Progress in Superconductivity and Cryogenics
Vol.16, No.4, (2014), pp.71~77
http://dx.doi.org/10.9714/psac.2014.16.4.071

Experimental investigation on No-Vent Fill (NVF) process using liquid Nitrogen

Youngcheol Kim[*], Mansu Seo, Donggyu Yoo, and Sangkwon Jeong

Korea Advanced Institute of Science and Technology, Daejeon, Korea

(Received 24 November 2014; revised or reviewed 19 December 2014; accepted 20 December 2014)

Abstract

For a long-term space mission, filling process of cryogenic liquid propellant is operated on a space vehicle in space. A vent process during transfer and filling of cryogenic propellant is needed to maintain the fuel tank pressure at a safe level due to its volatile characteristic. It is possible that both liquid and vapor phases of the cryogenic propellant are released simultaneously to outer space when the vent process occurs under low gravity environment. As a result, the existing filling process with venting not only accompanies wasting liquid propellant, but also consumes extra fuel to compensate for the unexpected momentum originated from the vent process. No-Vent Fill (NVF) method, a filling procedure without a venting process of cryogenic liquid propellant, is an attractive technology to perform a long-term space mission. In this paper, the preliminary experimental results of the NVF process are described. The experimental set-up consists of a 9-liter cryogenic liquid receiver tank and a supply tank. Liquid nitrogen (LN_2) is used to simulate the behavior of cryogenic propellant. The whole situation in the receiver tank during NVF is monitored. The major experimental parameter in the experiment is the mass flow rate of the liquid nitrogen. The experimental results demonstrate that as the mass flow rate is increased, NVF process is conducted successfully. The quality and the inlet temperature of the injected LN_2 are affected by the mass flow rate. These parameters determine success of NVF.

Keywords: No-vent fill (NVF), Cryogenic propellants, Low gravity environment

1. INTRODUCTION

Cryogenic liquid propellants have the following advantages. First, their specific impulses are superior to solid propellant. Second, the thrust controlling of a space vehicle is easier than that of solid propellants. Since a space mission is performed with consuming a certain amount of cryogenic propellants which is charged on the ground, there is a limit for its duration. Increasing the amount of the cryogenic liquid propellants is the only way to extend the duration of a space mission. In addition, additional thermal insulation systems and storage structures that are used to keep the cryogenic liquid propellants for a long-term space mission are also indispensable. Therefore, the weight of the space vehicle is increased at a launch pad. There is, however, the upper limit of charging propellant and adding thermal insulation structures. This is the inherent limitation of the method of charging process operated on the earth.

In order to overcome this problem, techniques, transfer and filling of cryogenic liquid propellants in space, have been suggested [1-3]. If this recharging process of liquid propellants is possible in space, extending the duration of a space mission and reducing the weight of the liquid propellants, which occupy most of the weight of the space vehicle weight, are possible. Since cryogens usually exist as a saturated liquid and have a small latent heat of vaporization, the cryogenic propellant is easily evaporated due to the heat leak and the thermal inertia of the tank. This phenomenon makes a rapid pressurization in a fuel tank. Therefore, the venting process should be included in the whole cryogenic propellant management, such as transfer, filling, and storage. It allows a propellant tank to maintain the tank pressure at the safe level as venting only the vaporized propellant on the earth [4, 5]. The venting process can be utilized when the location of the vapor is predictable under gravity field. However, in space, the exact configuration of the liquid and the vapor phase in a tank is unpredictable. If the venting process occurs in space, there is a possibility of the liquid phase to be vented into space [1]. Although it is possible that venting only the vapor phase in space by accelerating a space vehicle to make an artificial gravity field, this method consumes the additional cryogenic propellants, and needs unnecessary position control of a space vehicle due to the movement of the center of mass of a whole system [4].

