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A Method for Measuring the Leakage of Oxygen and Helium using Standard Gas Flow Rates in Cryogenic Valves

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Abstract

The relationship between the mass flow rate of oxygen and the volume flow rate of helium was presented using the mouthpiece method. The mouthpiece method can reduce test costs and time by using a similar experimental formula. Rather than performing an actual flow rate test using liquid oxygen, the mouthpiece method can be used to simply check the leakage of a cryogenic valve for liquid oxygen before installing a rocket engine. In order to obtain a leakage relationship between helium and oxygen at room temperature and cryogenic temperatures in the leakage measurement of a cryogenic valve, experiments were conducted and compared. It was confirmed that the leakage volume flow rate of helium [A.㎖/s] was 174 times larger than the mass flow rate [g/s] of the leakage of oxygen in the liquid state.

1. Introduction

Cryogenic valves which require strict leakage performance are tested for leakage after valve manufacturing to determine manufacturing quality. Common leakage test methods include the Soapsuds method, the Aquarium method, the Evacuation method, and the Mouthpiece method[1].
The first, the Soapsuds method sprays soap water on the area to be checked for leakage and fills the inside of the valve with gas to check if soap bubbles are formed. This method is commonly used when the leakage amount is small.
The second, the Aquarium method immerses the pressurized valve in a liquid tank and maintains the test pressure to observe for several minutes. If gas bubbles are formed, it is determined that external or internal leakage has occurred. This method is mainly used for medium to large sized structures with internal spaces such as containers. Even if leakage occurs, if the external shape is complex, the bubbles may not be separated by surface tension but may remain attached to the outer skin, which may cause errors in the test results.
The third, the Evacuation method places the valve in a sealed space and checks the amount of gas leaking with the readings of an additional connected measuring device. The gas used at this time is mostly helium, and it can measure even the amount of tiny leakage, but since the device is expensive, it has the disadvantage of requiring a lot of budget for the initial configuration.
The fourth, the Mouthpiece method is a method commonly used in valves, etc., in which the valve is not directly immersed in the liquid, but the outlet tube is immersed in the liquid to observe whether gas bubbles are generated. Since the test medium is gas, it does not adhere to the valve, so it is mainly used in cases where the cleanliness of the valve is required. The mouthpiece method can obtain quantitative results more precisely than the water bath method.
In the case of small valves rather than large containers, the mouthpiece method is mostly used for testing to minimize the test cost incurred during the factory test stage. For example, as shown in Figure 1, the valve is immersed in liquid nitrogen at atmospheric pressure. At this time, liquid nitrogen, which is an inert gas, is used for safety. The gas used to check internal bubbletigntness is helium, which does not liquefy even when it reaches the boiling point of liquid nitrogen, and the leak condition on the outlet side is checked. If a gas with a high boiling point and easy liquefaction is used, it will stagnate inside the product in a liquid state, making the leakage results unreliable. In valve testing, a gas that is not affected by the surrounding temperature should be selected and applied.
The mouthpiece method involves immersing the valve in a cryogenic fluid, allowing it to cool completely to a cryogenic temperature, then pressurizing helium into the internal inlet and allowing some leakage to occur through the opposite port. The leakage amount is then precisely measured. The gas used in the valve leakage test is not a liquid but a cryogenic gas, so it may vary depending on the development requirements.

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In the case of tests using liquid, the extremely low temperature and high pressure fluid is generated in the high pressure run tank, and at the same time, the valve leakage amount is tested depending on whether the valve is open or closed. The goal is to minimize the test cost as much as possible due to the limitations of the test device and the problem of excessive test cost. For this purpose, comparative data on the leakage amount between gas and liquid is required. There are various types of working fluid and medium used in the target valve, but this paper describes them only as gaseous helium and liquid oxygen[2].
In this paper, we try to confirm the relationship between the mass flow rate of liquid and the volume flow rate of gas in the leakage measurement of valves. Based on this, we try to present theoretical and empirical formulas so that the leakage condition by the mass flow rate measurement method can be sufficiently satisfied by the volume flow rate measurement method using a low-cost device at the factory test stage. The derived relationship is verified using the data of the National Institute of Standards and Technology.

