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極低温推進システム向けジェットミキシングを用いたサーモダイナミックベントシステムに関する研究(ジェット挙動の数値解析と検証実験)

Study on Thermodynamic Venting System with Jet Mixing for Cryogenic Propulsion Systems (Numerical Analysis of Jet Behavior and Verification Experiment)

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1　Introduction

Currently, space exploration organizations such as ISECG are planning further exploration into deep space, using the Moon as a gateway. This plan is expected to require longer missions and larger payloads for transportation systems than conventional space exploration. To solve these problems, cryogenic propellant propulsion systems with high specific impulse, such as those fueled by liquid hydrogen (LH2) or liquefied natural gas (LNG) and oxidized by liquid oxygen (LOX), will be used[1)]. However, when these propellants, which are classified as cryogenic liquids, are stored on long-duration missions, the propellant temperature rises and evaporates due to sunlight and heat input from the engine, causing the tank pressure to rise. Therefore, spacecraft operated in long-distance space transportation systems require propellant tank pressure control.

Therefore, the target of this research is to develop a TVS (Thermodynamic Vent System) as a method to realize long-term storage of cryogenic propellant by managing and controlling the thermal fluid behavior inside and outside the propellant tank2). Previous study has included ground-based experiments to demonstrate the effectiveness of jet mixing, one of the components of TVS[2)].

However, as this research progresses, it will be necessary to conduct microgravity experiments to simulate operation in a space environment. Conducting multiple such experiments is difficult due to the large amount of expense and labor required; if a model can be established that accurately predicts the behavior of jet mixing using CFD, the development of TVS with jet mixing can be made more efficient. Therefore, the objective of this study was to establish a CFD-based jet mixing prediction model.

2 Theory and Methodology

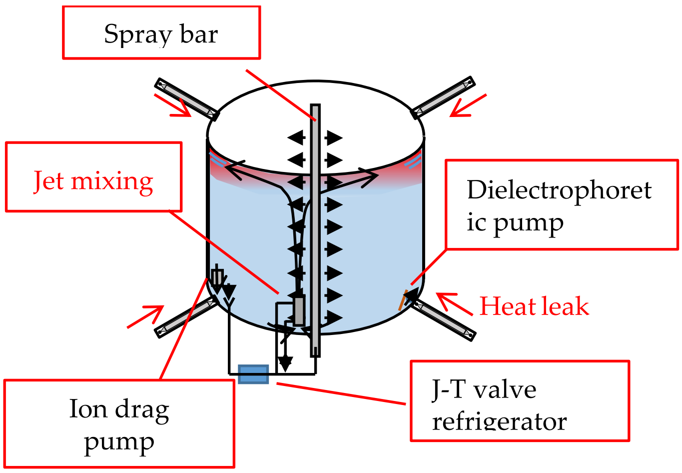


Figure.1 TVS over view

Fig.1 shows a schematic diagram of jet mixing. When the spacecraft receives heat from the sun, natural convection creates a temperature gradient in the tank and the gas-liquid interface becomes high temperature.
When the gas-liquid interface reaches saturation temperature, a large amount of BOG is generated and tank pressure increases. In jet mixing, liquid propellant taken out of the tank is subcooled by a refrigerator and injected through a nozzle at the bottom of the tank to cool the gas-liquid interface by forced convection, thereby suppressing BOG (Boil Off Gas).

Jet mixing can be efficiently developed and verified by creating a model that accurately predicts jet behavior through numerical analysis and incorporating it into development. In the previous study, a comparison was made between experimental values obtained from jet mixing experiments in a tank with temperature stratification and analytical values obtained from numerical analysis based on the experiments in order to evaluate and improve the jet behavior prediction model using numerical analysis. The comparison is based on temperature and jet behavior. However, there is a large discrepancy between the experimental and analytical values, and the jet behavior is not accurately predicted. Therefore, in this study, we aimed to achieve agreement between the experimental and analytical values by simplifying the experimental and analytical conditions. Specifically, jet mixing was performed in a homogeneous temperature field without forming a temperature stratification in the tank, and numerical analysis was performed based on the obtained data to compare the experimental and analytical values.