No-vent fill (NVF), which is proposed for a long-term space mission, is an essential technique to solve the venting problem in space and to increase the payload of a space vehicle at a launch pad [1]. D. Chato suggested a NVF thermodynamic model which regards the tank wall, the liquid phase, and the vapor phase as different nodes [4]. In addition, D. Chato suggested an improved NVF thermodynamic model which considers a source of main error and an adequate heat transfer coefficient [6, 7]. W. J. Taylor conducted NVF experiments with the tank that has a

---

[*] Corresponding author: youngcheol_kim@kaist.ac.kr

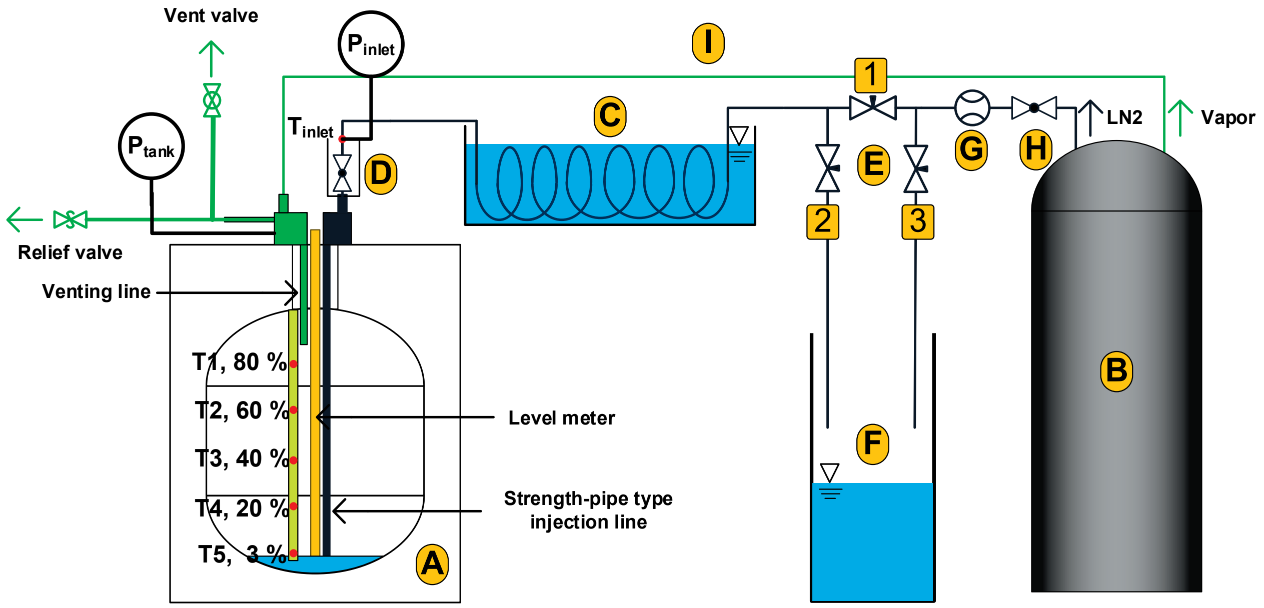


Fig. 1. Schematic diagram of the no-vent fill experiment apparatus; (A) Receiver tank, (B) LN_2 supply unit, (C) LN_2 bath heat exchanger, (D) inlet valve, (E) valve configuration with valve 1, 2, and 3, (F) LN_2 Dewar, (G) Coriolis mass flow meter, (H) Globe valve, (I) pressurizing line.

similar size of the actual space vehicle tank [3]. C. Wang observed the pressure characteristic during the vented fill and the no-vent fill process with various injecting methods [5]. He has also validated the lumped model developed by D. Chato with measuring the temperature distribution in the tank and the tank wall temperatures.

There are many coupled variables that affects the NVF performance, such as initial tank wall temperature, inlet condition of propellant, mass flow rate, and injecting type, etc. Although there are many experimental data with the various conditions, the effect of the mass flow rate is not well-characterized. In this paper, the NVF experimental results and discussion are described to confirm the feasibility of NVF using liquid nitrogen and to examine the effect of the mass flow rate with the constant inlet condition.

2. EXPERIMENT

2.1. Configuration of a NVF experiment apparatus

The experimental apparatus consists of the liquid nitrogen (LN_2) receiver tank, the LN_2 supply unit, the LN_2 bath heat exchanger, the cryogenic valves, and the Coriolis mass flow meter as shown in Fig. 1.

