A Leak Detection System for Valves Cooled to 20 K while Cooled with a GM Cryocooler

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Abstract. Cryogenic valves are widely used in cryogenic systems such as aerospace propulsion systems and various cryostats. Under cryogenic temperatures, thermal shrinkage and sealing material hardening may dramatically enlarge the sealing gap of the valves, which leads to a serious leakage. Therefore, a detection system for cryogenic valves is badly needed. In this paper, a cryogenic leak detection system is established, which has the capability of detecting internal and external leakage of the valves at temperatures around 20 K. Compared with the traditional cryogenic leak detection system, this system, getting rid of threats from cryogenic liquid, successfully enhances the overall safety and is able to test five valves simultaneously to improve efficiency. This system optimizes the heat exchanger structure and shortens the cooling time.

1. Introduction
Cryogenic valves are widely used in many fields such as aerospace propulsion systems and various cryostats [1-3]. Under cryogenic temperatures, thermal shrinkage and sealing material hardening may dramatically enlarge the sealing gap of the valves, which leads to a serious leakage. This leakage includes internal leakage and external leakage. Internal leakage is leakage through the closure member when the valve is closed while external leakage is leakage from the valve to the vacuum environment, which leads to loss of fluid and fault of the cryogenic system. In order to get reliable testing information on sealing performance of the cryogenic valves, the leakage test must be performed under cryogenic conditions [4].

However, leak detection systems designed for cryogenic valves are mostly using the cryogenic liquid bath method [5-6]. Temperatures are determined by cryogenic liquid and hard to regulate in these systems. Meanwhile, boiling cryogenic liquid will visually mask external leakage, making it difficult to discover seal integrity. In addition, some cryogenic liquid is dangerous such as liquid hydrogen, which would cause undue safety hazards for the personnel.

To solve this problem, a cryogenic leak detection system cooled by a GM cryocooler is developed, which has the capability of detecting internal and external leakage of the valves at temperatures around 20 K. Unlike traditional cryogenic leak detection system, this system, getting rid of threats from cryogenic liquid, successfully enhances the overall safety and is able to test five valves simultaneously to improve efficiency. This system optimizes the heat exchanger structure and shortens the cooling time.
simultaneously to improve efficiency. The details of the design of this system are described in this paper.

2. Experimental Principle

There are various leak detection methods for normal temperature applications, including water bubble test, mass flow detection, pressure change method and more sensitive detection methods such as halogen leak detection, acoustical leak detection, radioisotope method, and the helium mass spectrometer. Not all these methods can be applied to cryogenic leak testing. Here we use helium mass spectrometer as a detector because it has a sensitive response, high precision, and is not easily disturbed by other gas. According to the direction of helium gas in the detection process, helium mass spectrometry leak detection can be divided into positive pressure leak detection (helium gas flows out of the inspected container), which is applied in this system, and vacuum leak detection (helium gas flows into the inspected container). As shown in Figure 1, the test gas leaking through the gaps of the tested sample into the vacuum chamber is detected by the helium mass spectrometer connected to the sample chamber. The detection accuracy depends on the background levels of helium gas.

3. System Description

The experimental system is composed of a test cryostat with a GM cryocooler, vacuum pumping station, gas pipe network, pressure and temperature measuring unit and leak detector. Figure 2 shows the schematic diagram and structure of this system.

Figure 1. Configuration of positive pressure leak detection: (1) helium mass spectrometer; (2) tested sample; (3) vacuum chamber; (4) helium gas cylinder.
3.1. Test cryostat

Figure 3 shows the configuration of the test cryostat. A vacuum chamber (860 mm diameters and 437mm in height) provides a large cylindrical sample space and a vacuum environment to avoid heat convection and conduction. We use a single-stage Gifford-McMahon cryocooler (RDK-500B, Sumitomo Heavy Industries Company Limited, Japan) with cooling power around 40 W at 20 K as the cold source in this conduction-cooled system. Compared with multi-stage GM cryocooler, it can make the structure of the cryostat simple and offer sufficient cooling power. The top flange of the vacuum chamber has two KF type flanges providing the connection to vacuum pump station and helium mass spectrometer. There are three 31-pin electrical sockets on the top flange, providing four-wire measurements for temperature sensors and wire to control testing valves, and electric heater turning on or off. A gas pipe flange is set to provide gas pipes access into the cryostat. Both the vacuum jacket and flange are made of stainless steel.