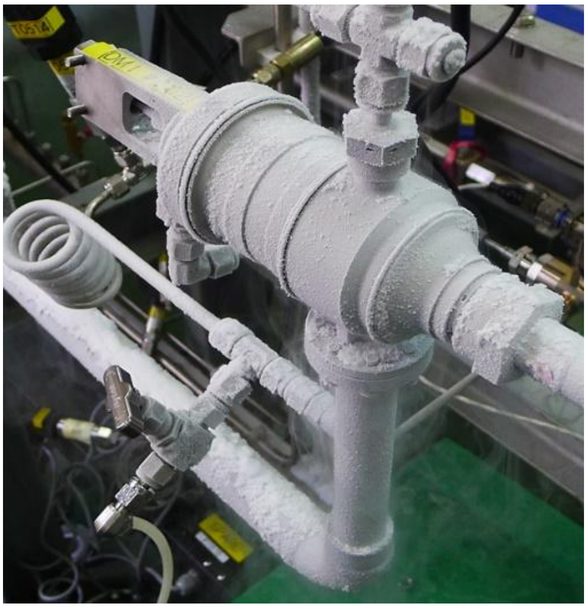

Figure 1: Cryogenic valve for flow testing using Lox

2. Theory

The standard flow rate(SCMH, Standard Cubic Meter per Hour) converted through the heat exchanger can be expressed as equation (1) using the pressure, temperature, and actual flow rate(ACMH, Actual Cubic Meter per Hour) obtained in the experiment [3].
In the leakage experiment using helium and oxygen, the volume flow rate generated through the valve can be converted to a standard flow rate using equation (1), which can then be expressed in mass flow rate equations (2) and (3). Here, since the actual flow rate is converted to a standard flow rate, the standard pressure and standard temperature of the gas used must be known. These are factors that must be obtained through experiments. From equation (1), it can be show that the larger the internal velocity of the flow passing through the flow meter, the larger the standard flow rate. However, if the gas flow is at room temperature rather than cryogenic temperature, the effect on the standard flow rate is minimal[4].

$$SCMH = \frac{\text{ACMH}}{\left[\frac{P_{std}}{P_{act}-P_{sat}\,\Phi}\right]\frac{T_{act}}{T_{std}}} \tag{1}$$

In equation (1), P_{std} is the standard absolute pressure, P_{act} is the differential pressure of the flow meter, P_{sat} is the saturation pressure at the actual temperature, Φ is the humidity ratio, is the temperature at the front of the flow meter, and is the standard temperature. Here, the standard state is 288 K for the temperature and 1 atm for the pressure.

$$\dot{m}[g/s] = \rho_{act} \times Q\ [S \cdot m^3\ /s] \tag{2}$$

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$$= \frac{P_{std} \times SCMH}{R \times T_{std} \times 3{,}600{,}018}$$

$$= \frac{97.7 \times SCMH}{R} \quad (3)$$

where, R = Specific gas constant [J/kg/K]

Equation (2) is an equation that converts the standard flow rate of gas into mass flow rate. Since equation (2) uses the standard flow rate, the pressure and temperature of the actual gas need to be standardized, and at this time, the standard flow rate and the specific gas constant can be used to calculate the mass flow rate as in equation (3).
If the area of the orifice front in the fluid system is larger than the orifice area, cavitation does not occur when passing through the orifice, and the viscous effect is ignored, it can be expressed as a flow rate equation as in equation (4). In addition, the flow rate equation passing through the orifice in the gas state is as in equation (5). In this paper, we aim to obtain the similarity relationship between oxygen in the liquid state and helium in the gas state, so equation (4) can calculate the liquid oxygen, and equation (5) can calculate the flow rates of gaseous oxygen and helium [5, 6,7].

$$\mathrm{Q} = C_q\, A \sqrt{\frac{2\, g\, |\Delta P|}{\rho}} \quad (4)$$

Where, C_q is the flow rate coefficient, A is the orifice area, and g is the acceleration of gravity.

$$\dot{m} = \mathrm{A}\ C_q\ C_m \frac{P_u}{\sqrt{T_u}} \quad (5)$$

Where, C_m is flow variable, P_u is upstream pressure, T_u is upstream temperature of gas.

