JASMAC
Conference of the Japan Society of Microgravity Application

OR2-2

小型超音速飛行実験機における 酸化剤タンク内模擬推薬熱流動挙動に関する研究 （タンク内熱流動解析技術の開発）

Study on Thermal-Hydraulic Behavior of Simulated Propellant in Oxidant Tank of Small Hypersonic Flight Experiment Aircraft（Development of thermal hydraulic analysis technology in tank）

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1. Introduction

Recently, the next generation supersonic transport and Spaceplane have been studied. The Aerospace Plane Research Center of Muroran Institute of Technology is developing the small-scale supersonic flight experiment vehicle as a flying test bed for technical demonstration in high-speed flight environment. The propellant tank is shown in **Fig. 1**. In the small-scale supersonic flight experiment vehicle, liquid supplying system for Bioethanol and LOX by pressurant gas has been studied. Since LOX is a cryogenic liquid, the pressurant gas is cooled by LOX and the inner wall of the tank when the propellant is supplied. When the pressurant gas is cooled, the amount of gas required for pressurization increases. The shortage of pressurant gas makes it impossible to maintain the pressure inside the tank, which adversely affects the propellant supply. However, excessive gas loading will cause the pressurant gas tank to become excessive, which will adversely affect the weight of the vehicle. Therefore, it is necessary to predict the amount of pressurant gas loaded [1)]. The purpose of this paper is to develop a design technique for a propellant supply system for the cryogenic propellant tank of the Small Hypersonic Flight Experiment aircraft. In a previous study, liquid discharge experiments were conducted using a simulated propellant. Using the results, a CFD analysis was performed considering the thermal hydraulics in the tank. In this study, the objective is to consider phase changes to improve the CFD analysis.

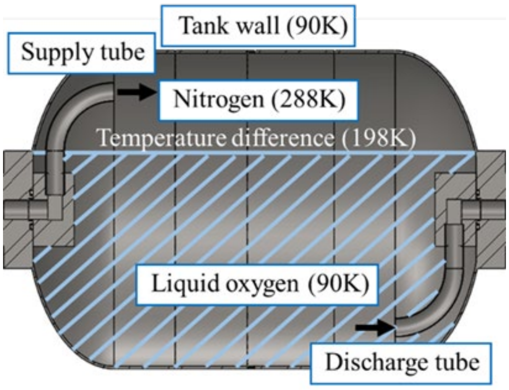

Figure. 1 Propellant tank

2. Experimental Method

Figure. 2 shows the measurement points of the internal temperature of the test tank, with the numbers starting from the bottom. The experimental set up is shown in **Fig. 3** and the experimental conditions in **Table.1**. Experiments were conducted using simulated propellant to confirm the thermal-hydraulic behavior in the cryogenic propellant tank. In this experiment, we used a test tank (216.3 mm in diameter, 311.3 mm in length, and 8.8 L in filling capacity). The material of the test tank was SUS304 because cryogenic liquid was used as propellant. A heat insulator was installed to prevent heat input. For the simulated propellant, liquid nitrogen with a close saturation temperature was used instead of LOX. And liquid nitrogen is also safer than LOX. Helium gas was used as the pressurizing gas. The liquid nitrogen was filled into the test tank from a self-pressurizing liquid nitrogen container. After the filling was completed, the inside of the tank was pressurized with helium gas, and the liquid nitrogen started to be discharged. PLC (programmable logic controller) was used for the pressure control system. Bang-bang control was used to regulate the pressure[2)]. When the pressure gauge reaches the lower limit of the target pressure, the electromagnetic valve opens. The electromagnetic valve is set to close when the pressure gauge reaches the upper limit. The measurement items were the temperature of the fluid inside the test tank (16 points), the temperature of the outer wall (3 points), the pressure inside the test tank, the pressurized gas flow rate, the pressurized gas temperature, and the liquid discharge temperature. A T-type thermocouple (sheath outer diameter: 0.5 mm) was used for temperature measurement. The liquid discharge flow rate of liquid nitrogen was calculated from the change in weight using a digital bench scale.

