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LOX recirculation characteristics of propellant feeding system with a filter installed at tank outlet

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Abstract
This paper describes the results of the propellant recirculation test, which is one of the cryogenic propellant temperature control methods. The test was conducted in a sub scaled propellant feeding system test facility using liquid oxygen. The tank diameter is 1 m and a filter is installed at the tank outlet. The evaporation of liquid oxygen in the feeding pipe during standby, liquid oxygen recirculation flowrate according to the amount of helium injection, and the effect of the propellant filling rate and pressurization of the tank on recirculation were examined. The filter installed at the tank outlet greatly affected the recirculation characteristics of the cryogenic propellant.

1. Introduction

The propellant feeding system of the liquid propulsion rocket should maintain the temperature of the cryogenic propellant supplied to the engine within the engine requirements. The temperature of the cryogenic propellant rises due to heat input from the outside during standby after completion of filling. This can cause turbopump cavitation problems. If the temperature keeps rising, the propellant reaches saturation state and begins to evaporate and in severe cases, geysering may occur [1].
Methods for controlling the temperature of the cryogenic propellant include direct cooling the propellant by helium injection, draining the temperature increased propellant, and recirculating the propellant [2]. The recirculation method prevents propellant temperature rise at the engine inlet by installing a recirculation pipe to form a loop composed of a propellant tank, a feeding pipe, and a recirculation pipe, and allowing the propellant to continuously flow through the loop. Due to the difference of the diameter of the feeding pipe and the recirculation pipe, the amount of heat inflow into the pipes are not the same, and this creates a density difference of the cryogenic propellant in the pipes so that the propellant is circulated by hydrostatic pressure difference [3]. Helium could be injected at the bottom of the recirculation pipe to promote propellant recirculation. A representative example of a rocket using the recirculation method is the Saturn V vehicle [4].
This paper describes the results of the recirculation test conducted in a sub scale propellant feeding system test facility with a tank diameter of 1 m using liquid oxygen. The test was conducted in four phases: standby after filling with liquid oxygen, recirculation test under atmospheric pressure, propellant refilling, and recirculation test under pressurized condition. The evaporation of liquid oxygen in the feeding pipe during standby, liquid oxygen recirculation flowrate according to the amount of helium injection, and the effect of the propellant filling rate and pressurization of the tank on recirculation were examined.

2. Principle of recirculation

In general, a recirculation pipe has smaller diameter or less insulated than that of the propellant feeding pipe. This makes the propellant in the recirculation pipe absorb more heat per unit mass than the propellant in the feeding pipe. As a result, the temperature of the propellant in the recirculation pipe rises faster than that of the propellant in the feeding pipe, and the propellant density in the two pipes become different. Due to this difference in density, the hydrostatic pressure of the propellant in the two pipes are not the same and a flow of the propellant in the recirculation loop takes place. Of course, recirculation can occur only when this pressure difference is greater than the flow resistance in the loop. If the propellant evaporates and the evaporated propellants is trapped in the pipe, the hydrostatic pressure significantly decreases and the flow resistance increases, so the recirculation can’t occur. If the pressure difference between the two pipes is not large enough to cause recirculation or the recirculation flowrate of the

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propellant is not sufficient, helium may be injected into the recirculation pipe to promote recirculation. The injected helium lowers the hydrostatic pressure in the recirculation pipe, increasing the amount of propellant circulation flow. The large propellant recirculation flowrate suppresses the propellant temperature rise at the engine inlet by reducing the heat absorption in the pipe from the propellant tank to the engine inlet.

3. Test facility

Figure 1 is a panoramic view of the sub scaled propellant feeding system test facility. It consists of an upper oxidizer tank, a lower fuel tank, a pressurization system, and a propellant feeding system. Figure 2 is a schematic diagram of the recirculation loop consisting of the propellant tank, feeding pipes, and recirculation pipes. It shows the locations of valves, flowmeters, temperature and pressure sensors installed in the test facility for testing.

The tank is 1 m in diameter and 3.2 m in height. The feeding pipe is 2.5 inches in diameter, 0.9 mm thick, and 4.4 m high. The recirculation pipe is 1 inch in diameter, 0.7 mm thick, and 6 m high. The pipes are insulated with polyurethane foam, and the insulation thickness is 25 mm for the feeding pipe and 20 mm for the recirculation pipe. There is a helium injection pipe of 0.25 inches diameter at the bottom of the recirculation pipe, so that the helium is injected vertically upward. A valve was installed at the horizontal pipe between the feeding pipe and the recirculation pipe to stop recirculation. The recirculated liquid oxygen flowrate and the injected helium flowrate were measured by flowmeters equipped at each pipe. Temperature sensors and pressure sensors were installed in the oxidizer tank, feeding pipe, and recirculation pipe to monitor the temperature and pressure variations of the propellant along the recirculation loop. The mounting height of each sensor based on the horizontal pipe is also indicated in the schematic diagram of Figure 2.