3.2. Valve cooling plate unit and T-shaped copper plate

The cooling objects include testing valve and helium gas in pipes for leak detection. As shown in Figure 3 and Figure 4, because the testing valve is in a vacuum, valve cooling takes place through conduction by a valve cooling plate unit, which could be designed in different styles according to the tested valves with different shapes and sizes. The thickness of the valve cooling plate unit, which includes 6 mm thickness bottom copper plate, 2 mm thickness rectangular upper copper plate couple...
with a thermal radiation shield and L-shape valve clamping, had been optimized. The reason is that as the cooling plate thickens, the thermal mass increases and the precooling time extend, on the contrary, as it gets thinner, temperature uniformity is getting worse. The valve cooling plate unit is assembled with testing valves by the L-shape valve clamping, which is used to fix and thermal anchor to the testing valves via screw for a convenient installation, and mounted inside the vacuum chamber by anchored to the cold head of the cryocooler and two screw rods and up to 5 valves could be placed on it. A cuboid thermal radiation shield, thermally contacted with the valve cooling plate unit, is covered with 50 layers of multi-layer insulation (MLI) to serve as both a radiative and conductive intercept. And a hold was set on the top of thermal radiation shield to improve detection sensitivity. At the same time, a T-shaped copper plate with 6mm thickness is thermally anchored to the cold head of the cryocooler for precooling helium gas. Indium film and high-conductivity grease are applied to strengthen thermal contact between contacting surfaces. Consequently, the valve cooling plate unit, the T-shaped copper plate and the thermal radiation shield, which are both made of copper due to the high conductivity, would maintain at around 20 K in the union after the precooling process. An electric heater with a heating power of 180 W is attached to the valve cooling plate unit for rapid rewarming up to room temperature after a completed test.

![Figure 4. Construction details(a) and photograph(b) inside test cryostat.](image)

3.3. Gas pipe network
Gas pipe network includes gas inlet pipes and gas outlet pipes, shown in Figure 2 and Figure 4. The gas inlet pipe from high-purity (99.999%) helium gas cylinder with relief valve (symbolized RV1), which can feed helium to the inlet of the testing valve to set the pressure, branches into five pipes to enter the test cryostat through gas pipe flange. It then passes through the T-shaped copper plate and connected with the inlet of the testing valves by spherical joint, providing a direct path for helium gas to the testing valves. To compact the structure, the pipes are bent into eight parallel channels and soldered with the T-shaped copper plate with grooves for making as a heat-exchanging coil to increase the thermal contact. There are five inlets and five outlets of T-shaped copper plate, including two pipes entrance and exits on each side of the long side, one entrance and exit on the short side. Another five
gas outlet pipes from the outlet of the testing valves exit the test cryostat via gas pipe flange and then merge into one pipe and connect to vacuum pumping station and leak detector. The diameter of the pipes outside the test cryostat is 1/4 inches while inside the test cryostat is 3 mm. A bypass pipe is set to connect with a nitrogen cylinder and a relief valve (RV2) for flushing pipes. Globe valves (V1, V2, …, V18) and safety valves are installed on each individual gas pipe to ensure safe and preventing any overpressure. The inlet and outlet gas pipe are coupled with one-way valves (OV1, OV2) for exhausting gas. All the gas pipes are made of stainless steel as this material can withstand high-pressure, and silver brazing method is used for pipes joint to minimize leakage from pipes to the test cryostat.

3.4. Vacuum pumping station and leak detector

The vacuum pumping station is used for evacuating the vacuum chamber and gas pipes. It includes a fore pump to initially pump the chamber to 10⁻¹ Pa. And then a turbomolecular pump (TMP) bring the chamber below 10⁻⁴ Pa. Vacuum gauges composing of one thermocouple tube and hot filament ionization tube is used for monitoring the vacuum. A Helium mass spectrometers leak detector (Phoenix L300, Oerlikon Leybold Vacuum Company Limited, Germany) with a sensitivity of 5×10⁻¹² Pa·m³/s is applied to leak detection.

3.5. Pressure and temperature measurement systems

As the pressure has an influence on leakage, pressure sensors, installed on each individual gas pipe, are employed to monitor the pressure during the test. To measure the temperatures of the testing valves, platinum resistance temperature detectors (RTDs) which were checked for proper calibration to 13 K are attached to the surface of the testing valves and the upper copper plate, and the lead wires were thermally sunk to the thermal anchor. All temperature values are acquired by four-wire platinum RTDs with the accuracy of ±0.5 K and recorded by a Keithley 2700 digital multimeter connected with a computer using an RS232 serial cable.

4. Experimental Procedure

4.1. Room temperature test

The installing of the cryogenic leak detection system is done, shown in Figure 5. One cryogenic electromagnetic valve was tested. After ensured that no leaks are found in the pipes and vacuum chamber, the gas pipe network and the vacuum chamber were evacuated. The inlet of the valve was then pressurized with 0.1–2.0 MPa helium gas by opening V1, V2, V11, V17 and RV1. An unknown internal leakage from the outlet of the testing valve, going through V2, was detected by the helium mass spectrometers leak detector, and measurements of the leakage rate were made at an interval of 0.1 MPa. After that, we detected the external leakage by closing V2 and opening V15, which required opening the testing valve. The equivalent leakage rate measurements at 0.1 MPa intervals were used. The V13 and V14 were opened for exhausting after room temperature test.