The receiver tank is to simulate a fuel tank of space vehicle. The vacuum insulated outer container is allocated to minimize the heat leak from the environment. The inner container is installed in the vacuum chamber and is a cylindrical-shaped stainless steel tank with dome cover in the upper and lower sides. The geometric dimensions of the tank are 227 mm in height, 250 mm in diameter, and 9.2-L in volume. A 1/4 inch diameter stainless steel pipe is installed 20 mm above from the bottom of the tank to inject LN_2 into the inner container for straight-pipe type injecting method. The venting pipe is installed at a height of 90% volume of the inner container. A level meter (AMI, Capacitance-based liquid level sensor) is installed to measure the amount of the charged LN_2 in the inner container with 0.1% accuracy of the total measuring length. Due to the dome-shape of the inner container, as shown in Fig. 1, the level meter can measure the amount of the LN_2 from 10% of the inner container volume. The temperature sensors (Lakeshore, DT-670D-SD,) are installed at the heights corresponding to the each volume of the inner container 3%, 20%, 40%, 60%, and 80% to measure the vertical temperature distribution in the tank. The accuracy of the silicon diode type temperature sensors is ±40 mK at 77 K. The temperature sensors are attached at a glass fiber reinforced polymer (GFRP) rod that is used as the support to minimize the heat conduction from the environment. The pressure transducer (SENSOTEC, FPA) is installed in the receiver tank to measure the pressure of the receiver tank. The accuracy of the pressure sensor is 0.15%. The pressure transducer can measure up to 35 bar.

The LN_2 supply unit supplies LN_2 which is used as a cryogenic propellant in this experiment. In the LN_2 supply unit, there are two lines: One line is for using liquid nitrogen, and another is for using vapor nitrogen. It is possible to use the liquid and the vapor nitrogen at the same time. The relief valve operating at 16 bar (abs.) is installed to prevent excessive pressurization in the LN_2 supply unit. In addition, the venting and pressure building system exist to control the pressure of the LN_2 supply unit.

The LN_2 bath heat exchanger makes the high-pressurized and subcooled state of the injected LN_2 by heat exchanging with the 77 K LN_2. The cryogenic globe valve (Dong-A, H015014/01880) is installed as close as possible to the inlet of the receiver tank. The valve is immersed in the LN_2-filled cup structure to minimize the heat leak along the transfer line. The temperature sensor and the pressure sensor, which are the same type used in the receiver tank, are installed at the inlet of the valve to measure the inlet condition of the injected LN_2. The Coriolis mass flow meter measures the mass flow rate of the injected LN_2. The globe valve is installed at the inlet of the Coriolis mass flow meter to control the mass flow rate of the injected LN_2 by adjusting valve opening. The valve configuration is used to precool the receiver tank and the transfer line before NVF experiment. No.1 and 2 valves are the cryogenic solenoid valve (Syntek, STH12C302T2S) for the rapid LN_2 control. Pressurizing line, a 1/4 inch copper tube, is used to apply the high pressurized nitrogen gas to the receiver tank when discharging of the LN_2 from the receiver tank.

2.2. NVF experiment process and the conditions

2.2.1. Process of precooling the receiver tank

When the LN_2 is injected into the receiver tank where the tank wall is approximately 300 K, the pressure in the receiver tank will increase rapidly and NVF should be failed because of the evaporation of the LN_2. Therefore, precooling process is necessary to prevent the rapid pressurization in the receiver tank. Cooling by a cryocooler or by evaporation cooling of a cryogens are used to precooling the receiver tank. In this research, the LN_2 is injected into the receiver tank while the vent valve of the receiver tank is opened to precool the receiver tank. During the precooling process, No. 1 valve is opened while No. 2 and 3 valves are closed. The vented fill process is terminated when the tank is fully charged with the LN_2. When the receiver tank pressure becomes the atmospheric pressure, the receiver tank wall temperature reaches 77 K. After that it is ready to drain the charged LN_2 in the receiver tank. The vent valve of the receiver tank and No.1 valve are closed. The No.2 and 3 valves are opened to drain the LN_2 from the receiver tank. The cold and high-pressurized nitrogen gas is injected through the pressurizing line. Since the outlet of the LN_2 injection pipe is located 20 mm above from the bottom, most LN_2 in the receiver tank is discharged passing through the LN_2 injection pipe. The remained LN_2 in the tank can be ignored because the volume, 0.27 L, corresponding to the height of 20 mm is negligible compared to the total tank volume, 9.2 L. During this draining process, the LN_2 flows through No. 3 valve to maintain the transfer line at a low temperature. Therefore, this vented filling and draining procedure cools the receiver tank and overall transfer line before the main NVF experiment.

