The effect of external heat inflow to the cryogenic liquid pressurized discharge process

Seungwhan Baek, Youngsuk Jung, Kiejoo Cho
Korea Aerospace Research Institute
169-84 Gwahak-ro, Yuseong-gu, Daejeon, 34133, Republic of Korea
sbaek@kari.re.kr

Abstract. The launch vehicle with a liquid propulsion system requires pressurization during the propellant discharge. While the launch vehicle is flying through the air layer, a process in which frictional heat is generated between the liquid propellant tank and the air layer can be assumed. External heat inflow occurs during the liquid discharging process, and it is necessary to investigate how the external heat influx affects the liquid pressurized discharge process. A test device was constructed to determine the effect of pressurization of external heat inflow. The test device consisted of a liquid tank located in a vacuum chamber and a heating device to simulate external heat inflow. The heating device is a halogen lamp. The cryogenic liquid discharge with and without external heat inflow was compared. It was confirmed that the amount of pressurant gas used was decreased when there was external heat inflow. External heat inflow contributes to the evaporation of the liquid, and the evaporated gas increases the pressure of the ullage.

1. Introduction
For a launch vehicle to perform its mission, it must travel from the earth into space. A launch vehicle passes the air layer of the atmosphere and into space. As it passes through the atmosphere, friction occurs between the air layer and the launch vehicle. The frictional energy is converted into a heat source on the outer wall of the launch vehicle. Most launch vehicles use cryogenic propellants and have a thin-walled propellant tank. Aerodynamic heating generated by frictional energy acts as a heat source for the outer wall of the propellant tank, and the heat affects the fluid inside the cryogenic propellant tank. For example, the heat may warm up the ullage gas temperature or the cryogenic liquid temperature.

While the launch vehicle is flying, the cryogenic propellant is discharged using pressurized gas in the propellant tank. Therefore, it is necessary to investigate how the heat changes in the fluid inside the cryogenic propellant tank.

The propellant discharge process was discussed and analysed by Roudebush [1] for the space launch vehicle applications. The experimental work was done with the different inlet temperatures of gas pressurant. The wall temperature profile and the ullage gas temperature profiles were compared with the simulation and experiments. However, the authors noted that the effect of the external heat flow is not considered in this study.

The effect of long-term (3000 seconds) aerodynamic heat effect on the liquid hydrogen tank was also discussed in 1991. [2, 3] The study purpose was for the trans-atmospheric vehicles. The tank's structural shape was a horizontal cylinder. The authors performed experiments and simulations to analyse boil-off rates, wall temperatures, fill percent, and heating levels. The study methods were similar to the objective
of this study. However, the test duration was comparatively long, and the propellants were not discharging.

Recently, Li et al. [4] and Liu et al. [5] discussed the effect of external heat flow on the propellant discharge process with CFD tools. The detailed heat transfer model developed by Fluent could include fluid-wall heat transfer, wall-foam heat transfer, and aerodynamic heating at foam surface. They compared the aerodynamic heating case with the zero-heating case when discharging propellant. They calculated internal temperature distribution both in ullage and liquid. The study objective was for the upper stage, and the effect of heat was not applied during the discharge. [5]

Previous literature introduces a comprehensive understanding of the effect of external heat on cryogenic propellant tanks and cryogenic fluids. This study will analyse experimental results of the external heat effect on the cryogenic liquid discharge process while varying the external heat flow level.

2. Experimental setup

2.1. Experimental hardware

Figure 1 shows the schematic of the experimental setup for the cryogenic liquid discharge process. First, there is a liquid storage tank. The tank diameter is 412 mm, and the height is 1300 mm. The 18 halogen lamps surround the liquid storage tank. There is a shield for concentrating the heat to the liquid storage tank. The halogen lamp is connected to the AC power supply. The heat input is controlled by regulating the current from the power supply. In order to accurately measure the amount of heat in the halogen heater, a liquid tank was installed in a vacuum chamber. The vacuum environment is enabled using the rotary pump, the booster pump, and the turbo-molecular pump.

A pipeline for supplying the liquid to the tank and a pipe for discharging the liquid are installed. In addition, a gas supply line for pressurizing the tank and a pipe for vent are installed. The two solenoid valves were installed to control the amount of gas for pressurizing. A flow meter for measuring the pressurized gas flow rate is installed in the vent line. Another flow meter for measuring the liquid discharge flow rate is included in the experimental setup.