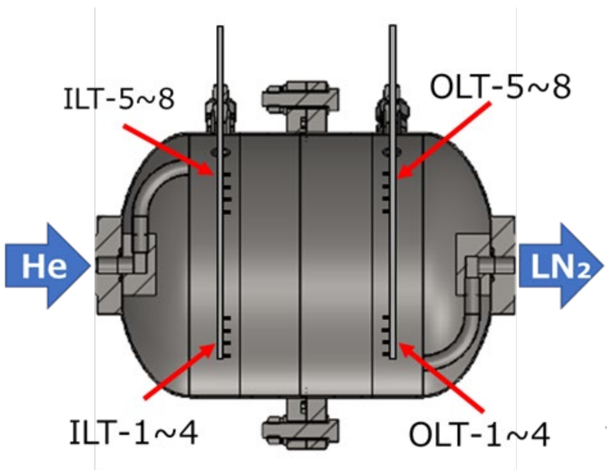

Figure. 2 Temperature measurement point

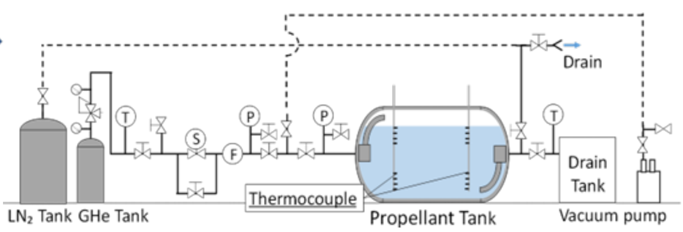

Figure. 3 Test system

Table.1 Experimental conditions	
Flow rate [L/sec]	0.3
Target Pressure [MPa]	0.2
Upper Limit [MPa]	0.205
Lower Limit [MPa]	0.195
Upstream Pressure [MPa]	0.4
Time[sec]	25

3. Analysis Method

The analytical conditions are shown in **Table.2**. **Table.2** shows the average values obtained from the experimental results. The thermal-hydraulic behavior in the tank is obtained using ANSYS FLUENT. The VOF method is used to simulate gas-liquid two-phase flow. And the liquid discharge characteristics are analyzed by considering the thermal flow in the tank. As the initial conditions, tank temperature is 80 K, a tank pressure is 0.2 MPa, and a liquid level is 180 mm. The analytical domain is the inside of the test tank and the solid wall, and these are treated two-dimensionally. The discharge flow rate of liquid nitrogen is inputted at the outlet, and the pressurized gas temperature is inputted at the inlet. These values are given as time variations from each experiment. The pressure inside the tank is given at a constant 0.2 MPa. Therefore, we simulate the situation of liquid discharge inside the tank. The basic equations are the equation of motion, the equation of energy, and the conservation equation of volume fraction (VOF). The flow field is assumed to be turbulent. The density, specific heat, heat transfer coefficient, and viscosity depend only on temperature in the gas and -liquid phase. A LeeModel was used to account for phase change. **Table.3** shows the equation of the LeeModel. The results of the analysis with and without phase change are compared.

Table.2 Analytical conditions	
Flow Rate [L/sec]	1.71
Helium Temperature [K]	291.49

Table.3 LeeModel equation		
$\dot{m}_{lv} = coeff_e \times \alpha_l \rho_l \frac{(T_l - T_{sat})}{T_{sat}}$	$(T_l > T_{sat})$	Evaporation rate
$\dot{m}_{vl} = coeff_c \times \alpha_v \rho_v \frac{(T_{sat} - T_v)}{T_{sat}}$	$(T_v < T_{sat})$	Condensation rate
α: volume fraction, **ϱ**: density, **T**: temperature, **m**: mass transfer rate (kg/sec/m^3)		
subscript **l**: liquid phase, subscript **v**: gas phase, subscript **sat**: saturation		

4. Temperature comparison and discussion

Figure. 4 displays the volume fraction of nitrogen gas. The yellow and green lines show the liquid level of liquid nitrogen. Below the lines represent the liquid. Above the line represents gas. Nitrogen gas is generated above the lines. Therefore, we can see that a phase change is taking place.

