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Design and thermal study of a test device for breakdown characteristics of insulation materials in low temperature vacuum environment

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Abstract. With the application and development of low-temperature superconductivity technology, the research on electrical properties of insulating materials under different low-temperature conditions has attracted more and more attention. According to the breakdown characteristics of materials in low-temperature environments, a test device for the discharge breakdown characteristics of insulating materials in vacuum low-temperature environments is designed. This device can meet test of the gaseous and solid insulating materials in different low temperature and vacuum conditions. Compared with the traditional low temperature electrical test device, it has the advantages of convenient replacement, short test cycle and multi-functional testing. The finite element simulation software is used to simulate the performance of the cooling device of gas and solid insulating materials, and the effects of liquid helium cooling and refrigerator cooling on the temperature distribution of the device are analyzed and compared. Finally, the flow field analysis of the cooling system defines the internal flow characteristics of liquid helium under liquid helium cooling, which provides theoretical guidance for the design of the low-temperature breakdown test device.

Keywords: low temperature; breakdown characteristics; insulation materials; cooling method.

1. Introduction

With the development of low-temperature superconductivity technology, low-temperature insulating media are more widely used. For different low-temperature conditions and vacuum pressures, the situation of temperature influence on the electrical properties of insulating materials is getting more and more attention. The electrical properties of low-temperature insulating media have become an important factor affecting the performance and reliability of low-temperature superconducting devices[1]. Therefore, it is far-reaching significance to have a discharge device that can efficiently perform dielectric breakdown tests in a wide range of low-temperature and high-vacuum environments for the study of low-temperature insulating materials.

In recent years, scientific researchers have conducted a lot of studies and developed a series of low-temperature dielectric electrical characteristic test devices. G. A. Farrall et al.[2] concluded that the breakdown voltage of vacuum insulation in a uniform electric field at low temperatures is related to the electrode spacing and electrode condition. The breakdown characteristics of vacuum insulation at low temperature and room temperature were compared by Hao Fengnian et al.[3] The spherical electrode attached below the cold bath was cooled by filling liquid nitrogen, and the results showed that the breakdown strength of vacuum insulation was significantly higher at low temperatures for high-voltage electrodes. J.Gerhold[4] found that the low temperature between 4.2-300K had different effects on electrical properties of solid insulating materials such as dielectric constant, dielectric loss and breakdown voltage. E. Husain et al.[5] designed a low-temperature experimental setup with test electrodes immersed in liquid nitrogen to measure and evaluate the AC breakdown voltage of insulating materials under different electrode configurations. The experimental results showed that the breakdown voltage was a function of the electrode geometry and gap length. I. Sauers et al.[6] designed and fabricated a cryogenic vacuum test device using a copper coil connected to a ground electrode and a liquid nitrogen pipe to achieve cooling, so as to study the effect of temperature on the breakdown strength of vacuum insulation and the flashover characteristics along the surface of glass fiber reinforced plastics. However, the controllable temperature range of immersion cooling device is small, and immersion may affect the performance of the insulation material. While the test device by cooling the electrode may lead to a difference between the insulation medium temperature and the electrode temperature. In this paper, a self-designed low-temperature insulation material breakdown characteristics test device is studied. The cooling process and temperature field distribution of the device under different cooling methods are simulated and compared.

2. Design of the test device

Insulation medium at low temperature plays a very critical role in the application of superconductivity technology. Insulation materials of electrical components work under high vacuum and deep low temperature for a long time, which may affect their electrical properties and lead to the generation of insulation medium discharge breakdown phenomenon. As a result, there is a need for a discharge device that can test the breakdown characteristics of insulation media in a low-temperature vacuum environment.

This paper presents a device for testing the discharge breakdown characteristics of insulating media in a low-temperature vacuum environment to meet the test experiment of discharge breakdown characteristics of solid insulating media under different low temperature, vacuum pressure and gas atmosphere conditions, and this device can also realize the test of insulating gas discharge breakdown performance at low temperature after replacing the test sample with a specific insulating gas and replacing the corresponding electrode. Figure 1 shows the schematic diagram of the structure of this device. In ultra-low temperature testing devices, refrigerators are commonly used, and their advantages such as reliability and stability are favored by many experts, so the device also chooses the refrigerator as the cold source to work[7-8].