![Figure 1 Schematic of the experimental setup for the cryogenic fluid discharge process with external heat input](image-url)
Figure 2 (a) shows the sensor map for the experimental setup. The fixed location of 54 thermometers was installed inside the liquid tank. Thermometers installed in fixed positions can show the temperature distribution inside the tank. The temperature sensors were placed in the direction above and below the liquid surface. Therefore, those sensors can check the temperature distribution at the surface. Ten temperature sensors were installed, and the length between the sensors was 1 cm. A temperature sensor was installed at the liquid discharging line. The pressure gauge was installed to measure the tank pressure behaviour. A load cell was installed to measure the weight of the liquid in the tank. Figure 2 (b) shows the picture of the liquid tank. Figure 2 (c) shows the image of the halogen lamp array with the shield. Figure 2 (d) shows the assembled experimental setup.

Figure 2 (a) sensor installation in the liquid storage tank (b) the picture of the liquid tank (c) the picture of the halogen lamp (d) the assembled experimental setup

2.2. Experimental Procedure

The test begins with a full charge of liquid nitrogen. Then, the liquid discharge test is started after confirming the tank's weight, temperature, and pressure. The pressure in the tank must be sufficiently raised before discharging the liquid. This process is called the pre-pressurization process. After the pre-pressurization process, the valve for liquid discharge opens, and the liquid discharges. The presurrant gas is supplied to maintain tank pressure during liquid discharge. This process is called the main discharge process.

| Set | Heater level | Experiments                 |
|-----|--------------|-----------------------------|
| 0   | 0.32 kW/m²   |                             |
| 1   | 0.45 kW/m²   |                             |
| 2   | 1.28 kW/m²   | 300 K helium as pressurant gas |
| 3   | 6.43 kW/m²   | 80 seconds of pre-pressurization |
| 4   | 12.87 kW/m²  | 120 seconds of main liquid discharge |
| 5   | 19.31 kW/m²  |                             |
During the pre-pressurization process, the gas supply is regulated through one solenoid valve to control the tank pressure. In the main discharge process, one solenoid valve is continuously open, and another solenoid valve is controlled according to the liquid tank pressure. The pre-pressurization process was held for 80 seconds in the test, and the liquid discharge proceeded for 120 seconds. The halogen heater was turned on as soon as the pre-pressurization process started. The time for the halogen heater to reach the specified power is 20 seconds.

The six sets of experiments were performed. Each set has a different level of halogen lamp heating. Table 1 shows the experimental condition for each set. The programmable logic controller (PLC) controls all hardware, and the personal computer gathers the measurement data.

3. Experimental results

Figure 3 shows the tank ullage pressure for different sets of the experiment. The pre-pressurization continues from zero to 80 seconds. The heater is on at zero seconds. After 80 seconds of pre-pressurization, liquid discharge starts for 120 seconds. The upper-pressure limit for pre-pressurization is 460 kPa. As the pressurant gas, helium, flow into the tank, the tank ullage pressure increases until the upper limit. After reaching the upper-limit pressure, the pressurant supply stops and ullage pressure decreases. The liquid discharge valve is opened automatically at 80 seconds, and a higher flow rate of helium is supplied with the control of two solenoids valves. The one solenoid valve is kept open, while ullage pressure reaches lower-pressure limit, and another solenoid valve is open to raise the ullage pressure. When the ullage pressure reaches the higher-pressure limit, the second solenoid valve is closed.

Figure 3 (a) shows the experimental results for the set 0, 1, 2, and 3. The external heat input increases. However, there are no significant pressure profile changes. Figure 3 (b) shows the pressure profiles for set 0, 4, and 5. The pressure profile elongates from set 4, and it is possible to observe a more extended pressure profile from set 5. The pressure decrease rate during the main discharge decreases with the higher heat flux. The heat input accelerates the liquid evaporation. The ullage gas mass increases faster with higher heat flux. Increased ullage gas mass keeps ullage pressure high, therefore, the ullage pressure decrease is suppressed compared to lower heat flux.

Table 2 shows the experimental results for used helium mass and discharged liquid volume for the different sets of the experiment. In addition, the table shows the discharged cryogenic liquid volume, and they show identical values for every set. Because the liquid discharge duration was identical to 120 seconds, this result verifies the consistency of the experiments.
As the heater level increased, the helium mass used for pressurization decreased. For example, when the heater level was high as 19.31 kW/m\(^2\), only 65 % helium was used compared to the no-heating experiment. It can be assumed that cryogenic liquid boiled by external heat and evaporated gas acted as the pressurant gas.