Figure 1: Panoramic view of test facility

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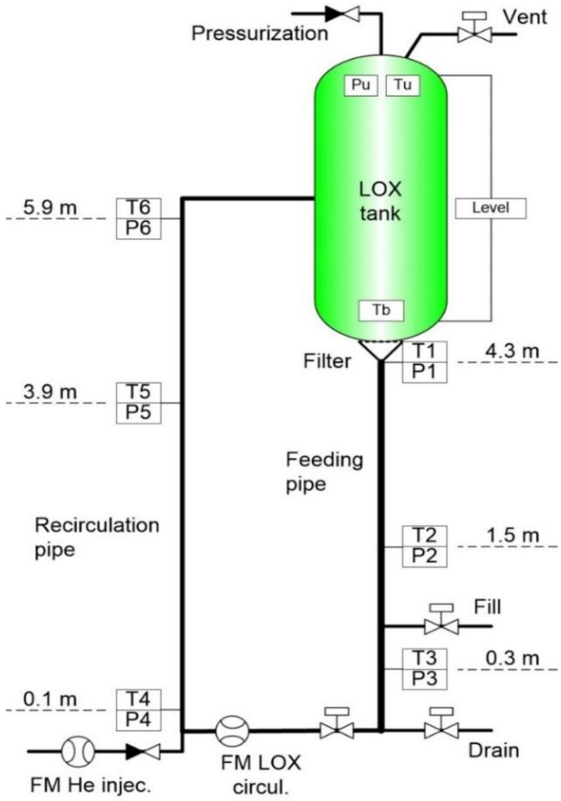

Figure 2: Schematic diagram of recirculation loop

There is a filter at the outlet of the oxidizer tank. It is a 7-ply sintered filter with a thickness of 1.7 mm and a diameter of 209 mm. Average pore size of the filter is 115 µm. As will be described in the test results later, the location of the filter greatly affected the propellant recirculation characteristics.

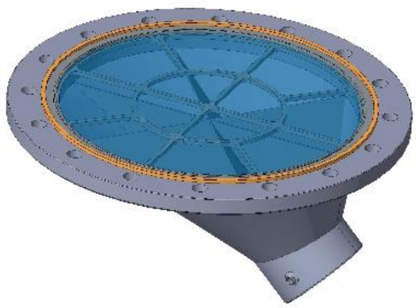

Figure 3: Tank outlet flange with filter

Figure 4: Filter mesh and support

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Liquid oxygen, an actual rocket propellant, was used as the working fluid. The test was conducted in four phases as follows.

Propellant filling and standby.
After liquid oxygen filling completed, the state change of liquid oxygen in the feeding pipe was examined with the vent valve open.

Recirculation under atmospheric pressure.
We examined whether natural recirculation occurred after long standby, and observed the liquid oxygen recirculation flowrate according to the helium injection flowrate.

Propellant re-filling.
The temperature distribution and recirculation of liquid oxygen in the loop were observed in both cases of rapid filling and slow filling of propellant.

Recirculation under pressurization.
We examined whether natural recirculation occurred when the propellant tank was pressurized, and observed the liquid oxygen recirculation flowrate according to the helium injection flowrate.

Unfortunately, the test data of each phase is not continuous because the data is cut and stored at each phase.

4. Test results

4.1 Standby after filling

It took about 90 minutes to fill with liquid oxygen up to a point of about 2.7 m in the height of the oxidizer tank, including cooling the tank. For about 15 minutes before completion of filling, the tank was filled slowly at a volume flowrate of about 11.2 l/min.

