Pressurized gas	nitrogen
Initial pressure	0.65 [MPaG]
Supply pressure	0.65[MPaG]
Gas entrainment occurrence	No

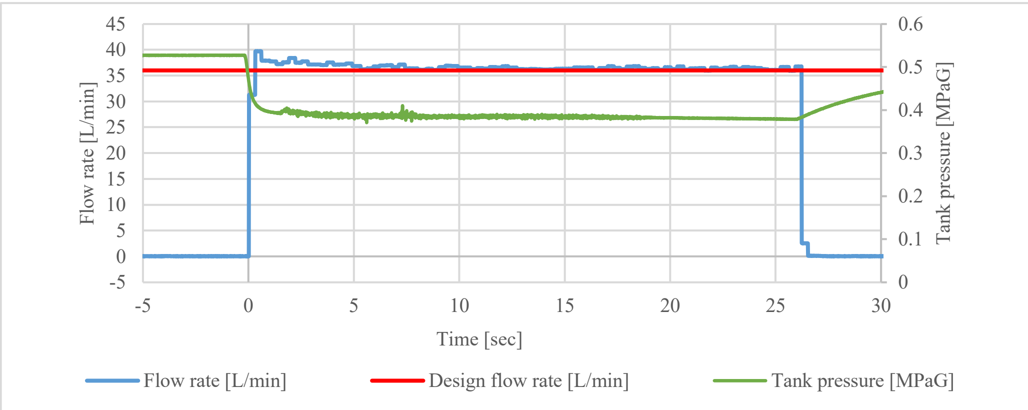


Figure 9. Results of liquid discharge test under sloshing suppression device performance evaluation test.

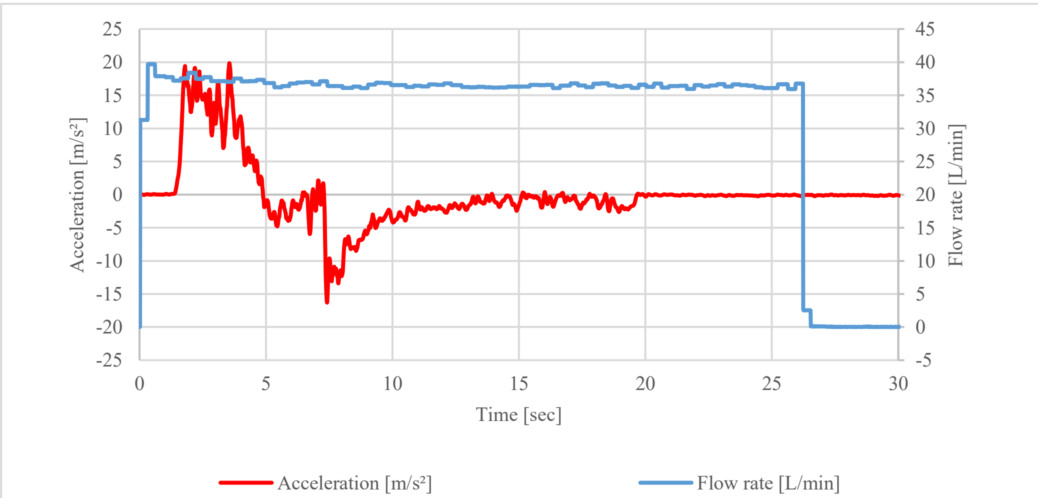


Figure 10. The acceleration history of liquid discharge under sloshing suppression device performance evaluation test.

6. Conclusion

In this study, the objective was to solve the problem of pressurized gas entrainment in the liquid tank of a small supersonic flight test aircraft. To this end, a propellant capture mechanism and a sloshing suppression mechanism were developed and installed inside the liquid tank. The performance of these mechanisms was evaluated under static and acceleration conditions. In the liquid discharge experiment under acceleration conditions using only the propellant capture mechanism, gas entrainment occurred due to the exposure of the lower nozzle, and stable discharge could not be achieved throughout the entire range from the start to the end of discharge. This finding suggests that the suppression of gas entrainment through the propellant capture mechanism alone is constrained by inherent limitations. In the context of acceleration conditions, the implementation of the sloshing suppression device ensured the consistent and reliable discharge of liquid at the predetermined flow rate of 36 liters per minute. This stability in liquid discharge persisted throughout the entirety of the discharge process, from its initiation to its culmination. The integration of a propellant capture mechanism with a sloshing suppression device is anticipated to facilitate the development of a stable system for liquid discharge,

References

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