2.2.2. NVF experiment

After the LN_2 is drained, the vent valve of the receiver tank is closed for NVF. The LN_2 supply unit pressure is set at 5 bar (abs.). The valve opening of the cryogenic globe valve located in the forward direction of the Coriolis mass flow meter is set to make various mass flow rates for each NVF experiment. When No. 1 valve is opened and No. 2 and 3 valve are closed, NVF experiment begins. The NVF experiment is terminated when the receiver tank pressure becomes same as the LN_2 supply unit pressure.

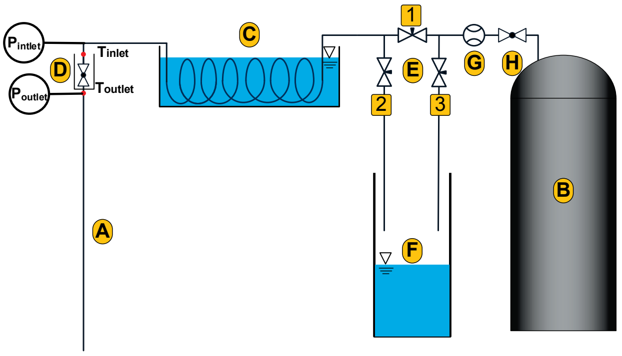


Fig. 2. Schematic diagram of the confirmation experiment for inlet condition apparatus; (A) A 2 m copper tube, (B) LN_2 supply tank, (C) LN_2 bath heat exchanger, (D) inlet valve, (E) valve configuration with valve 1, 2, and 3, (F) LN_2 Dewar, (G) Coriolis mass flow meter, (H) Globe valve.

2.3. Confirmation experiment for the inlet condition

The best way to measure the inlet condition of the injected LN_2 is to install the sensors in the receiver tank with vacuum insulation. Since there is the geometric limit of the receiver tank, the sensors are installed in front of the inlet valve of the receiver tank.

Therefore, the exact state of the injected LN_2 after the valve (D) is not measured. The additional experiment is performed to confirm the state of the LN_2 after the inlet valve. For the inlet condition confirmation experiment, the experiment apparatus is fabricated, as shown in Fig. 2. The temperature and the pressure sensors are installed at the inlet and the outlet of the valve to measure the state of the LN_2 which flows through the valve. A 2 m length copper tube is connected at the outlet of the valve instead of the receiver tank. The role of the copper tube is a pressure buffer to simulate the receiver tank in the NVF experiment. The test is conducted similarly as NVF experiment with the various mass flow rates. The injected LN_2 states in steady state are measured at the inlet and the outlet of the valve.

3. RESULTS

3.1. NVF experiment results

Table 1 summarizes the total 11 NVF experimental results with the various inlet mass flow rates. The average mass flow rate is the integrated average value of the fluctuated mass flow rate. The average value of T_{inlet}-T_{sat} is the average values of temperature difference between the temperature measured at T_{inlet} and the saturation temperature corresponding to the pressure measured at P_{inlet} in Fig. 1. Final Liquid nitrogen (LN_2) filled level is the liquid level in the receiver tank measured by the capacitance-based level sensor. Total filling time is the duration of the NVF process. The average inlet temperature

TABLE I

SUMMARY OF THE NO-VENT FILL EXPERIMENTAL RESULTS.