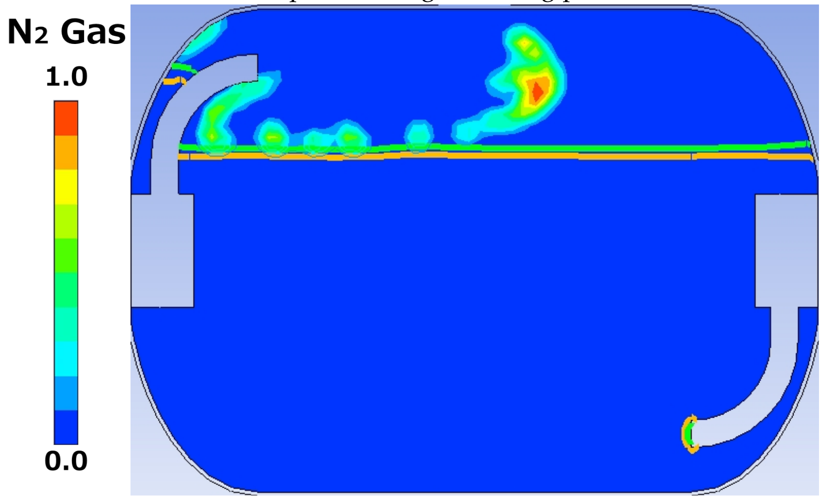

Figure. 4 Volume fraction of nitrogen gas

Next, the temperature results of the analysis without and with phase change are compared in the Contour diagram. The one without phase change is placed on the left. The one with phase change is placed on the right. The number of seconds is 5, 10, 15, 20, and 25 seconds. The temperature is lower overall for the one with phase change. The temperature is lower due to the latent heat of vaporization during the phase change.

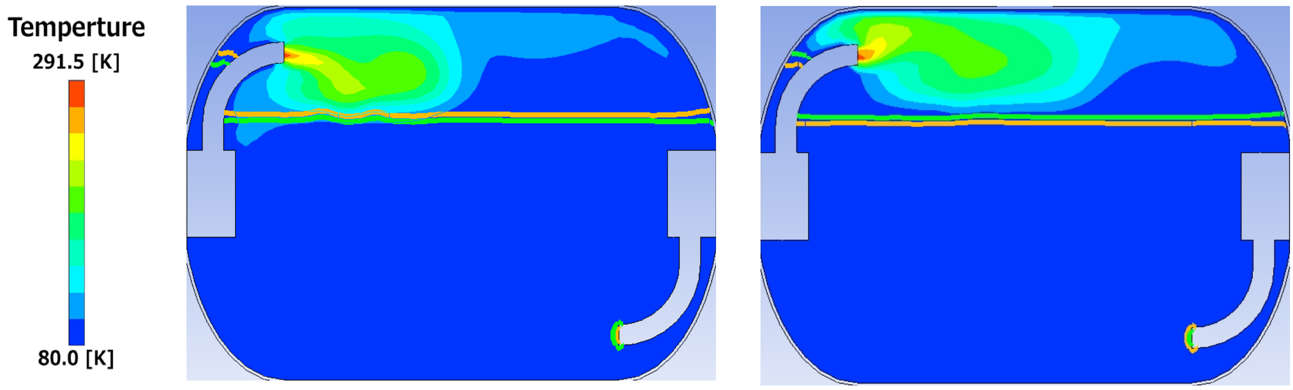

Figure. 5 Without phase change and With phase change [5sec]

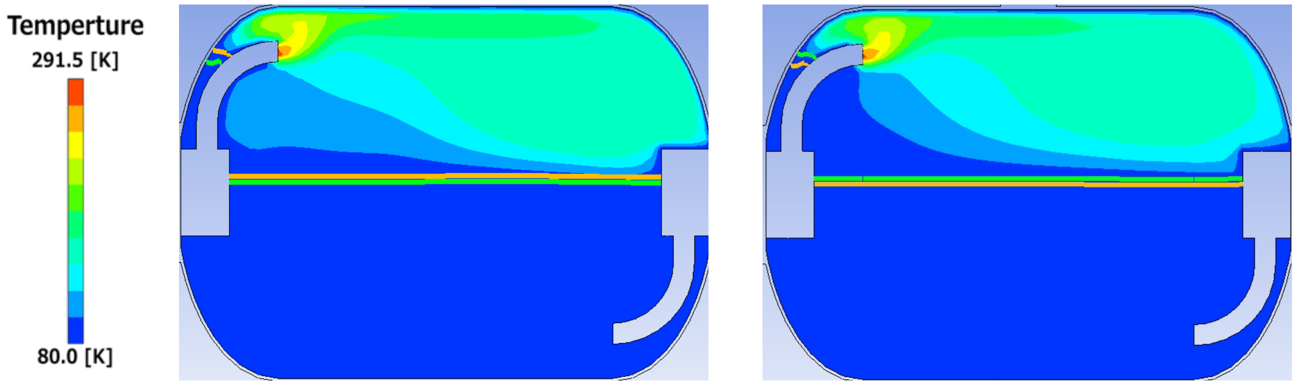

Figure. 6 Without phase change and With phase change [10sec]