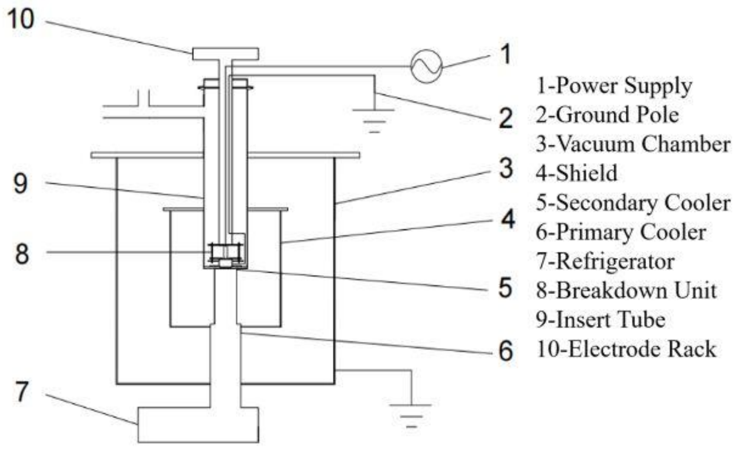


Figure 1. Device schematic diagram.

The vacuum cavity in this device provides a vacuum adiabatic environment for the test, and the refrigerator is used to provide cooling. The primary cold head of refrigerator is connected to the shield, which keeps the shield at a low temperature and plays a role in reducing the radiation heat leakage. The secondary cold head of refrigerator is connected to the copper bottom of the high-voltage electrode holder insertion tube, and the cold capacity is transferred to the test sample through the copper bottom, the insulated cold conductor and the lower electrode in turn, so that the replacement of the test sample does not destroy the vacuum adiabatic chamber vacuum environment. The copper bottom end is equipped with a heater and sensor to achieve the role of temperature control. The insulated cooler is used to transfer the cold and prevent the discharge current from flowing through other devices. The lower end of the high-voltage electrode holder is detachably connected to the high-voltage electrode testing device, which can be easily removed for quick sample replacement. The upper electrode also has a detachable threaded connection, which is used to replace the upper electrode with a different shape for testing. Figure 2 shows the three-dimensional model of the breakdown unit.

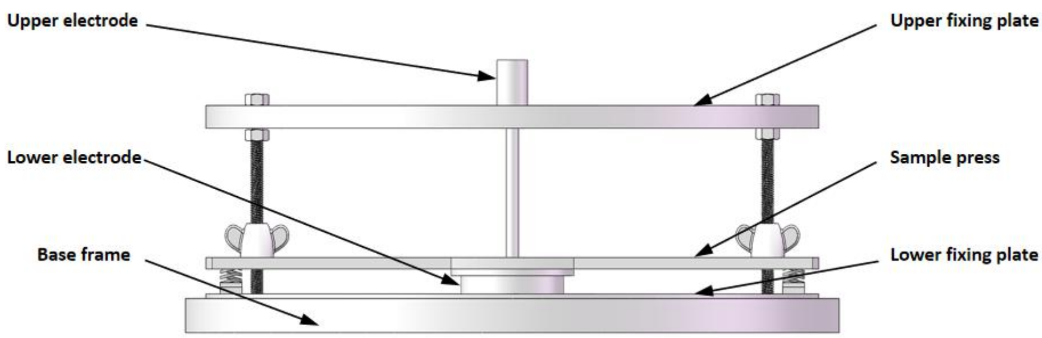


Figure 2. 3D model drawing of breakdown unit.

The upper end of the high voltage electrode holder insertion tube contains side pipe connections for connecting the vacuum pump unit, vacuum gauge and gas source bottle to obtain and monitor the vacuum environment for the high voltage electrode holder insertion tube as well as to introduce specific gases. The gas source bottle interface can be used to access different gas sources to achieve the discharge breakdown characteristics of low temperature solid insulation media under different gas atmospheres for testing and research. After the test sample is replaced with a specific insulating gas, the insulating gas discharge performance test at low temperature can be realized by changing the shape and length of the electrode. Therefore, the device designed in this paper has the advantages of convenient sample replacement, short testing cycle, high testing efficiency and multi-functional testing.

3. Simulation Analysis

3.1 Cooling model and simulation parameter settings

Two forms of cooling using liquid helium or refrigerators as the cooling source are commonly accepted in the design of ultra-low temperature devices. In this section, numerical calculations and simulations of the heat transfer between the two cooling methods are compared by finite element simulation software for this device. According to the literature [9-10], the relevant physical parameters of liquid helium can be obtained. Figure 3 shows the 3D model and its dimensions for the simulation calculation.