Equations (4) and (5) clearly show the phases of liquid and gas. However, this paper has limitations in proving the similarity between cryogenic helium and oxygen. Therefore, the standard flow rate equation of equation (1) was used to improve the unclear phase.
Equations (1), (2) and (3) can be summarized from an experimental perspective as follows. In the case of gaseous helium, even if it is cooled to the boiling point using liquid nitrogen used for cooling purposes, the phase does not change to liquid. To simulate this, if helium is passed through a heat exchanger in a liquid nitrogen container, it becomes cryogenic gaseous helium. Gaseous oxygen can be obtained as liquefied liquid oxygen through the same heat exchanger, and although the temperature is the same as that of the produced cryogenic helium, the phases are different. Therefore, the orifice equation presented in the liquid and gaseous states cannot be used. Therefore, in the case of oxygen generated in a liquid state, the gas that has undergone a phase change from liquid to gas through a drain pipe is converted into a standard flow rate. The purpose of the conversion is that the temperature of the heat exchanged with the target, ultra-low temperature helium, is different. For this reason, the standard flow rate of equation (1) is used and the temperature of the generated gas at the time of heat exchange is standardized.

3. Test Method

As shown in Figures 2 and 3, liquid nitrogen is filled around the heat exchanger contained in the container. As the room temperature gas undergoes heat exchange with a low temperature, the liquid nitrogen is consumed, so that liquid nitrogen can be continuously supplied, an device is configured as shown in Figure 3. It consists of a heat exchanger that replaces the valve, a tube that can be introduced into the heat exchanger, and an insulated container that can contain liquid nitrogen to cool the heat exchanger. The outlet tube is connected to a mass flow meter, which is a leakage meter. When helium is supplied from a helium cylinder into the interior of the test valve, heat exchange occurs with the cryogenic liquid nitrogen and it changes into cryogenic helium, and ultimately, all media passing through the cryogenic test valve changes to cryogenic conditions.
Figure 2 shows the device for measuring the leakage of oxygen and helium. The experimental conditions are all the same, and only the gases for the experiment are different. In order to verify the similarity, the target gases, high-pressure oxygen and helium, are required. As shown in Figure 2, there is a source for pressurization and a pressure reducing device that can be adjusted to a constant pressure. In order to make the measurement results reliable, only one pure gas is used, not a mixture of two gases [8,9]. As soon as the depressurized gas passes through the heat

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exchanger, its temperature drops rapidly, and the oxygen and helium passing through the orifice are allowed to rise to a certain temperature through the drain tube, and then the standard flow rate is calculated. The temperature of the gas is measured downstream of the orifice, that is, upstream of the mass flow meter.