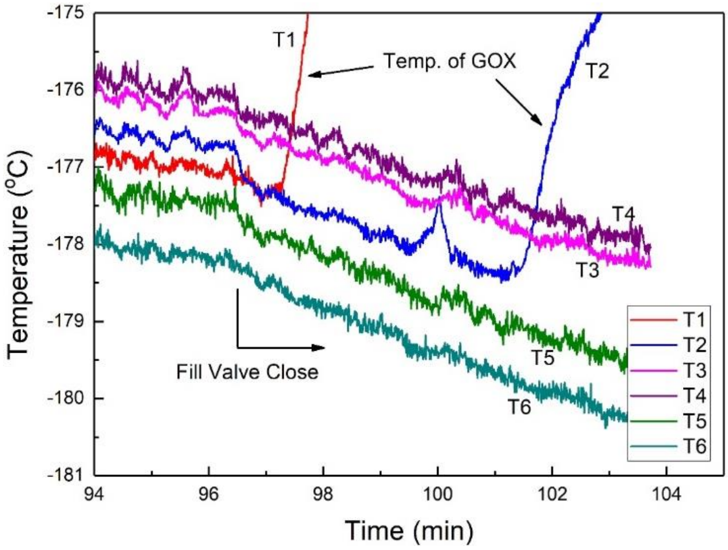

Figure 5: Temperatures of oxygen after completion of filling

Figure 5 shows the temperatures of the oxygen inside the pipes after completion of filling. As the tank ullage pressure gradually decreased after the fill valve was closed, the propellant temperature also decreased overall. However, the liquid oxygen temperature at the top of the feeding pipe started increasing rapidly. The temperature of T1 at the upper part of the feeding pipe started increasing within about 30 seconds after the fill valve was closed, and after about 4.5 minutes, the temperature in the middle height of the feeding pipe, T2 also rapidly increased. This rapid rise in temperature means that the oxygen inside of the pipe was not liquid state. The liquid oxygen supplied from the ground supply system was not subcooled state and the tank was being filled slowly to control the filling level. Therefore, the

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liquid oxygen in the pipe was already close to the saturation point before the completion of filling, and it started evaporating rapidly when the fill valve was closed.
This abnormal phenomenon in which the oxygen temperature in the feeding pipe rapidly rises sequentially from the top toward the bottom is because of the filter mounting position. Due to the filter installed at the outlet of the oxygen tank, the gaseous oxygen evaporated in the pipe do not flow into the tank, and liquid oxygen in the tank can't enter into the feeding pipe. So, an odd phenomenon occurred in which liquid oxygen was above the filter, and gaseous oxygen was below the filter as shown in Figure 6.

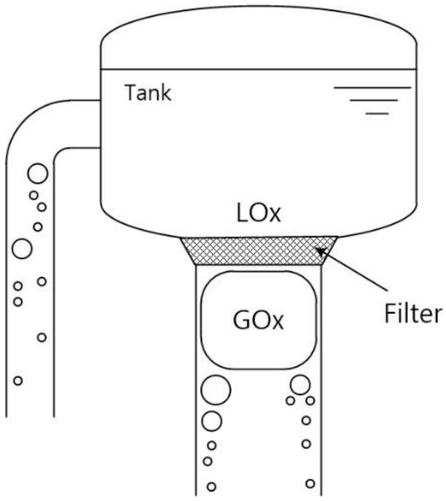

Figure 6: The effect of filter on the state of oxygen in the pipe

If no measures are taken to control the propellant temperature after filling is complete, the liquid oxygen in the feeding pipe is gradually reduced by evaporation and the pipe is filled with gaseous oxygen. Even if the filter is not at the outlet of the tank but in front of the turbopump, the accumulation of evaporated oxygen under the filter, i.e. in the turbopump, will be the same.

4.2 Atmospheric pressure recirculation

Natural recirculation did not occur due to gaseous oxygen accumulated in the feeding pipe during standby after completion of filling. This was because the hydrostatic pressure of the propellant in the feeding pipe greatly decreased as much as the height occupied by the gaseous oxygen. In order to generate recirculation, helium was injected, but recirculation did not take place until the helium injection flowrate reached about 95 standard l/min. Since there was a lot of gas inside the feeding pipe and the hydrostatic pressure was greatly reduced, as much helium enough to overcome the pressure difference between feeding pipe and recirculation pipe was needed.

Through the test results below, let's take a closer look at the beginning of recirculation process. Figure 7 shows the temperatures of the oxygen before and after the occurrence of recirculation. This data began to be measured about 7.5 minutes after the completion of filling. It can be seen from the temperature data that a lot of space in the feeding pipe were already occupied with gaseous oxygen. At the time the measurement started, the tank outlet temperature of T1 had reached -150 ℃, and the temperature of the middle part of the feeding pipe, T2 also started to rise. After about 25 minutes (about 17 minutes in Figure 7) after the completion of filling, the temperature of the lower part of the feeding pipe, T3 started to rise, also. It means that the entire feeding pipe was filled with gaseous oxygen. It took 25 minutes for all the liquid oxygen in the feeding pipe to evaporate without any temperature conditioning measures.
The temperature of the liquid oxygen in the feeding pipe and recirculation pipe was gradually decreasing according to the tank pressure decrease until recirculation took place. From about 4 minutes in Figure 7, helium injection was begun to generate forced recirculation, and as a result, the temperature of the liquid oxygen in the recirculation pipe was decreased. The more details on the liquid oxygen cooling by helium injection can be found in reference [5]. Due to the helium injection, forced recirculation occurred at about 20 minutes in Figure 7. As the liquid oxygen in the tank rapidly rushed into the feeding pipe, the temperature of the feeding pipe instantly decreased.