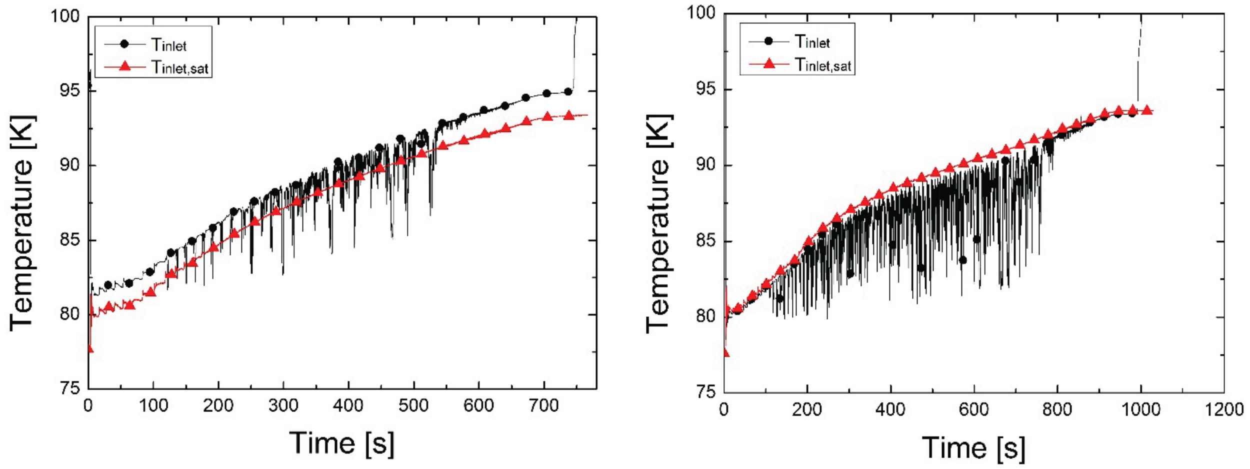
Case	**Average mass flow rate [g/s]**	**Average value of $T_{inlet} - T_{sat}$ [K]**	**Final filled LN_2 level [%]**	**Total filling time [sec]**	**Average T_{inlet} [K]**	**$T_{initial}$ in the receiver tank [K]**
1	1.72	0.97	0	750	88	77
2	1.58	-1.67	12	870	86	77
3	1.60	-1.90	35	1250	86	77
4	2.77	-4.17	89	1100	83	106
5	2.45	-3.13	94	2200	84	106
6	3.20	-1.19	100	870	81	77
7	3.46	-1.45	100	770	83	77
8	3.68	-0.73	100	850	81	77
9	3.78	-2.56	100	820	81	102
10	5.40	-1.67	100	600	80	78
11	6.48	-1.33	100	480	80	86

is the injected LN_2 average temperature measured by the T_{inlet} in Fig. 1. $T_{initial}$ in the receiver tank is an average temperature of the vapor nitrogen in the receiver tank just before the NVF process.

As shown in the table 1, there is an obvious effect of the mass flow rate on the LN_2 filled level. As the average mass flow rate is increased, final LN_2 filled level is increased. NVF achieves 100% final LN_2 filled level when the average mass flow rate is greater than the certain value, 3.20 g/s. $T_{initial}$ has no effect on the NVF. Since the average value of T_{inlet}-T_{sat} is negative value except the case 1, the whole injected LN_2 is subcooled state. There is a tendency that the average inlet temperature is decreased as the mass flow rate is increased. Although the effect between the mass flow rate and the average inlet temperature is not intended initially, they are not separated in this experiment.

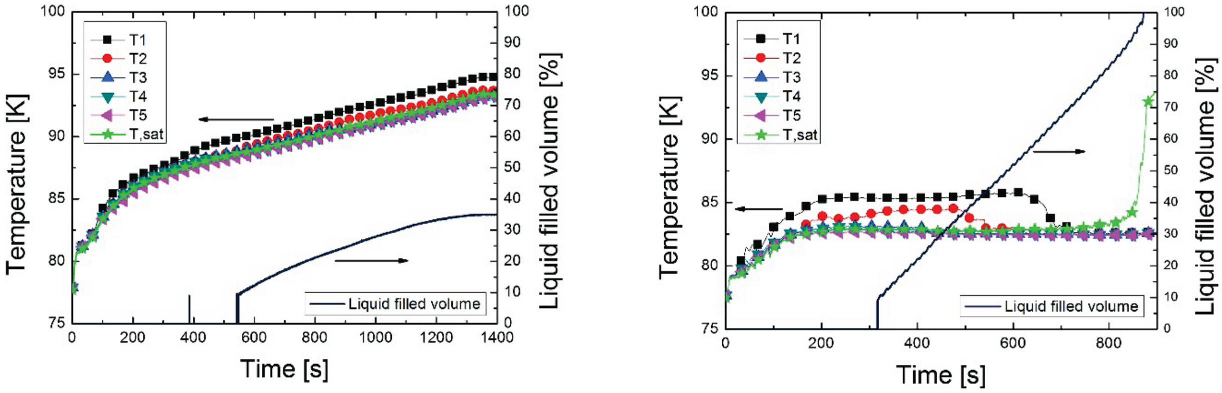
Internal energy and enthalpy are compared between the case 4 where the degree of subcooling is the largest case and the case 8 where the degree of subcooling is the smallest case using the commercial code REFPROP. The properties of the injected LN_2 are calculated with the parameters in Table 1. In the case 4, the internal energy is -110.65[kJ/kg]. The enthalpy is -110.29[kJ/kg]. In the case 8, the internal energy is -114.71[kJ/kg]. The enthalpy is -114.50[kJ/kg]. It is verified that the injected LN_2 state of the case 8 has lower energy than the case 4 although the degree of subcooling of the case 8 is lower than the case 4. Therefore, it can be estimated that the absolute temperature is more important than the degree of sub-cooling for the successful NVF.