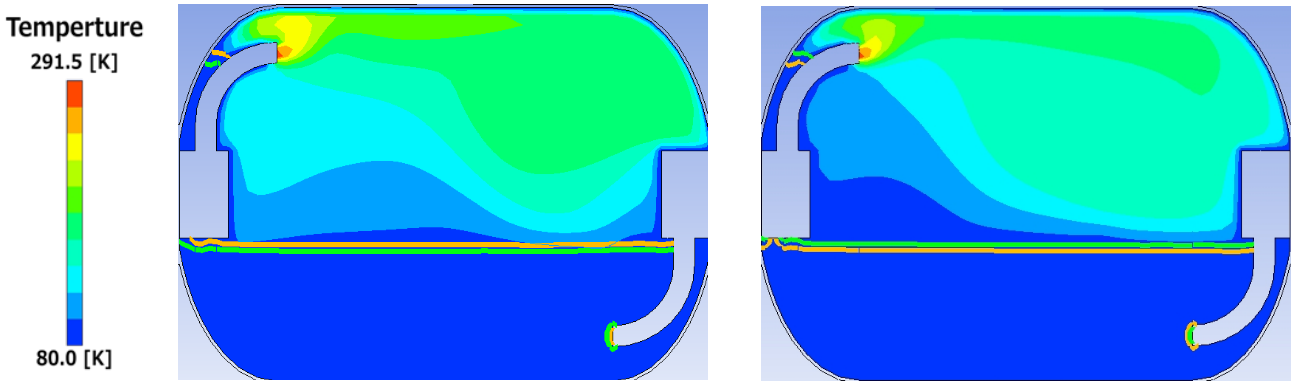

Figure. 7 Without phase change and With phase change [15sec]

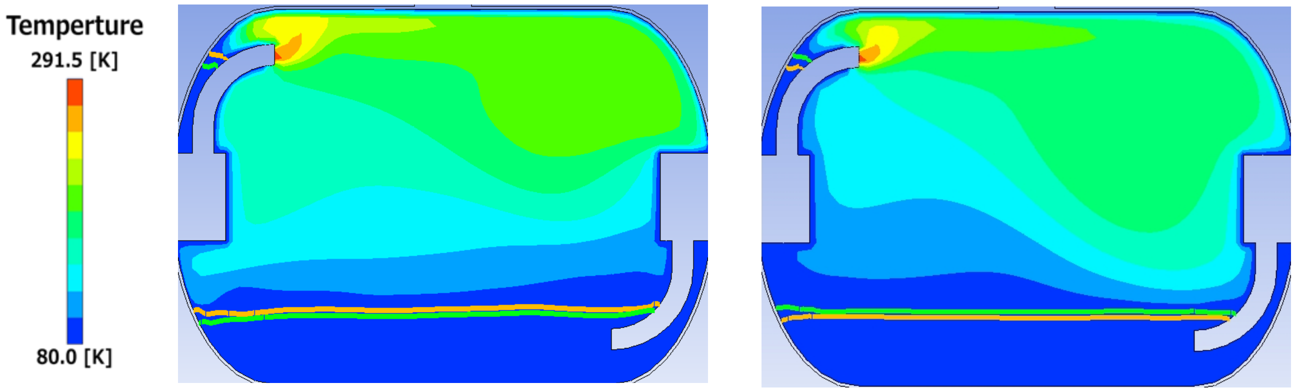

Figure. 8 Without phase change and With phase change [20sec]

