Visualization study of a cryostat with a large diameter flow channel for flowing high-pressure cryogenic fluid

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Abstract. For abundant cryogenic experiments, systems, and so on, visualization is necessary to observe the cryogenic fluid. Therefore, the visualization methods of cryogenic fluid have been widely studied, such as shadowgraph technique, schlieren technique, and laser holographic interferometry technique. A cryostat for visualization study must have optical windows to meet the requirement of various image acquisition equipment. Due to the difference of shrinkage between transparent glass and device materials at low temperatures, especially at large diameter flow channels, it is difficult to meet the requirement of visualization. This paper studies a kind of cryogenic visualization device with an inner diameter of 200 mm, which can meet the visualization requirements of cryogenic fluid with the maximum working pressure at 0.7 MPa and the lowest temperature at 77 K. Liquid nitrogen was used to test the visualization of the device at low temperatures. The device was also subjected to vibration conditions to test the ability of the device to withstand harsh environments. The results show that the device has good sealing performance and can meet the visualization requirements well.

1. Introduction
Cryogenic fluid is widely used in cryogenic physical experiments, cryogenic systems and so on. Generally, the phase state of the cryogenic liquid will change in the experimental device because the boiling point of the cryogenic liquid is much lower than the room temperature. On the one hand, this will cause gas-liquid two-phase flow in the system. Different flow patterns formed by gas-liquid two-phase flow have different flow characteristics [1]. Therefore, it is necessary to study the flow patterns of the gas-liquid two-phase flow of cryogenic fluid. On the other hand, due to the different boiling points of different fluids, some solid impurities may be mixed into the cryogenic fluids in the process of using cryogenic fluids, which may affect the operation of the system.

Visualization is needed to observe the flow pattern of two-phase flow [2]. The flow of the fluid and the impurities in the fluid can be observed visually. The most basic method of visualization of cryogenic fluid is cryostat with optical windows [3]. The high light source is used to provide backlight, and high-speed cameras and the macro lens are used to capture and record images [4]. The typical structure of the cryostat is to set glass windows inside and outside the system for visualization. The innermost glass is in direct contact with the cryogenic fluid and thermally insulated by vacuum [3]. However, such a structure has some limitations, and it is necessary to pay special attention to the
radiation heat leakage through the outer visualization windows at ambient temperature. To solve the problem of heat leakage, Rousset et al. proposed a new visualization method[5]. By placing the image acquisition device inside the cryostat, the outermost visualization window was canceled, effectively reducing the radiation heat leakage from the ambient temperature.

In the study of visualization in a cryogenic environment, the connection between the glass flow channel and metal flow channel is always one of the key issues. Due to the different shrinkage of transparent glass and device materials at low temperatures, it is difficult to ensure the sealing of the cryogenic chamber of the cryostat. Therefore, in the visualization of cryogenic fluids, the diameter of the visual flow channel in the cryostat is relatively small. In the study of the stratified type flow transition in a horizontal pipe, the diameter of the flow channel Rui Zhou et al. selected is 20 mm [6]. Esposito, C. et al. chose the flow channel with a diameter of 15 mm to study the influence of thermal phenomena during cavitation through an orifice, and the pressure of the system is 0.7 MPa [7]. In the visualization study of the relationship between volume flow rate and pressure drop of the cryogenic valve, the diameter of the visualization section is 10 mm [8]. However, when the diameter of the flow channel increases, the shrinkage difference between glass and the device materials increases at low temperatures, which makes it more and more difficult to ensure the sealing.

This paper designs and tests cryogenic visualization device in which the inner diameter of the flow channel is 200 mm. The maximum working pressure of the cryostat can reach 0.7 MPa. The visualization effect of the device is tested with liquid nitrogen. And subject the device to vibration conditions to test the device’s ability to withstand harsh environments. The results show that the device has good sealing performance and can meet the visualization requirements well.

2. The description of the visualized cryostat

The visualized cryostat can be used to study the flow characteristics of cryogenic fluids in a flow channel. The device can work at the temperature from 77 K to the ambient temperature. Therefore, cryogenic fluids with temperatures higher than 77K, such as liquid nitrogen and liquid oxygen, can be used in the device.

![Figure 1. The external structure of the visualized cryostat.](image)

1. Upper flange; 2. Vacuum chamber; 3. Optical window; 4. Lower flange; 5. Vacuum valve.
Figure 2 shows the internal structure of the visualized cryostat. The cryostat consists of an internal flow channel and an outer vacuum hood. Figure 2 shows the internal structure of the visualized cryostat. The top and bottom of the internal flow channel are made of stainless steel with a quartz glass tube in the middle. Three indium wire side seals are used to connect the stainless-steel tube to the quartz glass tube. For avoiding direct contact between glass and metal leading to glass breakage, Teflon gaskets between the both. The quartz glass tube has an inner diameter of 200 mm, a wall thickness of 15 mm, and a length of 340 mm. The inner diameter of the stainless-steel tube section is the same as the inner diameter of the glass tube section. The upper stainless-steel tube is connected to a section of bellows to compensate for the length of the core tube shrinkage at low temperatures. The outer vacuum cover can be divided into three sections for easy installation. Docking flanges are set at the upper and lower ends of the entire device for connection with other devices, and the docking type can be determined according to the specific experimental system. The optical windows are sealed with rubber O-rings, while a Teflon gasket is added to avoid glass breakage.