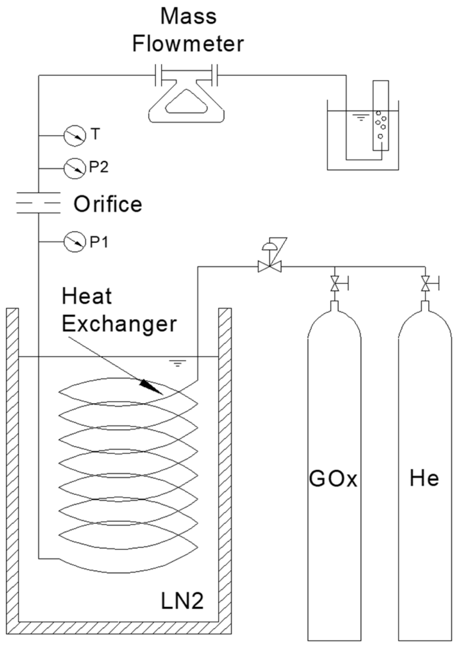

Figure 2: Schematic diagram of experiment

The heat exchanger in Figure 2 is a imitate of the valve in Figure 1. As mentioned above, in the case of the valve immersed in liquid nitrogen in the factory test, sufficient cooling is confirmed and then helium is pressurized. The reason the heat exchanger is in the form of a coil is to generate flow after pressurizing the gaseous oxygen and helium. The main purpose is to continuously input two gases at room temperature to maintain a constant pressurization. The heat exchanger is manufactured to maximize the contact area, so that pressurization and liquefaction can occur quickly. When conducting experiments using a test facility capable of high pressure and large flow control, a large amount of liquid oxygen must be charged and, pressurized to the corresponding high pressure, which may result in waste test fluid during the development test. To overcome this, a heat exchanger was designed and manufactured in the form of Figure 3. In the case of gaseous oxygen, when it passes through the heat exchanger, since the area around the heat exchanger is all liquid nitrogen, the oxygen that passes through changes into supercooled liquid oxygen at the outlet. Helium is an extremely low-temperature gaseous helium that does not undergo a phase change even when it passes through the heat exchanger (Figure 3).

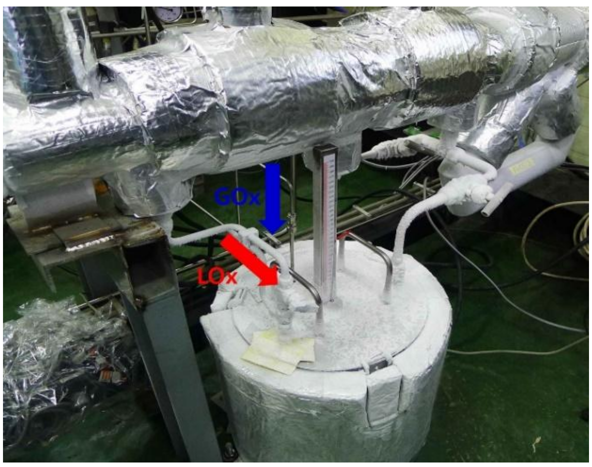

Figure 3: Heat exchanger

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In the Figure 4, micro motion coriolis flowmeter (CMF010) can be used to measure the mass flow rate of helium and oxygen passing through the drain tube. The accuracy of the mass flow meter is ±0.1% for liquid and ±0.35% for gas. In order to measure the flow rate generated from the valve, a differential pressure must exist, and an orifice was machined to generate the same differential pressure as the valve [10].

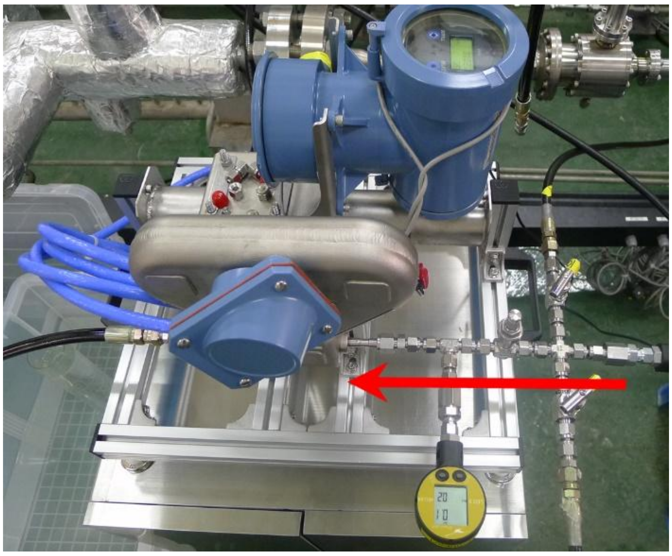

Figure 4: Coriolis mass flow meter

The volumetric flow rate was measured using a mass cylinder for oxygen and helium at room temperature, at the same time, the exhausted gas was passed through a mass flow meter to compare the volumetric flow rate and mass flow rate under room temperature. The process is performed using a mass cylinder and a stopwatch, similar to the mouthpiece method used in the factory test stage, as shown in Figure 5. For other pressure measurement sensors, a digital pressure gauge was used to enable visual confirmation on site, and the accuracy of the pressure sensor is ±0.1% .