The average inlet temperature of the case 1 is 2 K higher than that of the case 2. In addition, the average value of T_{inlet}-T_{sat} of the case 1 has a positive value, which means the state of the injected LN_2 in the case 1 is superheated vapor. Fig. 3 shows the history of T_{inlet} and the saturation temperature corresponding to P_{inlet} of the case 1 and 2. T_{inlet} is fluctuated due to evaporation by the heat penetration and condensation in the LN_2 bath heat exchanger. The temperature history in Fig. 3(a), excepting very short moments when T_{inlet} is lower than $T_{inlet,sat}$, shows that T_{inlet} is higher than $T_{inlet,sat}$ during the whole time in the NVF, which means the superheated vapor is injected in the case 1.



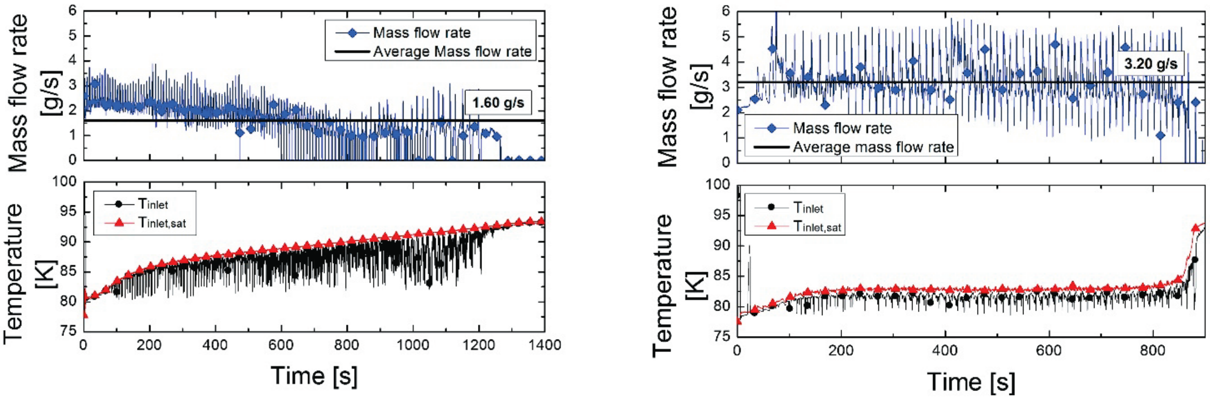
(a) (b)

Fig. 3. Inlet temperature history during no-vent fill experiments (a) Case 1 (b) Case 2.



(a) (b)

Fig. 4. Temperature and LN_2 filled volume of the receiver tank during no-vent fill experiment (a) Case 3, (b) Case 6.



(a) (b)

Fig. 5. Mass flow rates and inlet temperature during no-vent fill experiment (a) Case 3, (b) Case 6.

On the other hand, it is verified that the state of the injected LN_2 in the case 2 is subcooled as shown in Fig. 3(b). As mentioned earlier, since the location where the temperature is measured is the inlet of the valve (D) of Fig. 1, the state of the injected LN_2 after the valve may differ from the state of the inlet of the valve. For such a problem, it will be discussed in the section ‘3.2 Results of confirmation experiment for inlet condition’.