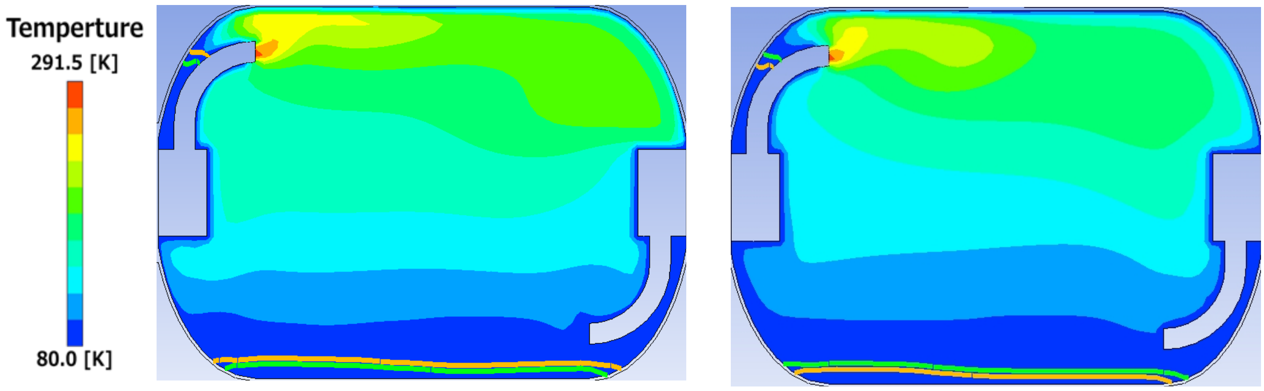

Figure. 9 Without phase change and With phase change [25sec]

Finally, the temperature results of the analysis without and with phase change are compared graphically. **Figure. 10** shows the temperature change at the top of the tank on the inlet side. **Figure. 11** shows the temperature change at the under of the tank on the inlet side. **Figure. 12** shows the temperature change at the top of the tank on the outlet side. **Figure. 13** shows the temperature change at the under of the tank on the outlet side. The dotted line in the graph shows no phase change and the solid line shows phase change. The triangular dots represent experimental values. **Figure. 11,13** shows that the temperature is kept below 80 K at the bottom of the tank. The temperature measurement point at this point is below the free surface. Comparing the two, the analysis that does not consider the phase change shows a temperature increase in the liquid. However, in the analysis considering the phase change, the temperature rise in the liquid is eliminated. Phase change has the effect of lowering the surrounding temperature by vaporization. Therefore, it is reasonable that the temperature rise in the liquid is eliminated. Next, in both **Fig. 10** and **Fig. 12**, the temperature at the top of the tank rises as the liquid is discharged. However, the analysis considering the phase change mitigates the temperature spike. In addition, the analysis considering the phase change shows lower temperatures overall. The reason is that the phase change of liquid nitrogen has the effect of absorbing heat and lowering the ambient temperature. The temperature is then lowered by the mixing of the vaporized heat in the gas phase. Therefore, the effect of the temperature change inside the tank due to the presence or absence of phase change was confirmed. However, it is far from the experimental value and needs to be improved.

