Study on break of thermal stratification in container targeted to thermodynamic vent system for future spacecraft

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Abstract. In the future space exploration mission, transfer vehicle using cryogenic propellant and oxidizer will be likely operated. Thermal management systems, such as thermal insulation, pressure control, and reduction of boil off gas must be installed on transfer vehicle since cryogenic fluid has high volatile characteristics. Final target of this study is the development of thermodynamic vent system (TVS) utilizing jet mixing. Numerical simulation and ground based experiment for thermal and fluid behaviours in tank partially filled with liquid nitrogen were conducted. Thermal stratification in tank was formed by creating heat input from side wall, and change of temperature field and break of thermal stratification by jet mixing were investigated. Numerical results were evaluated by comparing with experimental results.

1. Introduction
In the transport systems for exploration of the asteroids, lunar, and mars that are currently being under consideration, it is necessary to improve the performance of the propulsion system in order to the increase payload weight. Therefore, in order to realize high specific thrust, application of liquid oxygen as oxidizer, liquid hydrogen and LNG as fuel are considered, and these are cryogenic liquids with 110 K or less in a saturation temperature at atmospheric pressure. In order to store these liquids for a long time in a planetary exploration, a thermal management system such as a heat insulation and a pressure control system in the storage tank in order to suppress the pressure rise due to the heat input must be installed [1][2]. Pressure control under ground-based gravity can be easily realized by exhausting the gas phase from the upper part of the tank (gas vent) since the position of ullage is stably maintained. On the other hand, since the space propulsion system is operated in a microgravity environment, the ullage position in the tank are not stable, therefore it is difficult to adjust the pressure by the gas vent. To overcome this situation, thermodynamic vent system (TVS) in which liquid is stirred by subcooled liquid generated through the refrigeration cycle has been studied by NASA etc. In TVS, a method of destroying the temperature stratification by a mixing jet of subcooled liquid supplied from the lower part of the tank is being considered [3].
In this study, TVS combining jet mixing, spray, and heat spot removal by forced cooling by EHD (Electrohydrodynamics) is under consideration. Among them, numerical analysis and verification test using liquid nitrogen were carried out to confirm break of temperature stratification using jet mixing.

2. TVS by subcooled mixing jet
When the propulsion system on orbit is exposed to the heat input, heat accumulates inside the propellant tank, and pressure rise due to evaporation and boiling becomes remarkable. In particular, in the microgravity environment on the orbit, a heat spot on the tank is formed since natural convection becomes too weak. Therefore, the liquid phase expands and the gas phase is compressed, the pressure in the tank rises. Furthermore, when retention acceleration to acquire the propellant on the outlet is applied, even if the acceleration is small, the influence of natural convection cannot be ignored. As the result, the temperature gradient rising toward the free interface is stably formed. This temperature stratification causes increment of boil off gas (BOG) and the tank pressure. In order to distinguish the heat spot and temperature stratification, it is effective to stir the fluid by subcooled jet inside the tank. Figure 1 shows TVS which we are considering in this research. In this system, a jet mixing nozzle is installed at the bottom of the tank, and the subcooled liquid is supplied vertically upward to destroy the temperature stratification. The subcooled liquid is formed by tapping off the liquid in the tank and getting it flow through refrigerator installed outside. In the thermal roll operation to make uniform the heat load, the gas phase is located on the center axis of the tank by the centrifugal force. In this case, the spray is supplied from the central axis to cool the gas phase and promote condensation to reduce the tank pressure. Furthermore, in order to suppress the formation of heat spot on the tank wall, the EHD pump is installed in the vicinity of the strut where the heat intrusion amount is particularly large. The development of the EHD pump is being separately underway.

Figure 1. Thermodynamic vent system

3. Experimental Apparatus to Verify Breakdown Characteristics of Thermal Stratification by Mixing Jet
In order to verify TVS by the mixing jet under the ground based gravity, verification test using liquid nitrogen was carried out. Figure 2 shows the structure of test tank. The test tank (inner diameter \( \phi \): 210.7 mm, height 800 mm) was installed in vacuum chamber so that the lateral and bottom sides of the inner test tank could be maintained in a vacuum or low pressure helium gas. Liquid nitrogen was supplied into the test tank, and helium gas was injected into the gas phase to make the subcool condition. Furthermore, in order to form thermal stratification in the test tank, heat input from the side and bottom surface was applied through helium gas in vacuum chamber. Amount of heat input was adjusted by the helium gas pressure (maximum 10 kPa). The measurement items were the fluid temperature inside the tank (9 points), wall temperature on the side (9 points), and the bottom surface (4 points), tank internal pressure, and liquid height. A platinum resistance temperature sensors were applied for temperature measurement and a capacitance type liquid level sensor was utilized for measuring liquid height.
Figure 3 shows the system diagram of experimental apparatus. The mixing jet was supplied from the self-pressurized liquid nitrogen tank through the pre-cooling heat exchanger to make the sub-cool state and then was supplied from the bottom of the test tank. In the precooler a coiled tube in which self-pressurized liquid nitrogen flowed were submerged in liquid nitrogen pool at atmospheric pressure, therefore subcooled condition was formed at the outlet. The flow rate of the mixing jet was measured as a mass flow rate using a Coriolis flowmeter.

