Experimental Investigation of Liquid Helium Pressurization Method for Liquid Propellant Rocket

Sehwan IN**, Sangkwon JEONG**, Youngkwon KIM**, Kie-Joo CHO** and Seung-Hyub OH***

The liquid helium pressurization method using an electric heater makes the pressurization system of a liquid propellant rocket very simple and reliable with reducing the volume and the weight of the pressurant tank. In this pressurization system, the selection of the electric heater arrangement and the heating power is critical to its performance. This paper describes how to arrange the heaters and the effect of the heating power in the liquid helium pressurant tank of the liquid propellant rocket. The experiment was performed to find the proper heater arrangement and the results are discussed. The effect of the heating power on the pressurization performance is also investigated through the experiment.

Key Words: Pressurization, Helium, Heater, Arrangement, Rocket

1. Introduction

A pressurization system in a liquid propellant rocket is essential to avoid cavitation at the turbo-pump inlet by increasing the propellant tank pressure. Figure 1 shows the schematic diagram of the pressurization system in a rocket. High pressure helium gas generated by the pressurization device goes into the propellant tank through the flow control device. The flow control device regulates the pressure and the mass flow rate of helium into the propellant tank. The high pressure helium gas from the pressurization device creates the Net Positive Suction Head (NPSH) that a turbo pump requires by pressurizing the ullage of the propellant tank. Many researches have been performed for efficient system design considering the weight as well as the performance, because the pressurization system occupies a large portion of the vehicle weight(1)–(3). Among them, a liquid helium pressurization system is much superior to other systems using high pressure helium gas at ambient or cryogenic (~ 90 K, liquid oxygen temperature) temperature, because it uses liquid helium with high density as the pressurant. However, the previous liquid helium pressurization system needed another ambient and high pressure helium gas to keep the expulsion pressure of the liquid helium tank(3). The new method using an electric heater was suggested to maintain the expulsion pressure(4). This novel method makes the whole pressurization system very simple and reliable, because the electric heater power is easy to control. In the pressurization system using a heater, it is important how to arrange heaters and how much heating power to be given in the liquid helium tank under the required operating condition, such as the minimum expulsion pressure, the discharge helium mass flow rate and the discharge time. This paper deals with the experiment to find the proper heater arrangement for the pressurization process. The experimental results are discussed and the best arrangement is

Fig. 1 Schematic diagram of pressurization system

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suggested. In addition, the effect of the heating power on the pressurization performance is discussed through the experimental results.

2. Experiment

2.1 Operation scenario of the pressurization system

The operation scenario of the liquid helium pressurization system using a heater is divided into two sequential processes; the initial pressurization process and the discharge process. Figure 2 shows these processes on the temperature-entropy diagram of helium. The arrow from point 1 to point 2 indicates the initial pressurization process. In the initial pressurization process, the pressure in the liquid helium tank increases to a certain pre-determined value by the heater while the tank is closed. The liquid helium transforms into a supercritical state as the temperature and the pressure increase during the initial pressurization process. The discharge process is represented by the arrow from point 2 to point 3 in Fig. 2. During the discharge process, the supercritical helium is discharged from the helium tank to the propellant tank in order to pressurize the propellant tank at the required pressure. The heater prevents the helium tank pressure and temperature from decreasing steeply and maintains the expulsion pressure during the required time.

2.2 Experimental apparatus

Figure 3 shows the schematic diagram of the experimental apparatus. The liquid helium tank is thermally insulated by the outside vacuum chamber and superinsulation. The pressure sensor is installed in the top flange of the outside vacuum chamber to measure the tank pressure. The heat exchanger and the pressure regulator adjust the pressure and the temperature of helium to the adequate values for the mass flow controller. The discharged helium mass flow rate is measured and controlled by the helium mass flow controller. Figure 4 shows the detailed drawing of the liquid helium tank. The liquid helium tank has the volume of approximately 0.001 m³ with 82.3 mm in diameter and 196 mm in height. 5 heaters are installed with the spacing of 30 mm each other from the top flange. The heater is made of thin stainless steel sheet with 0.025 mm thickness. The outlet port for helium discharge is apart from the bottom by 20 mm. The helium temperature is measured by 4 silicon diode sensors at each position, as
shown in Fig. 4. Table 1 indicates the each position of silicon diode sensors from the bottom. The initial mass of helium is measured by a liquid helium level meter.

2.3 Experimental conditions and procedure

The experiment is performed to know the effect of heater arrangement and heating power on the pressurization performance. Table 2 indicates the fixed operating experimental conditions. In Table 2, the final pressure after the discharge process is set as 6 bar. It means that the minimum expulsion pressure of 6 bar is needed to discharge the supercritical helium for the propellant tank pressurization. So, the liquid helium tank pressure must be maintained over 6 bar during the whole discharge process. This value is determined for the small-scale experiment and may be changed for the actual rocket pressurization system according to the system requirements. For the effect of heater arrangement, heating power is fixed for both the initial pressurization process and the discharge process, while the heater combination is changed. The experiment is performed for three heater combinations; total 5 heaters, bottom 3 heaters, and top 2 heaters. To investigate the effect of heating power, heating power is changed for each heater combination. The experimental procedure is as follows. After a liquid helium charging process is finished, the liquid helium height is measured by the liquid helium level meter. All valves are closed. The heat input is given to the helium tank through the electric heater, while the temperatures, the pressure and the heat input are measured simultaneously. When helium tank pressure reaches the final pressure of the initial pressurization process, the heat input is reset and supercritical helium is discharged at a pre-determined value from the helium tank. The temperatures, the pressure and the heat input are also measured during this process.