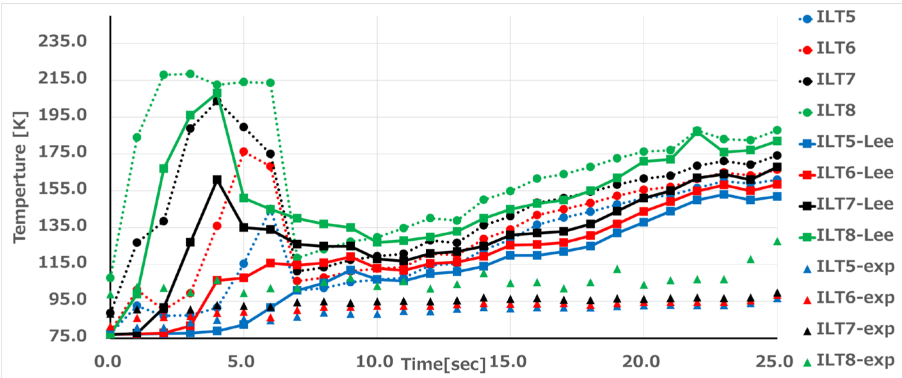

Figure. 10 Temperature change at the top of the tank on the inlet side

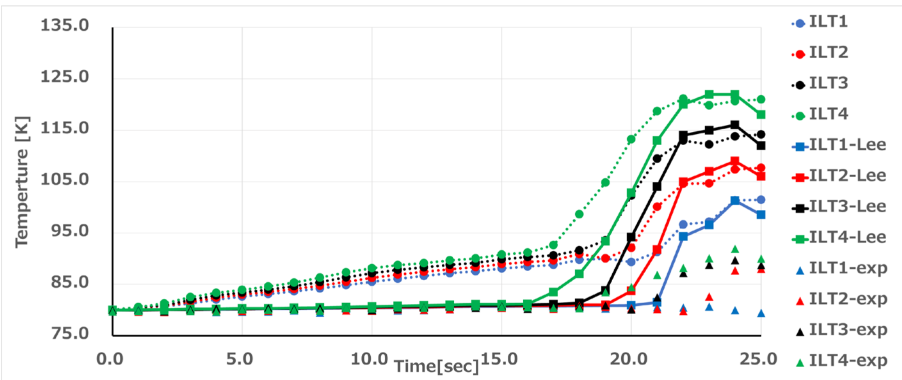

Figure. 11 Temperature change at the bottom of the tank on the inlet side

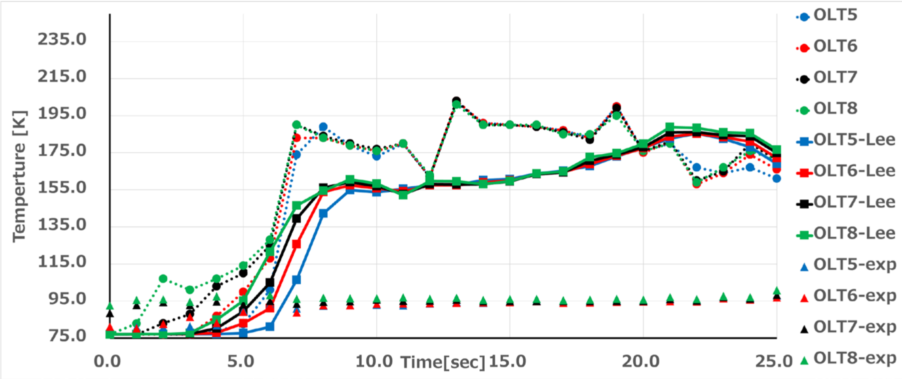

Figure. 12 Temperature change at the top of the tank on the outlet side

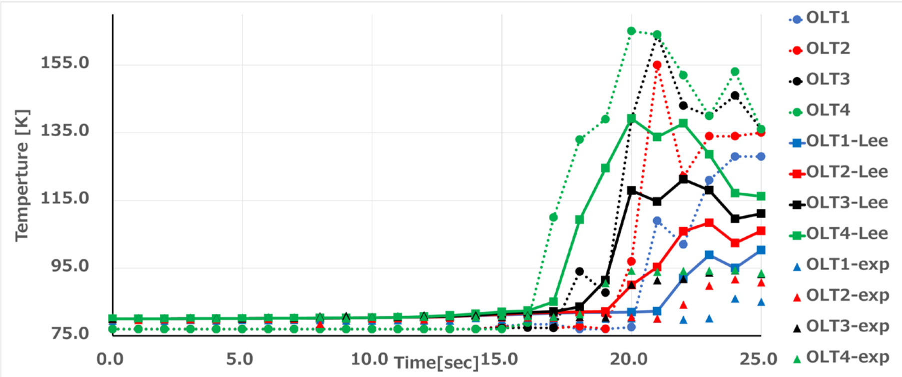

Figure. 13 Temperature change at the bottom of the tank on the outlet side

5. Conclusion

The temperature variation of the results of the analysis with and without phase change was compared. In the liquid phase, the temperature increase was eliminated and the validity was improved. In the gas phase, the temperature spike was mitigated. In the future, the temperature of the pressurized gas will be determined by analysis. The validity of the analysis will then be improved by adapting the obtained values.

References

1) Yukiya SATO, Ryoji IMAI, Daisuke NAKATA, Ryojiro MINATO, Masaharu UCHIUMI, Study on Propellant Supply System for Small-scale Supersonic Flight Experiment Vehicle (Development of LOX Supply System design technology), International journal of Microgravity Science and Application, 2019.

2) Ryoji IMAI, Yuki KAMEYA, Norio SUGI, Takuma INOUE, Shinichiro ISHIZAKI, Masumi FUJITA, Isao KUBOTA, Thermo-Fluid Analysis and Evaluation Test in Propellant Tank for Rocket Propellant System, 62nd Space Sciences and Technology Conference, 2018.