3. The experiments and the result of the visualized cryostat

Different study topics have different requirements for visualization and there are different parameter requirements for applying visualization devices. Therefore, in testing this visualized cryostat, typical operating conditions were chosen to meet as many usage requirements as possible.

3.1. The description of the experiment system

The experiment of the visualized cryostat includes both ambient and cryogenic conditions. An experiment system was designed to make the experiment process convenient and efficient, using the experiment system to complete all experiments simultaneously. Figure 3 shows the flow diagram of the experiment system. For ambient experiments, line 1 is used to supply ambient nitrogen and to pressurize the device, and line 2 is used to exhaust. For the cryogenic experiments, the liquid nitrogen is supplied by line 3, the line 2 is used for exhaust and the pressure in the cryostat can be adjusted by controlling the exhaust volume, and the line 4 is used for discharging the remaining liquid nitrogen.
3.2. The experiments of the visualized cryostat

Before experimenting, a basic test of the cryostat's hermeticity is required. The gas leak inspection of the devise's flow channel and vacuum chamber are tested separately using a helium mass spectrometer. A leak inspection was performed on the flow channel and the leakage rate was $5.4 \times 10^{-9}$ torr·L/s. A leak inspection was performed on the vacuum chamber and the leakage rate was $4.5 \times 10^{-9}$ torr·L/s. Figure 4 shows the leak inspection system.

![Figure 4. The leak inspection system.](image)

Table 1 shows the helium leakage rate of the device at each pressure. The experimental results show that the device has good sealing under the working pressure of 0.1-0.7 MPa at ambient temperature. The surface of the visualized flow channel was observed by the glass observation check, and the glass tube did not have any obvious changes. It shows that the device has good sealing and pressure resistance.

![Figure 3. The flow diagram of the experiment system.](image)

1. Cylinder; 2. Pressure gauge; 3. Pressure reducing valve; 4. General ball valve; 5. Safety valve; 6. The visualized cryostat; 7. Visualized fluid channel; 8. Camera; 9. The light source; 10. Cryogenic ball valve.
Table 1. The helium leakage rate of the device at each pressure.

| Pressure of the flow channel (MPa) | 0.1   | 0.2   | 0.3   | 0.4   | 0.5   | 0.6   | 0.65  | 0.7   |
|----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| The helium leakage rate (x10^-8 torr·L/s) | <1.6 | <1.3 | <1.2 | <1.1 | <1.0 | <1.0 | <0.91 | <0.79 |

3.2.2. Low temperature experiment and results. The device was subjected to experiments at low temperature using liquid nitrogen. During the experiment, liquid nitrogen is charged to the device by line 3. Figure 5 shows the visualization of the flow channel by the glass window during the pressurization of the device after filling with liquid nitrogen. During the process of liquid nitrogen filling, the bubbles in the flow channel were visible, and the bubbles decreased with the increasing pressure. After increasing the pressure to 0.7 MPa, the flow channel was stabilized at the liquid nitrogen temperature after 2 hours of stabilization. After reaching the stabilization condition, the observation window was visible, indicating that the device has good visualization at liquid nitrogen temperature.

The devices are tested for repeated use performance in cryogenic conditions. After the device has undergone liquid nitrogen cooling, the residual liquid nitrogen in the device is drained to allow the device to naturally return to ambient temperature, and then it is filled with liquid nitrogen again to cool it down. After stabilization and standing for 2 hours at atmospheric pressure, the glass surface of the observation window fogged up, and the fog had to be wiped clean before observation. The result shows that when the indium wire is deformed after the first cooling, the deformed indium wire cannot meet the sealing requirement of successive cool-downs. The liquid nitrogen in the flow channel partially leaked into the vacuum chamber, which causes the glass surface temperature to cool and condense on its surface. After increasing the pressure to 0.7 MPa, there is still fog on the glass window opening. Figure 6 shows the fogging of the glass viewing window. The test results show that the device can still be met in the second low temperature cycle use, but the effect is not as good as the first use.

3.2.3. Experiment and results after vibration conditions. The sealing performance of the device after vibrating conditions is checked in accordance with the dynamic conditions that the device may encounter in the actual application. Vibration is applied to the device at ambient temperature. Figure 7 shows the time domain and frequency domain diagram of the vibration applied to the device. The duration of the vibration is 500 seconds and the vibration strength is up to 4G. The vibration frequency is concentrated in the range of 20-30 Hz. After the device was subjected to vibration testing, a helium mass spectrometry leak detection was performed on the flow channel of the device, and the test results are shown in Table 2. The experimental results show that the device has good sealing and pressure resistance even after strong vibration.
Figure 7. The time domain and frequency domain diagram of the vibration.

Table 2. The helium leakage rate of the device under vibration conditions.

| Pressure of the flow channel (MPa) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.65 | 0.7 |
|------------------------------------|-----|-----|-----|-----|-----|-----|------|-----|
| The helium leakage rate (x10^{-8} torr·L/s) | <4.8 | <3.8 | <3.2 | <2.5 | <2.0 | <1.7 | <1.2 | <0.61 |

4. Conclusion
The visualized cryostat can meet the visualization demands of cryogenic fluids with a flow channel diameter of 200 mm and a pressure of 0.7 MPa, down to a temperature of 77 K for liquid nitrogen, and can withstand harsh environments such as strong vibration. The device has good sealing performance both before and after vibration, with helium leakage rates not exceeding 10^{-8} torr·L/s orders of magnitude. This greatly widens our capability in conducting flow visualization experiment under high pressures and in a large-diameter channel.

5. References
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