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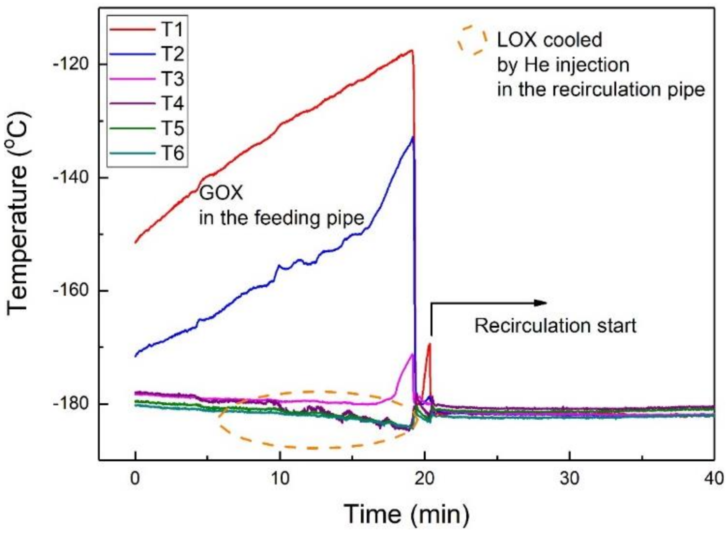

Figure 7: Temperatures of oxygen at atmospheric pressure recirculation test

Figure 8 shows liquid oxygen recirculation flowrate according to helium injection flowrate ac atmospheric pressure recirculation test. Recirculation did not occur even though the amount of helium injection was gradually increased to cause forced recirculation. This was because the hydrostatic pressure in the feeding pipe had been greatly reduced due to the evaporation of all the liquid oxygen in the feeding pipe. Recirculation began only when the amount of helium injection reached 95 standard l/min or more at about 20 minutes in Figure 8. When helium is injected, it takes up space in the pipe and the hydrostatic pressure in the recirculation pipe is reduced. As helium injection flowrate increases, the hydrostatic pressure in the recirculation pipe decreases lower than in the feeding pipe. In addition to this, with the help of gas-lift effect of injected helium, forced recirculation takes place.

Once the feeding pipe was filled with liquid oxygen and the recirculation flow started, active recirculation was maintained even when the amount of helium injection was reduced. From about 45 minutes, it can be seen that the recirculation continued naturally even though the helium injection was stopped. The recirculation flow rate decreased as the amount of helium injection decreased, but down to about 50 standard l/min of helium injection, the recirculation flow rate increased very slightly as the injection amount was reduced. This means that there is an appropriate amount of helium injection for the system, and it is not always good to increase the amount of helium injection. If the amount of helium injection is larger than necessary, there is too much gas in the recirculation pipe, and the flow resistance increases. As a result, the recirculation flow rate decreases.