3 Jet mixing experiment

3.1. Experimental Apparatus and Techniques

Fig.2 shows a schematic diagram of the experimental apparatus. This experimental apparatus was developed based on the one used at the University of Hyogo[3)]. In this experiment, after forming a homogeneous temperature field by injecting pure water into the test tank, jet mixing is performed by supplying a jet that has been given a subcooling degree by a heat exchanger into the test tank. As a method of giving subcooling to the jet, a cooling loop is constructed from the reserve tank, where the jet liquid is stored, through the gear pump, flow meter, and heat exchanger, returning to the reservoir tank. The temperature of the jet liquid in the cooling loop is measured by thermocouple TC-1. The right side of Fig.2 shows an overview of the test tank. The test tank is made of copper and heat-resistant glass (Tempax float) to observe jet behavior during jet mixing. TC-3 to TC-9 in the Fig.2 are thermocouples to measure the liquid temperature in the tank. In the experiment, pure water is injected into the test tank to form a homogeneous temperature field, and when the liquid temperature in the tank and the jet temperature in the cooling loop reach a predetermined difference, the three-way valve is switched to supply a cooling jet into the test tank. The jet liquid temperature after switching the three-way valve is measured by thermocouple TC-2.

Next, a visualization method for jet behavior is described. In this experiment, the backlight method is used to visualize the jet behavior. An LED light source was installed behind the test tank, and a digital video camera was used to capture images. The jet liquid was stained with food coloring.

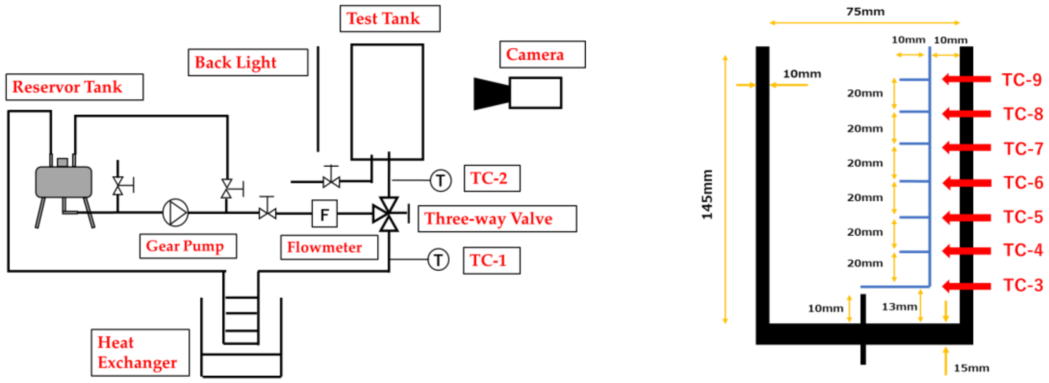


Figure.2 Overview of experimental apparatus

3.2. Experimental Condition

Table 1 shows the experimental conditions. Flow rate in the table show the time-averaged value of the jet during jet mixing, and temperature difference is the difference between the temperature near the liquid surface and TC-1 immediately after the jet is fed.

Table.1 Experimental Conditions

Exp.No	Exp-1
Flow rate [mL/min]	59.44
Jet supply time [sec]	9.5
Liquid level [mm]	60
Temperature difference [K]	14.67

3.3 Experimental results

Figure.3, and Fig.4 shows the results of the Exp-1 experiment. Since the liquid level in this experiment was 60 mm, we focused on the temperature change of thermocouples TC-4 and TC-5 in the liquid phase. As a result, the temperature at the thermocouple TC-4, which is closer to the tank bottom, was lower than that at thermocouple TC-5, which is near the liquid surface and is considered to be most susceptible to the influence of the low-temperature jet. The temperature of TC-5 should have dropped first because the jet diffused throughout the tank after reaching the liquid surface, but the temperature of TC-4 dropped after 2.0 seconds, while the temperature of TC-5 dropped after 5.0 seconds. One possible explanation for this phenomenon is the possibility of poor sensitivity of TC-5, but the detailed cause is unknown.