Fig. 4 shows the temperature and the liquid level history in the receiver tank of the case 3 and 6, which are representative results of failed and successful case respectively. All of the NVF experiments are conducted when the LN_2 supply unit pressure is set to 5 bar (abs.). Saturation temperature, T_{sat}, is calculated by the receiver tank pressure. The pressure history is shown as T_{sat} in Fig. 4. The experimental result of the case 3 as shown in Fig. 4(a) is the case where the receiver tank is filled only up to 35%. Fig. 4(a) represents the results from the case 1 to the case 5. The temperatures from T1 to T5 and T_{sat} corresponding to the pressure in the receiver tank in Fig. 4(a) are increased as time elapses. Since the receiver tank pressure is increased while the LN_2 supply unit pressure is constant at 5 bar (abs.), the pressure difference between the LN_2 supply unit and the receiver tank is decreased. Decrease of the pressure difference makes not only the decrease of the driving force of the mass flow rate but also the increase of the saturation pressure and temperature at the inlet of the valve. These phenomena are shown in Fig. 5(a). Fig. 5 shows the history of the mass flow rate and the comparison between T_{inlet}, the inlet temperature, and $T_{inlet,sat}$, the saturation temperature corresponding to the measured pressure. The mass flow rates have a fluctuation, ±2 g/s in amplitude. Accordingly, in the case 1 to case 5, evaporation is more dominant than condensation in the receiver tank. As a result, the negative feedback loop, which is both pressurization in the receiver tank and decrease of the mass flow rate, occurs and makes worse condition for successful NVF. In other word, if the mass flow rate is not enough to make a rapid pressurization in the receiver tank in the initial NVF process, evaporation of the injected LN_2 is dominant than the condensation of the vapor in the receiver tank. This increasing pressure tendency during NVF can be observed in other previous research with the bottom injection method [3, 5].

The case 6 to 11 represents the different tendency of the temperatures and the pressures from the above experiments. Although the vent valve is closed during NVF process, the

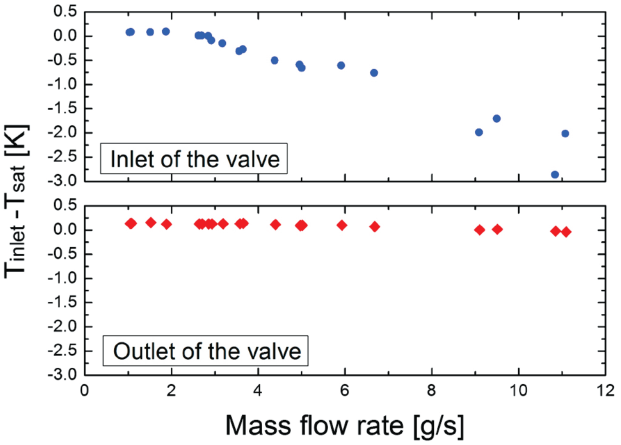


Fig. 6. Results of confirmation experiment for inlet condition.

receiver tank pressure is maintained. The pressure history is shown as T_{sat} in Fig. 4(b). The temperatures in the receiver tank are converged to T_{sat}. In these cases, since the pressure difference is maintained constantly between the LN_2 supply unit and the receiver tank, the mass flow rate is averaged constant with some fluctuation as shown in Fig. 5(b). Thus, if the mass flow rate is enough to make a rapid pressurization in the receiver tank in the initial NVF process, the condensation of vapor is dominant than the evaporation of the injected LN_2. This is a positive feedback that can make a condition for the successful NVF. Consequently, as the injected mass flow rate is increased with the same LN_2 supply unit condition compared to the case 1 to 5, NVF is successfully conducted in the case 6 to 11.

Since this NVF experiment have been conducted in the normal gravity environment, there is a difference from the low gravity environment. In the low gravity environment, a liquid-vapor interface in the receiver tank is larger than that of in this experiment. An arbitrary movement of the liquid and the vapor in the low gravity environment makes favorable conditions to condense the vapor in the receiver tank. These phenomena in the low gravity environment makes thermal equilibrium conditions in the receiver tank. In the previous research, they have found that when the receiver tank is in the thermal equilibrium condition, the NVF process can be succeeded [8, 9]. Therefore, the NVF process can be succeeded easily in the low gravity environment.