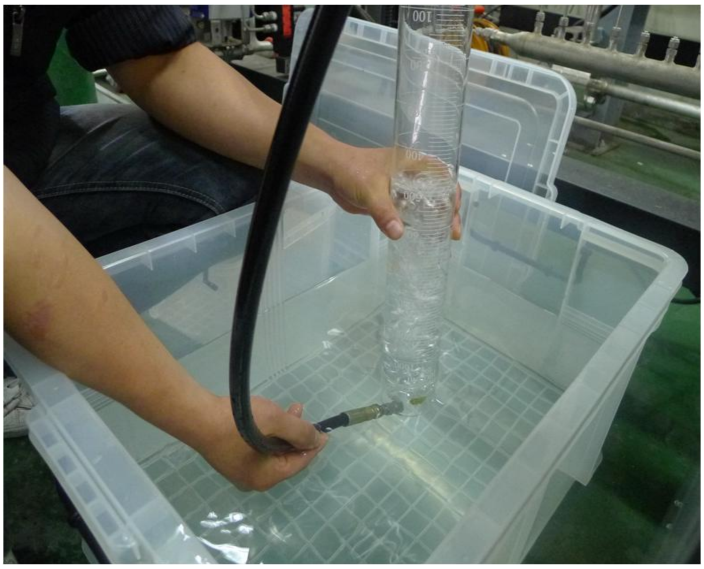

Figure 5: Volumetric flow measurement using mouthpiece method

The leakage of the cryogenic valve in Figure 1 is mostly caused by damage to the sealing part. The amount of leakage can be simulated through the diameter of the orifice. If the standard flow rate can be measured according to the orifice diameter and the type of gas, the leakage of the cryogenic valve can be measured simply and at low cost.

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The devices in Figure 3 and Figure 4 were prepared, and various orifices were configured to perform flow experiments. The upstream pressure of the orifice was maintained at approximately 1 MPa to ensure choking conditions, and there was no differential pressure up to the flow meter. The flow rate experiments were performed on room temperature helium and oxygen while maintaining the upstream pressure and replacing the orifice.

4. Test results

The Figure 6 compares the results of measurements using the mass flow meter(Figure 4) and the mouthpiece method(Figure 5) to find the relationship between helium and oxygen at room temperature. The results in Figure 6 show the volume flow rate and the mass flow rate relationships of oxygen and helium.