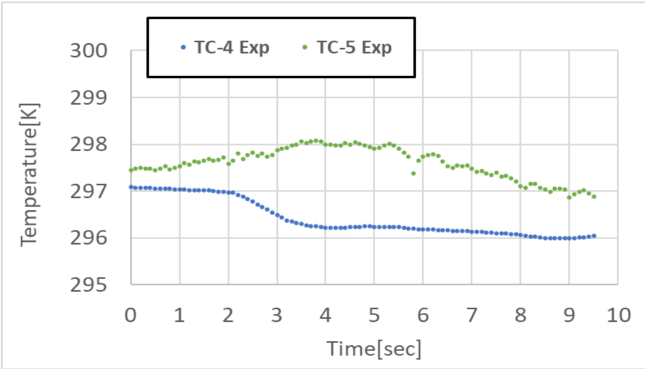
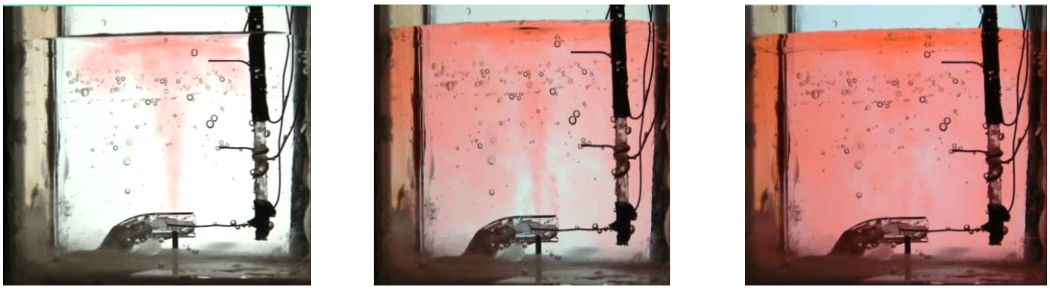


Figure.3 Temperature change in tank during mixing experiment



1.0sec **5.0sec** **9.5sec**

Figure.4 Images of jet behavior at each time

4 Developed Numerical Analytical Model

4.1 Numerical Analysis Summary

To develop an analytical model to predict jet behavior, a numerical analysis was performed based on the experimental values. The analytical model was based on the jet mixing analytical model developed by Kassemi et al[4]. A three-dimensional model of the test tank was created using ANSYS FLUENT by ANSYS, Inc. and the experimentally obtained values were input and analyzed.

4.2 Analysis conditions

As for the boundary conditions of the analytical model, values obtained from the experiment were input and set. The nozzle opening in the test tank was set as the velocity inlet, and the values measured by the flow meter during the experiment were input. As the outlet condition, the pressure outlet condition was set at the atmospheric opening of the test tank. The analytical model was created with the wall surface as the adiabatic condition, and heat input from the outside was not taken into account.

Fluid flow and heat transfer in the liquid and vapor phase regions of the tank are defined by the equations of motion, energy, volume fraction (VOF), and continuity. The turbulence model used was k-ωSST. The analysis range is from 0 second, the time when the jet begins to feed the tank, to the time when the jet feed ends. The main analytical conditions are listed below.

Table.2 Analysis conditions

Acceleration [m/sec]	y=-9.80665	Discretization method	
VOF Model		P-V Coupling Scheme	PISO
Time Discretization	Explicit	Gradient	Least Squares Cell Based
Courant Number	0.73567	Pressure	PRESTO!
Surface Tention Model	CSF	Momentum	Second Order Upwind
Initialization		Turbulent Kinetic Energy	
Temperature	Input from Experiment Data	Turbulant Dissipation Rate	
Pressure		Energy	
Velocity	0	Volume fraction	Geo-Reconstruct

These analytical conditions were set with reference to the analysis performed by Kassemi et al[4]. The time discretization method for the volume fractions was explicit, and the Courant number was derived by the following equation.

$$\Delta t_V = C\frac{\Delta x}{v_{fluid}} \tag{1}$$

Where Δt_V is the time step width in the analysis, v_{fluid} is the velocity normal to the interface, Δx is the mesh size, and C is the Courant number. In this analysis, the time step Δt_V was set to 0.001sec in consideration of the computer load and the number of days required for the analysis and v_{fluid} was the average flow velocity at the time of jet supply.