The refrigerator cooling model uses the physical field of "solid and fluid heat transfer" for the control solution. The boundary conditions are set as follows: the bottom contact surface temperature is set to 4.2 K, the boundary cold source is set to 1.5 W, and the top surface heat source is naturally connected with the air. The physical process of the liquid helium cooling involves fluid flow, fluid heat transfer, and solid heat transfer. "Solid and fluid heat transfer", "turbulent flow (k-ε)" and "non-isothermal heat transfer multi-physics field" of the multi-physics field coupling module are used for the solution. The boundary conditions are set as follows: the left pipe port is the inlet, and the inlet boundary condition is the mass flow rate; the right pipe port is the outlet, and the boundary condition is the average pressure of fully developed flow, and the reference temperature is 293.15K. One of the difficulties of turbulence calculation is that the flow of fluid near the wall is complicated, so the mesh division at the boundary layer of the wall should be refined to improve the computational convergence and correctness. The inlet mass flow rate is set to 20g/s, 40g/s, 60g/s and 100g/s, and the simulation is compared with a 1.5W refrigerator for comparative analysis.

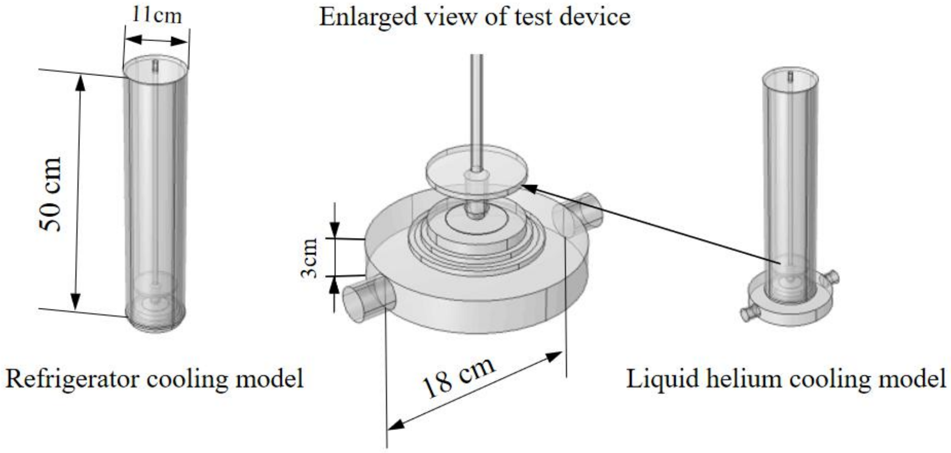


Figure 3: 3D simulation model and its dimensions.

3.2 Analysis of simulation results

3.2.1 Comparison of refrigerator cooling and cooling process under different mass flow.

Both the refrigerator and the liquid helium start to cool down from the device at 293.15 K. Since the sample is closer to the cold source end, the device cools down from the bottom to the top end. Therefore, the cooling rate at the sample end is very fast at the beginning, and the rate of temperature decrease becomes smaller as the cooling time increases. Figure 4 shows the temperature distribution at different cooling moments for a mass flow rate of 20 g/s.