3.2. Results of the confirmation experiment

The temperature difference between T_{inlet} and $T_{inlet,sat}$ with the various mass flow rates is shown in Fig. 6. The degree of subcooling of the inlet of the valve is increased as the mass flow rates are increased in Fig. 6. However, the temperature difference at the outlet of the valve is irrelevant to the mass flow rates and the degree of subcooling at the inlet of the valve. Therefore, there is a two-phase flow at the outlet of the valve. The effect of pressure drop through the valve is negligible because the pressure difference between the inlet and the outlet of the valve is within 1 kPa which value can be considered as the error of the pressure sensor. Although the valve is submerged in the 77 K LN_2, the heat leak along the transfer line and other parts for sensors is major.

Based on this results of the confirmation experiment for inlet condition, the state of the injected LN_2 at the outlet of the valve can be considered as a two-phase state in this NVF experiment. Since the amount of the heat invasion through the valve is similar to the whole cases in these NVF experiments, it can be speculated that two-phase nitrogen is injected for the whole cases. However, there is the limitation to obtain the exact inlet condition because the quality of the injected two-phase nitrogen is not measured. Thus, when the mass flow rate increases, the quality of the injected two-phase nitrogen is decreased and the condition for a successful NVF is created in the receiver tank.

4. CONCLUSIONS

In this research, No-vent fill (NVF), one of the promising techniques to perform a long-term space mission, is verified by experiment. In order to verify NVF technique,

1. The experimental apparatus has been fabricated with the double layer receiver tank, the LN_2 supply tank, the LN_2 bath heat exchanger, and the transfer and venting systems.
2. In the receiver tank, the vertical temperature distribution, the pressure, and the LN_2 filled level are measured during NVF. Also, the injected mass flow rates and the inlet condition of the receiver tank are measured.
3. The 11 NVF experiments have been conducted with the various mass flow rates at constant supply condition. As a result, as the mass flow rate is increased, both T_{inlet} and the quality at the inlet of the receiver tank are decreased due to the active heat exchange in the LN_2 bath heat exchanger.
4. NVF is successfully conducted with control the injected mass flow rate or T_{inlet}.

ACKNOWLEDGMENT

This research is supported by a grant from Space Core Technology Development Program of National Research Foundation of Korea (NRF-2013-042033) funded by Ministry of Science, ICT & Future Planning (MSIP).

REFERENCES

[1] D. J. Chato, "Cryogenic fluid transfer for exploration," *Cryogenics*, vol. 48, pp. 206-209, 2008.

[2] P. R. Chai and A. W. Wilhite, "Cryogenic thermal system analysis for orbital propellant depot," *Acta Astronautica*, vol. 102, pp. 35-46, 2014.

[3] W. J. Taylor, D. J. Chato, M. M. Moran, and T. W. Nyland, "On-orbit cryogenic fluid transfer research at NASA Lewis Research Center," *Cryogenics*, vol. 32, pp. 199-204, 1992.

[4] D. J. Chato, "Thermodynamic Modeling of the No-Vent Fill Methodology for Transferring Cryogens in Low Gravity," *AIAA-88-3403*, 1988.

[5] C. Wang, Y. Li, and R. Wang, "Performance comparison between no-vent and vented fills in vertical thermal-insulated cryogenic cylinders," *Experimental Thermal and Fluid Science*, vol. 35, pp. 311-318, 2011.

[6] D. J. C. M. E. Moran and T. W. Nyland, "Initial Experimentation on the Nonvented Fill of a 0.14 m^3 (5 ft^3) Dewar With Nitrogen and Hydrogen," *Prepared for the 5th Thermophysics and Heat Transfer Conference cosponsored by the AIAA and ASME*, 1990.

[7] W. Taylor and D. Chato, "Improved Thermodynamic Modelling of The No-Vent Fill Process," *AIAA*, Thermophsics Conference, 26th, pp. 19, 1991.

[8] W. J. Taylor and D. J. Chato, "Comparing the results of an analytical model of the no-vent fill process with no-vent fill test results for a 4.96 cubic meters (175 cubic feet) tank," *Presented at the 28th Joint Propulsion Conference and Exhibit, Nashville, TN, 6-8 Jul. 1992; sponsored by AIAA, SAE, ASME, and ASEE*, 1993.

[9] R. B. Schweickart, "Thermodynamic analysis of a demonstration concept for the long-duration storage and transfer of cryogenic propellants," *Cryogenics*, vol. 64, pp. 283-288, 2014.