2.4 Experimental results

Table 3 indicates the heating power applied to each heater combination to know the effect of heater combinations on the pressurization performance. Figures 5 and 6 show the tank pressure and temperature variations for each heater combination during the initial pressurization process. As shown in Fig. 5, the pressure arrives at 10 bar most rapidly in the case of using the bottom 3 heaters. In general, the heater efficiency gets higher as the heater area increases, because the heat transfer coefficient is limited. However, Fig. 5 shows the heater efficiency of the 5 heater combination can be lower than that of the bottom 3 heater combination with identical heating power in spite of its large heater area. It is because the relatively hot helium which is heated by bottom heaters gathers at the top, and it makes the efficiency of the upper heaters (of 5 heater combination) decrease. The hot helium prevents the upper heaters from efficiently releasing heat into helium and makes some of heat which should be absorbed by helium accumulated in the heater and the supporter surrounding it. In the case of using the top 2 heaters, the heater efficiency is the worst because they have the smallest area being installed in the upper space. Temperature variation of T4 for each combination in Fig. 6 supports this interpretation. Figures 7 and 8 show the tank pressure and temperature variations during the discharge process. While the discharge process begins, the temperature throughout the helium tank steeply tries to decrease due to helium discharge. T4 in Fig. 8 indicates this temperature decrease in the early time of the process. Under this condition, 5 heater combination transfers heat to helium in a spatially uniform way and also has the largest heat transfer area, whereas 3 heater and 2 heater combinations release heat locally. This local heating doesn’t efficiently compensate temper-

<table>
<thead>
<tr>
<th>Process</th>
<th>Power (W)</th>
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<tbody>
<tr>
<td>Initial pressurization process</td>
<td>22.4±0.8</td>
</tr>
<tr>
<td>Discharge process</td>
<td>14.3±0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid helium height</td>
<td>101 mm</td>
</tr>
<tr>
<td>Helium discharge rate</td>
<td>5.2×10^{-4} kg/s</td>
</tr>
<tr>
<td>Final pressure after initial pressurization process</td>
<td>10 bar</td>
</tr>
<tr>
<td>Final pressure after discharge process</td>
<td>6 bar</td>
</tr>
</tbody>
</table>

Fig. 5 Pressure variations during initial pressurization process
shown in Fig. 8, 2 heater combination has higher temperature near the heater than that of 3 heater combination due to its position and small heat transfer area. This high temperature near the heater accelerates the decrease of heater efficiency, because the hot helium impedes the release of heat from a heater. Therefore, as shown in Fig. 7, the combination using the 5 heaters maintains the pressure over 6 bar during the longest time and has the highest heater efficiency in the discharge process. Figures 9 and 10 show the heating power effect in the 3 heater and 5 heater combinations. As the heating power increases, the initial pressurization time is shorter and the discharge time can be longer. In the 3 heater combination, the increasing or decreasing rate of the time is almost linear with respect to heating power. However, the 5 heater combination shows the decrease of the heater efficiency with heating power. The tendency is more serious in the discharge process. It is because the increase of heating power results in the larger temperature increase of helium in the upper space.
and it causes the heating efficiency to decline. This effect is more serious in the discharge process where the starting temperature of the process is higher.

3. Discussion

The heater arrangement greatly influences the pressurization performance. As shown in Figs. 5 and 7, the identical heating power can cause very different results according to the heater arrangement. From the experimental results, we can conclude that the heaters must be installed in the lower space of the liquid helium tank for the initial pressurization process and uniformly distributed for the discharge process under the moderate heating power. However, in the discharge process, the excessive heating power which may result in large increase of upper helium temperature makes the efficiency of uniform distributed heaters steeply decrease with heating power. In a pressurization system design, if the heating power for operation time is proportional to battery mass, the heating power will be determined by battery mass which minimizes total pressurization system mass (≈ battery mass + helium tank mass + liquid helium mass) with the required operation condition, such as minimum expulsion pressure, discharge time and discharge mass flow rate. Therefore, by considering such an actual heating power, the heater arrangement for the discharge process should be determined in the real rocket application.

4. Summary

A novel concept of using an electrical heater for the liquid helium pressurization is described in this paper. The cryogenic pressurization method applicable to a liquid propellant rocket is simpler and more reliable than the conventional pressurization method. The experimental investigation with a small scale system not only verifies the proposed concept but also reveals quantitatively the effect of several design parameters. The heater arrangement is believed to be a great impact to optimum design of the pressurization system using liquid helium.

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References