| Set | Heater Level | Discharged liquid volume (L) | Volume compared to Set 0 | Used helium mass (kg) | Used helium compared to Set 0 |
|-----|--------------|------------------------------|--------------------------|-----------------------|-------------------------------|
| 0   | 0.32 kW/m\(^2\) | 8324                         | 100%                     | 0.249                 | 100%                          |
| 1   | 0.45 kW/m\(^2\) | 8416                         | 101%                     | 0.251                 | 100.8%                        |
| 2   | 1.28 kW/m\(^2\) | 8583                         | 103%                     | 0.260                 | 104.42%                       |
| 3   | 6.43 kW/m\(^2\) | 8466                         | 101%                     | 0.217                 | 87.15%                        |
| 4   | 12.87 kW/m\(^2\) | 8449                         | 101%                     | 0.169                 | 67.87%                        |
| 5   | 19.31 kW/m\(^2\) | 8446                         | 101%                     | 0.162                 | 65.06%                        |

Figure 4 (a) shows the tank top (ullage) temperature profiles for the different sets of experiment. For the no-heating experiment, the tank top temperature increases from 77 K to 150 K. The tank top temperature gradually increases during the main discharge process. As the external heat input increases, the tank top temperature decreases during the pre-pressurization. While the heater is on at the start of pre-pressurization, evaporated gas also affects the lowering of the tank temperature. When the heater level is high, the tank top temperature only increases to around 110 K. The tank top temperature increases due to the pressurant gas supply during the main discharge. The final tank top temperature for all sets of experiments reached around 160 K.

Figure 4 (b) displays the liquid discharge temperature at the tank bottom. For the no-heating case, the liquid discharge temperature holds around 79 K. There is no distinguishable temperature change until the experimental set 3. Then, however, the liquid discharge temperature sharply increases from set 4 and set 5. This suggests that most of the external heat input is transferred to the liquid inside the tank.

![Figure 4](image-url)
5 (a) shows the measurement results from set 0 (no-heating case). The surface temperature at 5 cm high increases up to 130 K due to the turbulence gas supply and decreases gradually in the main discharge process. The liquid temperature was kept below 80 K. Figure 5 (b) shows the results for set 5, when the heat flux is high. The surface temperature at 5 cm high only increases to around 105 K and gradually decreases. The rapid liquid temperature rise is observed from 77 K to 90 K in this experiment. An increase in the temperature of the liquid surface indicates that active evaporation occurs.

Figure 5 Liquid surface temperature measurement for (a) set 0 and (b) set 5

Figure 6 shows the temperature distribution inside the tank. The temperature distribution is visualized from the fixed position thermometer array. Figure 6 (a) shows the temperature distribution for the no-heating case. The graphs show the temperature distribution at the end of liquid discharge. The upper tank temperature indicates a temperature around 170 K. The lower part of the tank indicates 90 K. Figure 6 (b) shows set 5. The tank upper part indicates 150 K and the lower portion indicates 100 K. The temperature at the middle part shows lower values tank set 0. It can be inferred that most of the external heat inflow is not transferred to the gas layer but the liquid layer. If heat is transferred to the gas layer, the ullage gas temperature should be increased during the discharge. However, as indicated in Figure 5 and Figure 6, the gas temperature measurements show lower values with higher heat influx.

Figure 6 Inner tank temperature distribution at the end of experiments (a) set 0 (b) set 5

4. Discussion and summary
The effect of the cryogenic liquid discharge process of external heat inflow was experimentally investigated in this study. In addition, the pressure profiles and helium pressurant consumption was compared. The low pressurant consumption at high heat flux indicates that external heat increased the evaporation of the cryogenic liquid. The evaporated gas lowered the ullage gas temperature. It can be
assumed that external heat flux mostly goes to the liquid. The measurements of tank top ullage temperature, the temperature distribution inside the tank, and the liquid surface temperature measurements support this hypothesis. At the same time, the external heat input also increased the temperature of the liquid. The rising surface temperature profile approves the energy increase in the liquid. The liquid discharge temperature noticeably also increased with the high external heat inflow.

Summarizing the results, most of the external heat input is transferred to the liquid, increasing the internal energy of the liquid. As a result, evaporation of the liquid increases, and the vaporized gas at a saturation temperature lowers the temperature inside the tank. The amount of pressurant gas supply decreases as the amount of vaporized gas is added due to the evaporation. Through several tests, it was possible to confirm the path of external heat inflow as Figure 7. Most of the external heat flows to the liquid. The higher two-phase heat transfer coefficient between the liquid and the wall, and the higher thermal conductivity of liquid than gas may have increased the heat flow to the liquid.

Figure 7 The path of external heat input during the cryogenic liquid discharge process. Most of the external heat flows to the liquid.

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