4. Numerical analysis of thermal and fluid behaviour in formation of thermal stratification and mixing by subcooled liquid

Numerical analysis for thermal and hydraulic behaviours is now being developed as a thermal design tool for TVS. For this analysis, the commercial numerical code of ANSYS Fluent was used. Figure 4 shows the analytical domain. This domain included a liquid phase, a gas phase, solid wall in the tank, and fluid in the vacuum chamber same as those used in the test described in the previous section (Figure 4 (a)). This domain was assumed to be two dimensional asymmetric. For the simplicity, only the heat exchange is considered as the interaction between gas-liquid phases. Therefore we did not account for the deformation of the gas-liquid interface and the mass transfer due to phase change. Additionally, the gas phase was a single component of helium. Boussinesq approximation was applied to represent the natural convection. The boundary condition was set at the side wall and the bottom of the vacuum chamber as the heat transfer boundary, that is the heat transfer coefficient was 50 W/m²/K assuming the natural convection of the air, and the ambient temperature was 293.15 K. In addition, the physical property of each fluid were calculated by using the database NIST REFPROP [4] and were given as polynomial algebraic equation concerning temperature. Additionally we prepared another calculation domain shown in Figure 4 (b). This domain included gas and liquid phase as well as side, bottom, and flange wall. Time histories of measured values of temperature by experiments were inputted as the boundary condition on side and bottom wall.

We confirmed the formation of thermal stratification in test tank due to the heat input through helium gas in vacuum chamber by numerical analysis. Also temperature stratification was verified to be broken by the mixing jet with more than 1.2 m/s in the inlet velocity [5].

5. Verification test for formation and break of thermal stratification

Figure 5 shows the time history of the fluid temperature in the tank and the mass flow rate of the mixing jet after the formation of the temperature stratification. TL1 to TL7 indicate fluid temperature in tank. Temperature sensors were located with 80mm distance, sensors with larger index number were set at higher positions. TMJ2 is the inlet temperature of mixing jet. Here the initial liquid level was about 500
mm from the bottom of the tank, the pressure inside the tank was controlled to be 200 kPa by exhaust from the top of the tank after filling with helium gas. Here, the effect of height of mixing jet nozzle from the bottom of test tank, that is 0 mm and 100 mm were also investigated. From this figure, temperature stratification was confirmed at the time zone when the temperature inside the tank linearly increased up to about 1200 sec. Subsequently, a mixing jet was supplied, however a subcooled state in the jet could not be obtained until about 1400 sec and 1300 sec in case of 0 mm and 500 mm in height of jet nozzle shown in Figure 5(a) and (b). After a stable subcooled state was obtained, we confirmed that the liquid temperature decreased and the thermal stratification was broken by a mixing jet with 0.5 to 0.6 kg/min in mass flow rate. At present, the experimental apparatus must be improved in order to form a stable subcooled state immediately after supplying of mixing jet.

In order to verify analytical model described in previous section, comparison of experimental and analytical results in liquid phase temperature was made. Here, analytical domain and boundary condition are shown in Figure 4 (b). This domain includes the liquid and gas phase inside the test tank, the solid wall and the top flange. Furthermore, the boundary condition was given by inputting the history of the measured value of the temperature sensor installed at the side and bottom wall of the tank. Temperature data between measurement points and between each sampling times were given by linearly completing concerning position and time.

![Figure 4. Calculation domain](image)

(a) For design of test tank  (b) For comparing with experimental results

![Figure 5. Experimental result. History of temperature distribution and mass flow rate of mixing jet.](image)

(a) Height of jet nozzle : 0mm  (b) Height of jet nozzle : 100mm

Figure 6 shows a comparison of the experimental and numerical results in the liquid phase in the test tank during stratification formation process. From this figure, we found the experimental and numerical result generally agreed with each other. However difference became larger near the bottom with time.
That is, the temperature gradient at this part became smaller in experimental results. This implies that the heat input from the bottom becomes larger in the numerical results, the cause of this tendency is currently under consideration.

![Comparison of experimental and numerical results in formation of thermal stratification in case of 0 mm in height of jet nozzle.](image)

**Figure 6.** Comparison of experimental and numerical results in formation of thermal stratification in case of 0 mm in height of jet nozzle.

### 6. Conclusion

Concerning TVS by jet mixing targeted to the application to propellant tank in future spacecraft system, numerical analysis of formation and break of temperature stratification and verification test in ground based gravity condition were carried out. These results are summarized below.

1. Numerical results shows that thermal stratification was formed by heat input due to natural convection of low pressure helium gas outside the test tank, and that temperature stratification could be destroyed by mixing jet from the bottom of the tank.
2. Temperature stratification was investigated by conducting the verification test under the ground gravity using liquid nitrogen and these results were compared with the numerical ones where measured temperature on the tank wall were given as the temperature boundary. It was confirmed that the experimental and the numerical results generally agreed.
3. Verification test using liquid nitrogen was carried out to realize the break of thermal stratification. We could confirm the break of thermal stratification by mixing jet with 0.5 to 0.6 kg/min in mass flow rate, however, we found there existed unstable injection duration prior to stable subcooled one. Improvement of test apparatus is required to resolve this problem.

### References

- [1] Chato D. J, 2008 NASA TM-2008-215286
- [2] Chato D. J, 2005 AIAA-2005-1148
- [3] Poth L J, Van Hook J R 1972 *J. of Spacecraft and Rockets* 9 332
- [4] NIST Chemistry Webbook, SRD 69, https://webbook.nist.gov/chemistry/fluid/
- [5] Imai R, Kawanami O, Umemura Y, Himeno T 2018 *Proc. of multiphase flow symposium* in Japanese

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