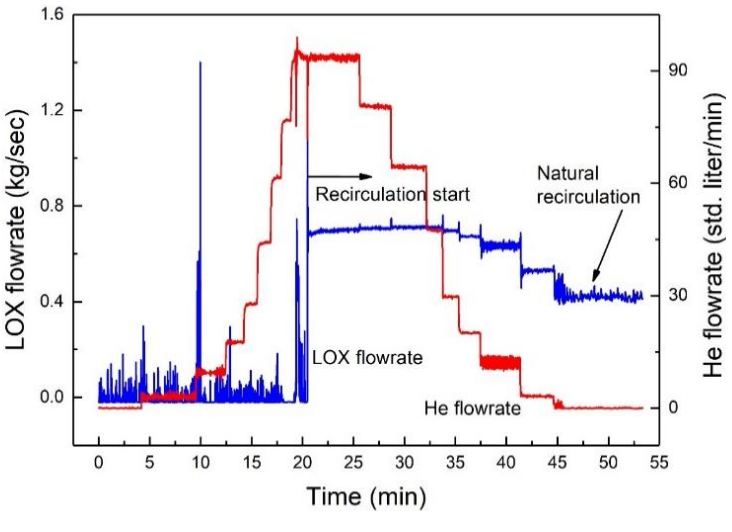

Figure 8: LOX and He flowrate at atmospheric pressure recirculation test

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Figure 9 shows the pressures in the pipes. The height difference between the pressure sensors P1 and P3 installed in the feeding pipe is about 4 m, so the pressure difference between the two points should be about 0.4 bar in normal conditions. However, at the beginning of measurement, the pressure difference was about 0.15 bar, and almost the same pressure was recorded about 25 minutes after completion of filling (about 17 minutes in Figure 9). From this, it can be thought that the inside of the feeding pipe is completely in a gaseous state. At about 20 minutes in Figure 9, forced recirculation by helium injection occurred, and liquid oxygen in the tank passed through the filter and rapidly flowed into the feeding pipe. As a result, a pressure shock was applied to the bottom of the feeding pipe and the recirculation pipe. The reason why the pressure shock occurred twice is explained in Figure 10 below. After the feeding pipe was filled with liquid oxygen, the pressure difference between P1 and P3 was more than about 0.4 bar, and the hydrostatic pressure distribution was formed according to the height.

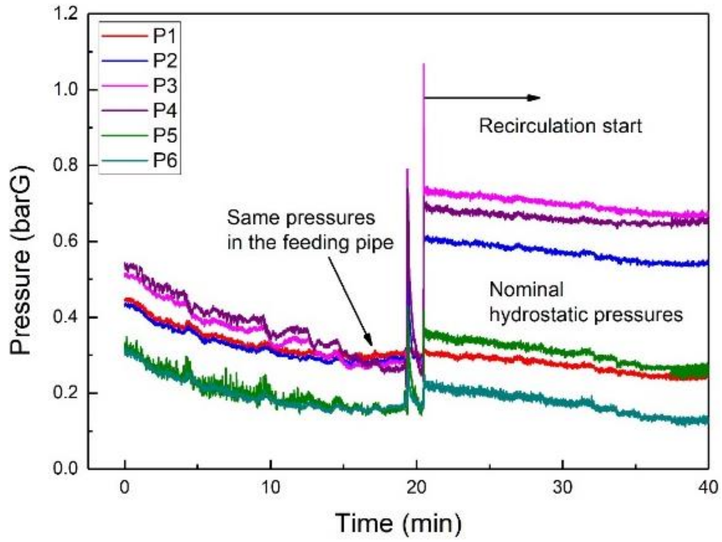

Figure 9: Pressures in the pipes at atmospheric pressure recirculation test

Figure 10 shows the liquid oxygen level in the tank. It can be seen that the filling level inside the oxidizer tank was changed rapidly as recirculation took place. The empty feeding pipe was filled with liquid oxygen in a short time, which affected the level inside the tank. Recirculation did not occur immediately after the first inflow of liquid oxygen. The lowered filling level at the time of the first inflow of liquid oxygen was restored for about 1 minute, and then the second inflow occurred again. This is because the temperature of the feeding pipe filled with GOX was high, so that liquid oxygen flowing into the feeding pipe evaporated. Since the feeding pipe was cooled by liquid oxygen evaporation, recirculation occurred after the second inflow of liquid oxygen.

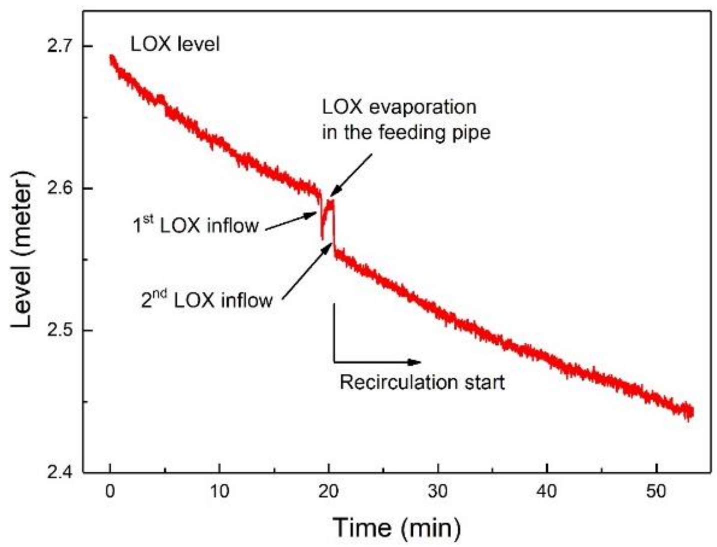

Figure 10: LOX level in the tank at atmospheric pressure recirculation test

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4.3 Propellant refilling

Because the test time was quite long and the propellant in the tank vaporized a lot, the tank was refilled. During this phase, the filling rate of liquid oxygen was varied and the effect of it on the occurrence of natural recirculation was examined. Fast filling volumetric flowrate was 36 l/min which was about 4 times of the slow filling rate of 9.3 l/min.