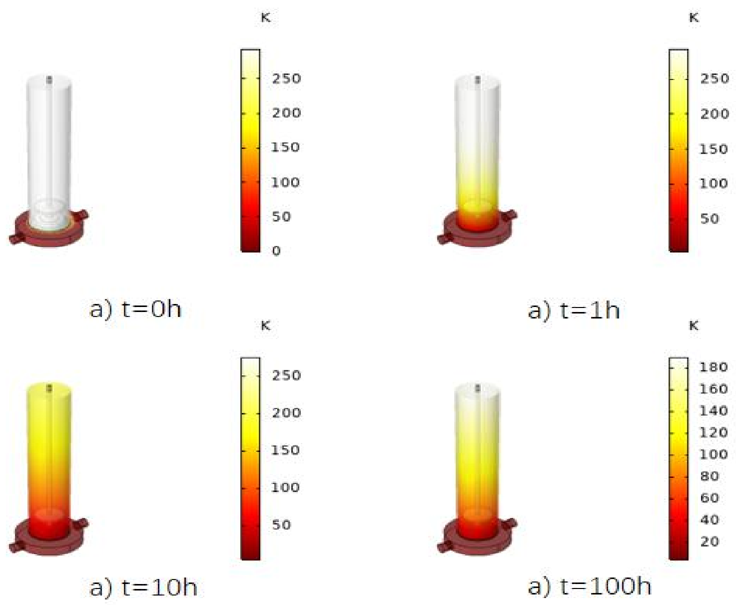
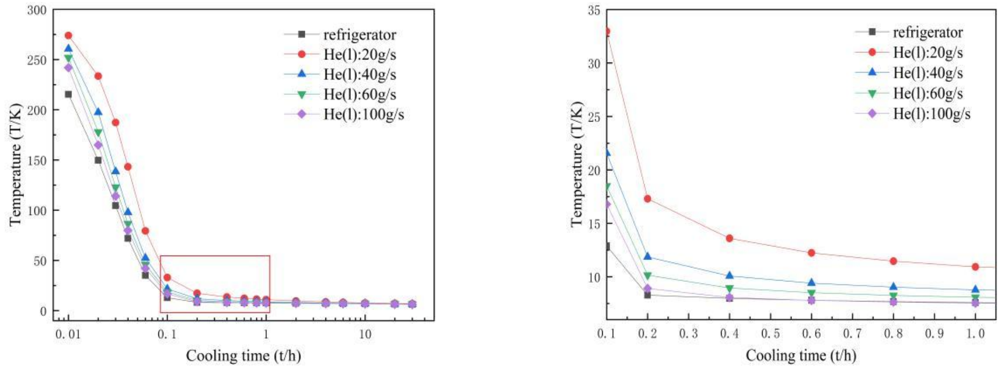


Figure 4: Temperature distribution at different cooling moments.

Figure a) in Figure 5 shows the data curves for the cooling of the refrigerator versus the cooling of the liquid helium at different mass flows. Within one hour, the refrigerator cooling is lower than 20 g/s to 100 g/s at each time period, which indicates that the cooling rate of the refrigerator is highest at the beginning of the cooling phase. Figure b) is a partial enlargement of Figure a). However, after about one hour of cooling, the cooling temperature of liquid helium with a mass flow of 100 g/s starts to be lower than the cooling temperature of the refrigerator. And the higher the mass flow, the faster the cooling rate.

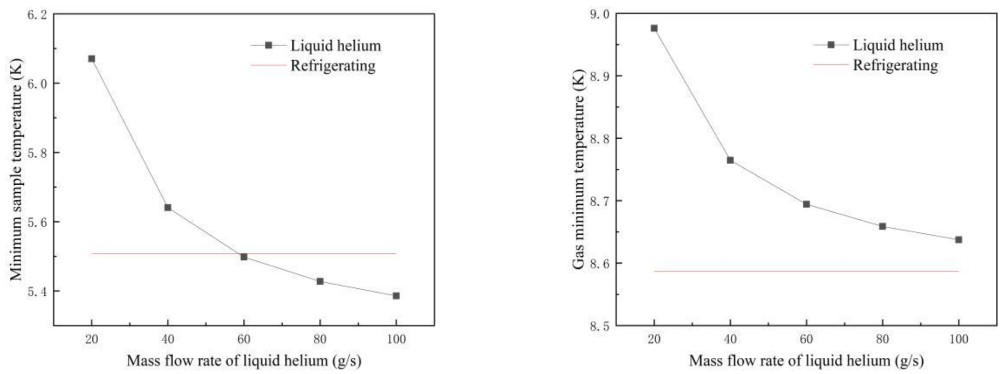


a) b)

Figure 5: a) The average temperature of the sample varies over time.
b) Local amplification diagram in Figure a).

3.2.2 Comparison of the effect of two cooling forms when cooling is stable.

Figure a) in Figure 6 shows the simulation data of the cooling temperature of the solid breakdown sample at steady state cooling, where the lowest temperature that the refrigerator can lower is similar to the temperature of 60 g/s liquid helium when reaching steady state. It is only when the mass flow exceeds 60 g/s that the temperature of the liquid helium cooling is lower than that of the refrigerator. Figure b) in Figure 6 shows the simulation data of the cooling temperature of the breakdown gas under steady-state cooling. In contrast, when cooling the breakdown gas, the final average temperature of the gas achievable by the refrigerator is lower than that achieved by liquid helium cooling at 20 g/s to 100 g/s. The final temperature that the solid sample to be tested can reach is lower than that of the gas to be tested, because the heat transfer of solids is better than that of gases. The higher the mass flow of liquid helium, the higher the amount of liquid helium consumed, the lower the final temperature and the shorter the cooling time, but the cooling efficiency decreases significantly as the final temperature is approached. Therefore, liquid helium cooling is not a suitable cooling method for this device, and a refrigerator cooling method is more efficient. The simulations show that this device can reach a minimum test temperature of about 5.5 K for solid breakdown samples and below 10 K for gases to be tested.



a) b)

Figure 6: a) Average temperature of the sample to be measured when the cooling is stable.
b) Average temperature of the gas to be measured when the cooling is stable.