As for the physical properties of the fluid, the values of density, thermal conductivity, and viscosity are given as polynomials of temperature.

4.3 Analysis Results

A graph comparing experimental and analytical values of temperature in the tank during jet mixing is shown in Fig.5. Experimental values are plotted, and analytical values are shown as lines. The measurement points are thermocouples TC-4 and TC-5 placed inside the tank, and the tip of the thermocouple is used as the measurement point in the analysis. Fig.6 to 8 show the jet behavior photographed during the jet mixing experiment and temperature contour plots obtained by numerical analysis. The points in the temperature contour represent the temperature measurement points, TC-4 and TC-5 from the bottom of the tank. The lines in the temperature contour indicate the liquid surface.

The graph in Fig. 5 shows that the difference between the experimental and analytical values is less than 1K. The jet behavior taken by the experiment in Fig. 6 shows that the jet reaches the liquid surface and diffuses to the vicinity of thermocouple TC-5. However, the temperature contour

in Fig. 6 shows that the low-temperature jet does not reach the liquid surface, and the temperature graph shows no decrease in the temperature of TC-5 in both the experimental and analytical values. This is because the temperature of the jet increased due to heat exchange between the jet and the liquid in the tank before the jet reached the liquid surface. The jet behavior taken by the experiment in Fig. 7 and 8 shows that the jet diffuses throughout the tank along the liquid surface and wall surfaces. The temperature contours in Fig. 7 and 8 also show that the low-temperature jet diffuses throughout the tank, resulting in a decrease in the liquid temperature of the entire tank. From these results, it can be said that the experimental and analytical results are in good agreement and that a numerical model has been successfully developed to predict the jet behavior under the experimental conditions of Exp-1.

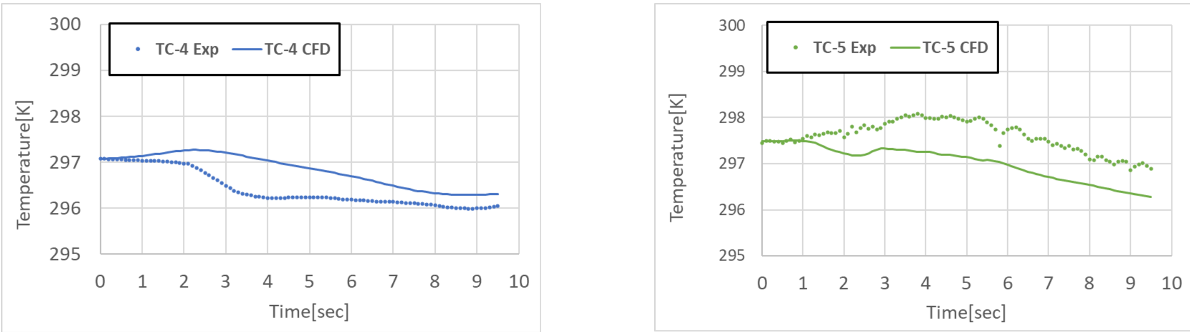


Figure.5 Comparison of experimental and analytical values according to temperature

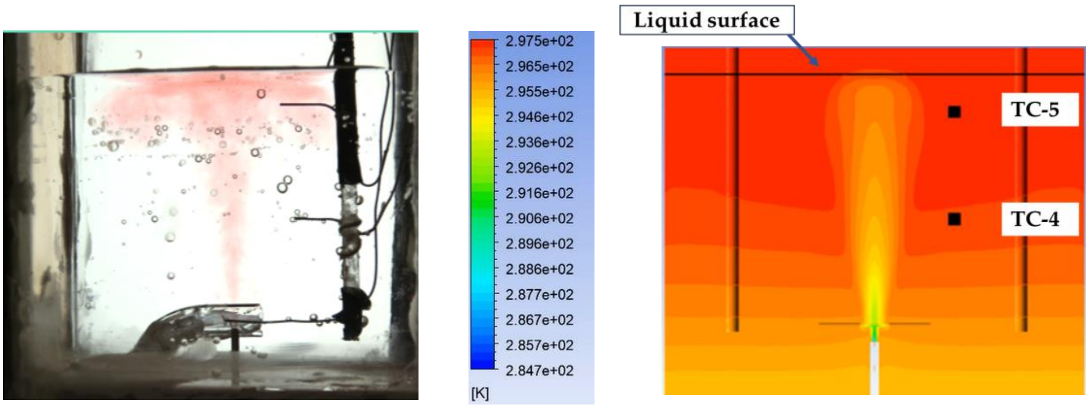


Figure.6 Comparison of jet behavior and temperature contour plot at 1 sec.