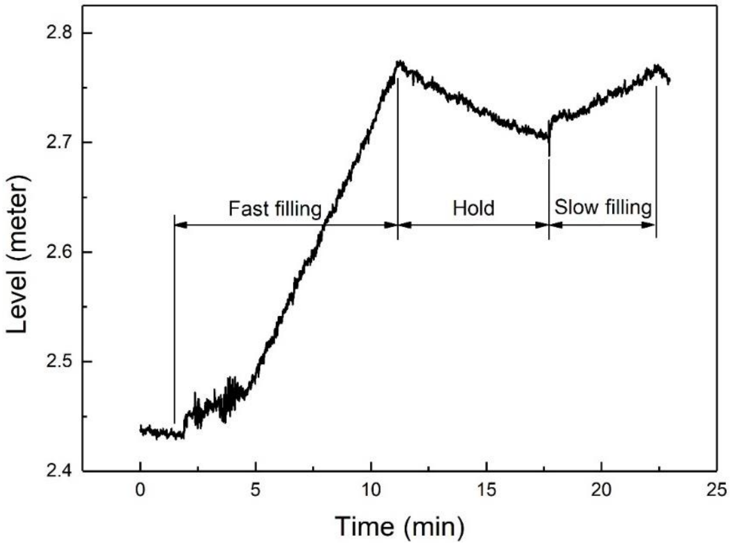

Figure 11: Refilling rates of liquid oxygen

When liquid oxygen is rapidly filled into the tank, the gaseous oxygen evaporated inside the tank cannot be sufficiently discharged to the outside, and the ullage pressure increases. Then, a high hydrostatic pressure is formed inside the pipe, and the liquid oxygen is under a subcooled state. If the liquid oxygen inside the pipe is in a subcooled state at the point of completion of filling, it maintains liquid state, so natural recirculation occurs due to the density difference between the feeding pipe and the recirculation pipe. Once recirculation is established, it continues even if the tank ullage pressure decreases during the standby. However, in the case of fast filling, it is not easy to properly control the filling level of liquid oxygen. When liquid oxygen is slowly filled into the tank, the ullage pressure inside the tank is kept low. The hydrostatic pressure in the pipe is also low, so liquid oxygen approaches saturation state. In this case, when filling is stopped, the liquid oxygen rises in temperature and subsequently begins to evaporate.

Let's look at the effect of the filling rate on the recirculation through the test results.

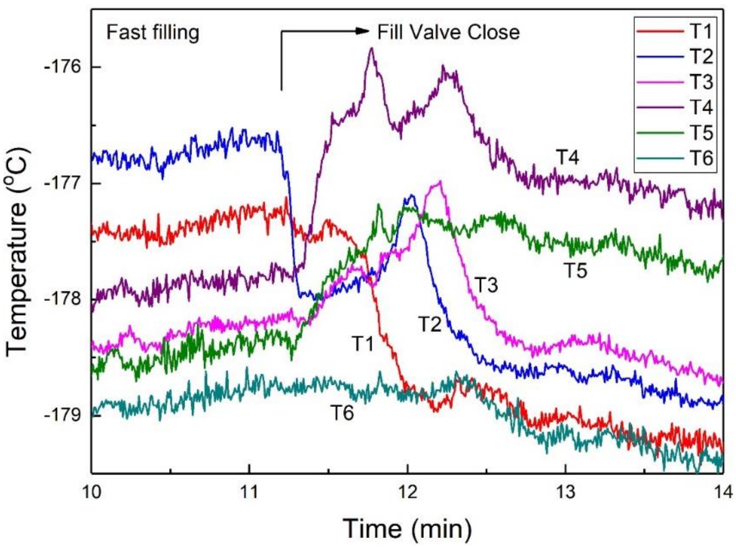

Figure 12: Temperatures of oxygen after fast filling

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Figure 12 shows the temperatures of oxygen in the pipes after fast filling. In the case of fast filling, a relatively high hydrostatic pressure was formed inside the pipe at the point of completion of filling (at about 11 minutes in Figure 12). At this time, all the liquid oxygen temperatures, except T1, T2 in the section of liquid oxygen filling flow path, maintained a subcooled state with respect to the static pressure of the corresponding height. Liquid oxygen supplied from the test facility is nearly close to saturation state. So, during filling, the liquid oxygen temperatures in the feeding pipe was higher than that in the recirculation pipe, but when the filling valve was closed, the liquid oxygen temperatures in the feeding pipe and recirculation pipe reversed. Except for T5, T6, a temperature gradient was naturally formed along the loop and natural recirculation occurred. T5, T6 are located at the upper part of the recirculation pipe, and the temperature decrease of them along the loop is because of liquid oxygen evaporation due to low hydrostatic pressure at that height. This process took about 1.5 minutes. The pressure distribution in the pipe also formed a normal hydrostatic pressures.