Figure 5. Photo of the experimental setup.
4.2. Cryogenic temperature test
At cryogenic conditions, the purer the helium carrier gas, the higher the reliability the system has. Prior to the actual test, the cryogenic leak detection system was flushed (pumped vacuum and filled with pure helium) a number of times to minimize the presence of other gases. This is especially necessary when cooling down the valve to 20 K since these gases might freeze, forming solid particles which might get trapped in the valve. After the vacuum chamber and the gas pipe network was evacuated ($\leq 10^{-4}$ Pa), GM cryocooler is worked to cool down the testing valves to operating temperature (~20K). At this time, the operation procedure of internal and external leakage detection was repeated at cryogenic temperature test.

After the completion of the test, GM cryocooler was turned off and the electric heater switched on for a quick return to room temperature. To avoid the overpressure of the pipes, the over-pressure relief valves were set to open if the pressure rises above the prescribed control pressure.

5. Results and Discussion
The leakage rate of the cryogenic electromagnetic valve was carried out at both room temperature and 20 K. Figure 6 shows the temperature change in the cool-down period. We can see that it takes around 6 h to make the temperature of the testing valve cool down to 17.4 K. With high cooling power, the temperature drops quickly in the beginning. The cooling curve begins to smooth at the time of 2.5 h. At the cooling time of 6 h, the testing valve temperature drops to 17.4 K and the upper copper plate temperature drops to 14.8 K. The temperature difference between them is 2.6 K and the system achieves thermal equilibrium.

![Figure 6. Temperature change in the cool-down period.](image)

For the leakage test at room temperature and 20 K, the pressurized helium (0.1–2.0 MPa) against the external vacuum was applied to the testing valve. Typically, when the testing valve had a detectable leak, the leakage appeared as soon as the helium was introduced upstream of the valve. The measured internal and external leakage rate are plotted in Figure 7. As the pressure increased, internal leakage rate through the testing valve decreased from $6.9 \times 10^{-4}$ Pa·m$^3$/s to $5.0 \times 10^{-7}$ Pa·m$^3$/s at room temperature. It can also be noticed that the leakage rate was not proportional to pressure. As can be seen, the leakage rate curve declined to a low level and kept in a relatively stable region when the pressure exceeds 0.5 MPa. The sealing performance improved with the stress increased, which is thought to be a result of the particular structure of the high-pressure electromagnetic valve. However, the external rate curve rose from $2.5 \times 10^{-8}$ Pa·m$^3$/s up to $1.3 \times 10^{-6}$ Pa·m$^3$/s as the pressure goes up.
As a contrast, this valve exhibited a high leakage rate at 20 K. The internal leakage rate did not vary obviously as the pressure increased, keeping at $10^{-2}$ Pa·m$^3$/s (2.7×10$^{-2}$–4.7×10$^{-2}$ Pa·m$^3$/s). Likewise, the external leakage rose from 1.8×10$^{-3}$ Pa·m$^3$/s up to 8.6×10$^{-3}$ Pa·m$^3$/s with increasing pressure. The result indicated that the internal and external leakage rate at 20 K were several orders of magnitude larger than the leakage rate at room temperature under the same pressure conditions for this valve. Hence, the sealing performance might get worse at low temperature for the sealing material hardening and thermal shrinkage.

At the same time, we observed this testing valve was not flexible to open or close at cryogenic temperatures. Important to note is that the testing valve had been used for many times, which might cause mechanical wear or contamination on the valve. It is possible that the moving parts and sealing pairs of the valve have grazed. Another possible explanation is that nitrogen and other possible impurities such as hydrogen may have entered the valve and could possibly have augmented leakage rate at 20 K. Additional research is needed to refine the test method and test apparatus to eliminate the impurities that impact the test.

6. Conclusion
In this work, we have developed a leak detection system for cryogenic valves at 20 K with a GM cryocooler. From the test carried out on one kind of cryogenic electromagnetic valve, it is confirmed that the cryogenic facility shows reliable characteristics for evaluating the valves at 20 K with high pressure of 2 MPa. The results indicate that the testing valve shows a high leakage rate at 20 K. Compared with the cryogenic liquid systems, this system, getting rid of threats from cryogenic liquid, successfully enhances the overall safety and is able to test five valves simultaneously to improve efficiency. Additional research is needed to refine the test method and test apparatus and the system will be extended to higher pressure in the future.

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