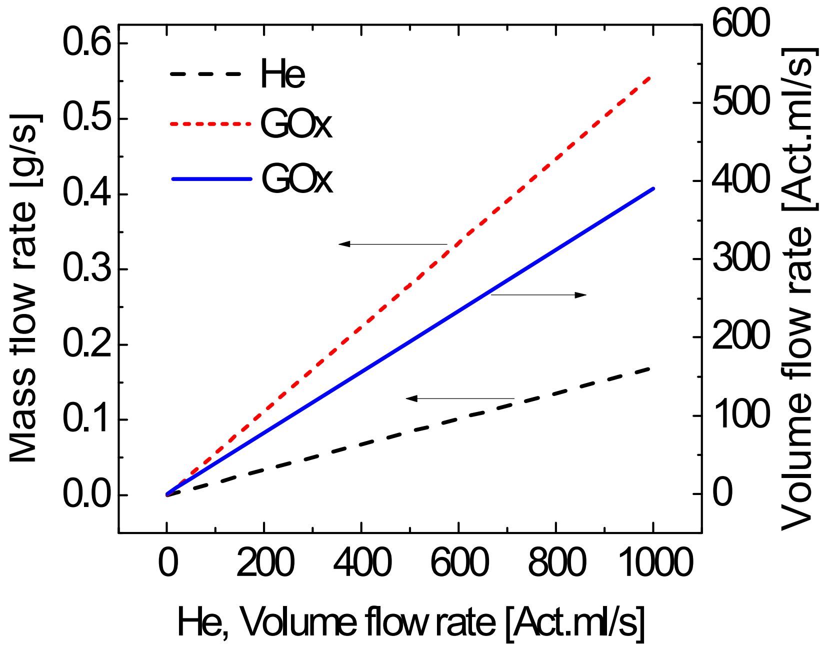

Figure 6: Comparison between volume flow rate and mass flow rate

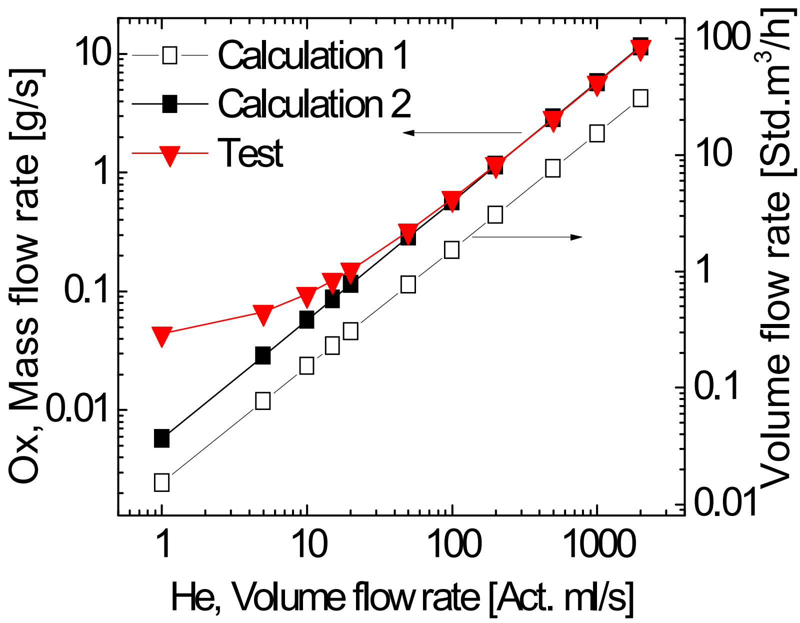

Figure 7: Comparison between experiments and calculational results

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Figure 7 shows the experimental results of oxygen and helium when the temperature after section of the orifice in Figure 2 is approximately 173 K. The x-axis of Figure 7 is helium at a temperature of 173 K, and the y-axis on the left is the mass flow rate for oxygen under the same temperature condition. The y-axis on the right is the standard flow rate before the gas constant is determined. The mass flow rates of helium and oxygen can be obtained using equation (3) and the standard flow rate. The relationships obtained through the experiment can be simply expressed as equation (6) and equation (7).
The volumetric flow rate of helium at room temperature, x [mℓ/s], and the mass flow rate of oxygen at room temperature, y [g/s], have the relationship as in equation (6). This is indicated in calculation 2 of Figure 7.

$$y = 0.000489116\,x + 0.01032 \tag{6}$$

Using equation (3) and equation (5), the orifice diameter for the volume flow rate of helium is calculated, and then the mass flow rate for oxygen at room temperature is calculated using the calculated diameter, and the result is consistent with equation (6). The empirical formulas for the volume flow rate x[mℓ/s] of helium at room temperature and the volume flow rate y[mℓ/s] of oxygen at room temperature are as in equation (7), and are calculation 1 in Figure 7.

$$y = 3.9\,x \tag{7}$$

From the comparison of the calculation and the experiment in Figure 7, it can be seen that an error occurs in 100 mℓ/s or less for helium. This is because the temperature of helium at the time of the experiment was 173 K, and the experimental mass flow value exceeded the measurement flow rate range under the corresponding temperature conditions, which is thought to have caused the error.

5. Conclusion

In the leakage measurement method of the valve, if the test fluid is liquid oxygen and the measurement requirement is mass flow rate, the test fluid cost is high, it takes a lot of time, and the measurement method is difficult. To overcome these problems, we performed a similarity experiment between oxygen and helium, and established a relationship based on the experimental results. Using the similarity equation, the mass flow rate can be converted into the volume flow rate accurately and easily at the same time. The similarity relationship between gaseous helium and liquid oxygen can be summarized as follows.

1. The mass flow rate[g/s] of gas oxygen at room temperature is 0.000489 times the volume flow rate[A.mℓ/s] of gas helium.
2. The volume flow rate[A.mℓ/s] of gas oxygen at room temperature is 3.9 times the volume flow rate[A.mℓ/s] of gas helium .
3. The mass flow rate[g/s] for the leakage of liquid oxygen is 174 times the leakage volume flow rate[A.mℓ/s] of gas helium.
4. We plan to quantify the flow rate and leakage rate relationship of various gases using the established correlation between standard flow rate and mass flow rate.

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