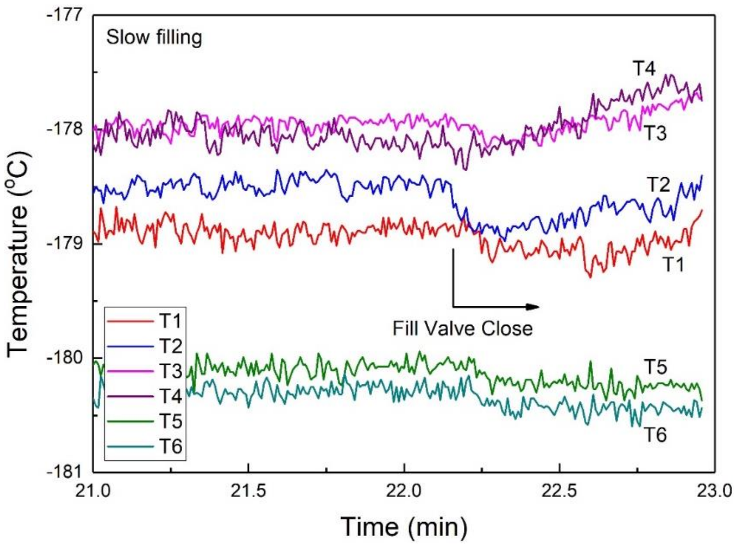

Figure 13: Temperatures of oxygen after slow filling

Figure 13 shows the temperatures of oxygen in the pipes after slow filling. In the case of slow filling, a relatively low hydrostatic pressure was formed inside the pipe at the time of filling completion (at about 22 minutes in Figure 13). At this time, all of the liquid oxygen in the pipe showed a temperature close to saturation state with respect to the static pressure at each location. When the fill valve was shut off, the liquid oxygen inside the pipe did not show any significant temperature change, which is unfortunately because data recording was stopped too early. However, in the subsequent pressurization test, the temperature of T1 was already rapidly rising when data recording started, indicating that gaseous oxygen evaporated in the feeding pipe began to accumulate below the filter.

4.4 Pressurized recirculation

Even if gaseous oxygen evaporated during standby exists in the feeding pipe, it disappears immediately when the tank is pressurized. As the pressure rises, the volume of gaseous oxygen in the feeding pipe decreases and liquid oxygen flows into the pipe. Then, the gaseous oxygen condenses and the volume of it decreases more. Now, the feeding pipe is filled with liquid oxygen come from the tank and natural recirculation occurs along the loop.

Figure 14 shows the temperature change of liquid oxygen in the pipe immediately after closing the vent valve of the tank. At the time of data recording start, the temperature of T1 was rapidly rising. It means the gaseous oxygen was already accumulating below the filter in the feeding pipe. However, as soon as the vent valve was closed, the temperature of T1 abruptly decreased, and the temperatures of the liquid oxygen in the feeding pipe and recirculation pipe reversed. There was a clear difference between the temperatures of the feeding pipe and the recirculation pipe, and a gradually rising temperature gradient was formed along the loop from the feeding pipe to the recirculation pipe. After the temperature gradient was formed, the temperature of the liquid oxygen was rising as a whole, especially in the recirculation pipe. This was not due to evaporated gaseous oxygen, but rather the rise in temperature of the liquid oxygen because the tank pressure was maintained at about 4 bar during the test.

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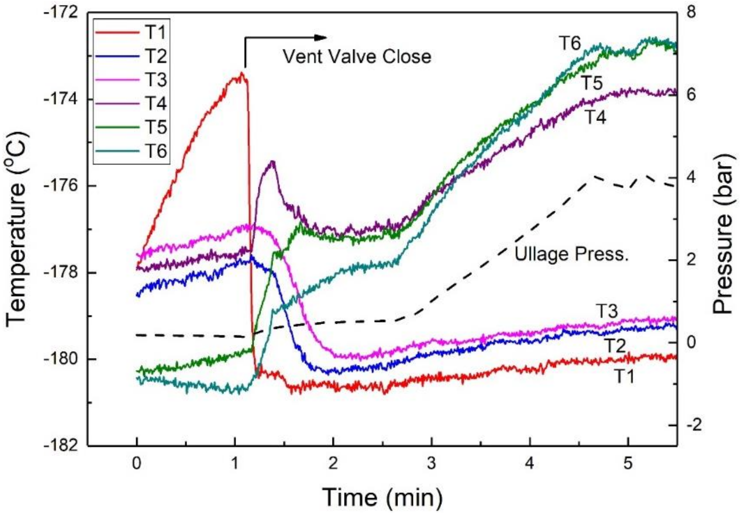