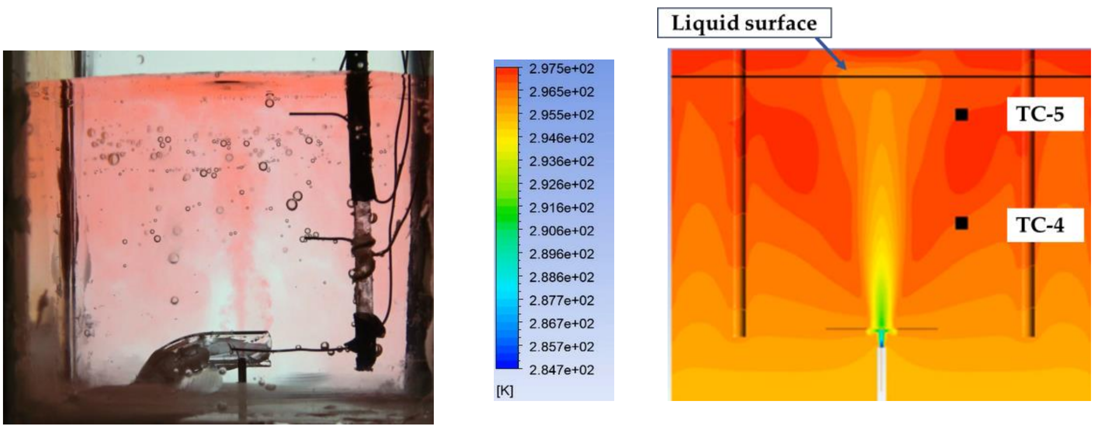


Figure.7 Comparison of jet behavior and temperature contour plot at 5 sec.

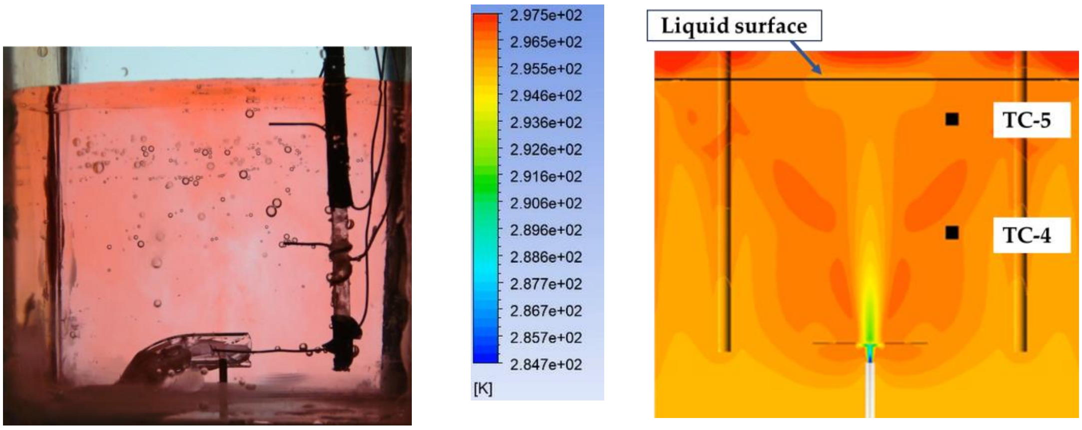


Figure.8 Comparison of jet behavior and temperature contour plot at 9.5 sec.

5. Conclusion

In order to construct a numerical model that accurately predicts jet behavior, a numerical model was built and validation experiments were conducted. The numerical model was created based on the conducted experiments, and numerical analysis was performed. Therefore, it can be said that we have succeeded in developing a numerical model that accurately predicts jet behavior under specific conditions.

In the future, we plan to conduct experiments and analyses under a variety of conditions to verify the validity of the numerical model developed in this study.

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