3.2.3 Liquid helium tank flow field analysis.

Figure 7 shows the flow field distribution in the liquid helium tank for different mass flows. The liquid helium flows into the liquid helium tank through the inlet and flows out from the outlet. The volume of the liquid helium tank is much larger than that in the pipe, so the flow velocity in the liquid helium tank decreases greatly, and the farther away from the inlet and outlet of the pipe, the smaller the flow velocity is. Due to the circular shape of the liquid helium tank, there is a weak reflux in the liquid helium.

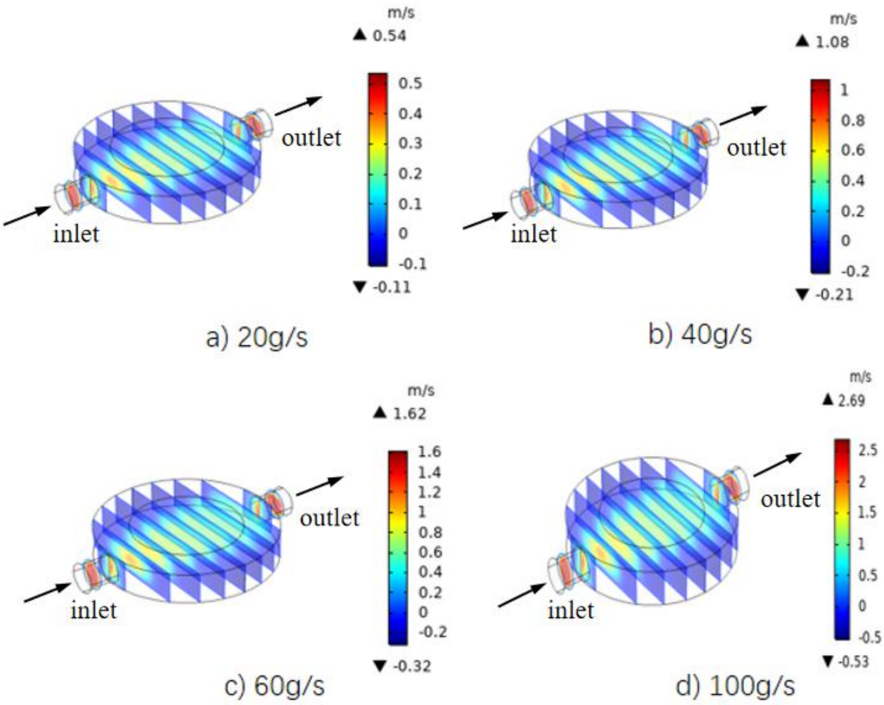


Figure 7: Flow field profiles of liquid helium tank at different mass flow rates.

As shown in Table 1, the average velocity in the liquid helium tank is more than ten times lower than that at the tube port, and the flow rate between the inlet and the outlet is larger, so it may lead to some of the liquid helium flowing out of the tank before complete heat exchange, which is an important reason for the very low cooling efficiency of liquid helium.

Table 1. Flow field data at different mass flow rates.

Inlet mass flow rate(g/s)	20	40	60	100
Inlet flow velocity(m/s)	0.73	1.47	2.2	3.67
Average flow velocity(m/s)	0.060455	0.12096	0.18146	0.30245

4. Conclusion

In this paper, a multi-functional test device that can effectively meet the breakdown characteristics of insulation materials in deep low-temperature vacuum environment is designed. The performance of the device is simulated by finite element simulation software, and the cooling effects under different refrigeration modes are compared. From the aspect of refrigeration efficiency, it is verified that the refrigerator is more suitable to be selected when designing this kind of similar devices. The reasons for the defects of liquid helium refrigeration are also preliminarily analyzed. The expected minimum temperature for the theoretical calculation of the device was obtained. This research method is also applicable and instructive for the design of similar cryogenic devices.

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Acknowledgments

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