Figure 14: Temperatures of oxygen at pressurized recirculation test

Figure 15 shows the liquid oxygen recirculation flowrate according to the helium injection flowrate at pressurized recirculation test. Liquid oxygen was already recirculating naturally when the flowmeter was powered on. As the helium injection flowrate was increasing, the recirculation flowrate also increased, but it was smaller than in the atmospheric pressure test. It's because at the same mass flowrate of injected helium, the volume flowrate under the pressurized condition was lower than that in the atmospheric pressure, so the effect of raising the liquid oxygen in the recirculation pipe was reduced. In other words, the volume flowrate of injected helium should be the same to obtain the same liquid oxygen recirculation effect. The recirculation flowrate had a maximum value in the atmospheric pressure test, but it continuously increased in the pressurized test. It's also because the helium volume in the recirculation pipe is smaller, so the circulation flow of liquid oxygen was less hindered than in the atmospheric pressure test.

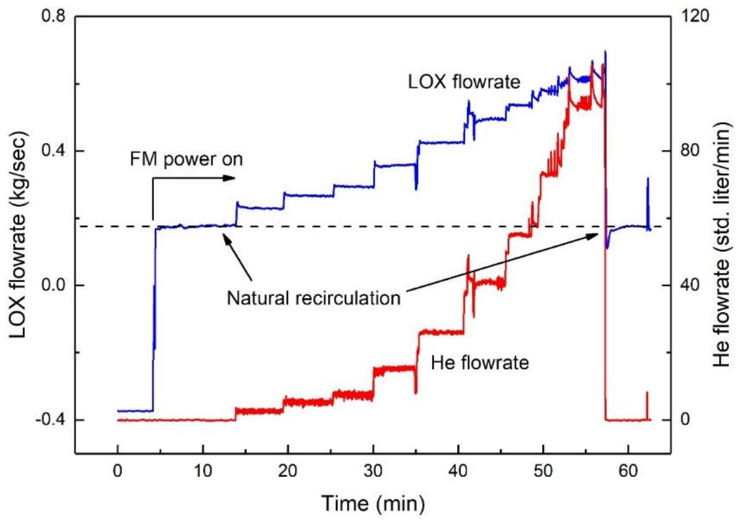

Figure 15: LOX and He flowrate at pressurized recirculation test

5. Conclusion

Recirculation characteristics were tested using liquid oxygen in a sub scaled propellant feeding system test facility. Test was conducted in four phases: standby after filling with liquid oxygen, recirculation test under atmospheric pressure, propellant refilling, and recirculation test under pressurized condition. The evaporation of liquid oxygen in the feeding pipe during standby, liquid oxygen recirculation flowrate according to the amount of helium injection, and the effect of the propellant filling rate and pressurization of the tank on recirculation were examined.

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Standby after filling.
Due to the filter installed at the outlet of the oxidizer tank, gaseous oxygen generated by evaporation of liquid oxygen in the feeding pipe did not flow up into the tank and continued to accumulate inside the feeding pipe.

Atmospheric pressure recirculation.
If gaseous oxygen accumulates inside the feeding pipe, natural recirculation cannot occur. As the amount of gaseous oxygen accumulated in the feeding pipe increases, much more helium injection is required to cause forced recirculation. The amount of recirculation of liquid oxygen increases as the amount of helium injection increases, but when helium flowrate reaches at a certain point, the bubbles obstruct the smooth flow of liquid oxygen and the amount of recirculation begin to decrease.

Effect of filling rate.
If the propellant is rapidly filled, the tank ullage pressure increases and the propellant in the pipe maintains subcooled state, resulting in natural recirculation. On the contrary, if the propellant is filled slowly, the propellant will be close to saturation state and immediately begins to evaporate when filling is stopped.

Pressurized recirculation.
When the tank is pressurized, liquid oxygen rushes into the feeding pipe and gaseous oxygen in the pipe immediately condenses. And recirculation begins naturally. In the pressurized condition, when the same mass flowrate of helium was injected, the amount of liquid oxygen recirculation was smaller than in the atmospheric pressure condition. This is because the smaller helium volume in the recirculation pipe under the pressurized condition makes the hydrostatic pressure difference smaller.

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