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ORIGINAL RESEARCH

Experimental Study on Paschen Discharge in Helium for High Voltage Cryogenic Insulation Material

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Abstract According to the requirements of large superconducting components, all the solid superconducting insulation of current leads, magnets, cooling and measurement pipeline at high potential should withstand 80–300 K thermal cycles. If helium leak or pipe leak taken place, and insulation has been formed some flaws, Paschen discharge would be occur. The experimental program aimed at analyzing the low-temperature electro-physical performance of solid superconducting insulation, which was designed with different configuration such as thickness, material structure and so on. The dielectric performance of both pre-preg cryogenic insulation and the wet wrap cryogenic insulation were studied. Both of the dielectric strength of the two type insulation is in the range from 11 to 23 kV/mm at 80 K helium condition. Besides, both of the two type insulation samples of 3 and 5 mm thickness can withstand 30 kV under various helium pressures at 80 K.

Keywords Paschen · High voltage · Insulation · Superconducting

Introduction

Superconducting insulation materials in fusion magnet technology are required to withstand low temperature, high voltage and thermal cycles. Besides, the insulation material is especially required to good work in the event of fast discharge of a coil. Because the machine would be damaged if a Paschen discharge [1–3] is triggered by an insulation defect that is caused by faulty manufacturing.

Glass fiber reinforced plastics (GFRPs) consisting of boron-free glass fibers and organic matrix materials, especially epoxy resin based composite, have been widely used as insulating materials in cryogenic engineering fields because of their low cost, ease of processing, thermal and electrical properties [4, 5]. It can be found that glass fiber tape with epoxy resin and the polyimide film is chosen as the composite insulation materials for EAST, ITER Feeder and joint. Besides, similar insulation of leads and feeders was used in KSTAR, SST-1 and W-7X [6]. Nevertheless, most of the insulation used in above equipments was made by the wet wrap technology [7, 8] which indicates the mixed resin is smeared on the tapes to make all the fiber filaments permeated (wetted) by resin during winding. This insulation technology is an option which was suggested by ITER international organization. However, seven breakdowns occurred during the coil tests at operating voltage $\sim<3$ kV [6]. All of the breakdown accidents are initialed in the areas which are current leads, cooling and measurement pipeline at high potential. So far, one insulation area of ITER current lead mock up was severely damaged when the 80 K test has been done after 5 times thermal cycles, which results in Paschen discharge phenomenon [9].

Due to the liquid mixed resin that is difficult to be well-proportioned controlled, defects (such as bubbles, air vent) in the manufacturing process of the insulation can't be avoided completely by use of the wet wrap technology. Once the vacuum is damaged (it can't be completely ruled out in theory), the fissure will be filled with air or cooling helium under various gas pressure, and then the breakdown discharge maybe will take place. However, pre-preg tapes winding technology is an option to avoid using the liquid

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mixed resin during the whole insulation manufacturing process but it needs strict experimental verification. This method is considered to be less possible to generate defects (such as bubbles, air vent) compared with the wet wrap technology. However, the analysis of low-temperature electro-physical performance between these two types of insulation should be conducted by experiment.

For any gas, the breakdown voltage is a unique function of the gas pressure and the distance between surfaces with high differential voltage. It is the so-called Paschen law [10]. From the V-Pd curve we can find that each gas has a Paschen minimum point where the gas will breakdown at a very low voltage level, for example, at room temperature the breakdown voltage of helium is only 150 V at 3.3 Pa m (gas pressure multiplied by electrodes distance). Due to the low temperature and complex loading operational condition of the superconducting components, especially the superconducting busbar, feeder and coil, there are potential hazards of insulation layer generate micro cracks during long term operation. In comparison, the Paschen test at low gas pressure condition can be performed at a lower voltage to effectively measure the electro-physical performance of insulation. This is the reason why experimental study on Paschen discharge of insulation under low-temperature condition was done with superconducting insulation samples.

Materials and Test Samples

The main material of the pre-preg insulation sample is isovalta pre-preg tape (main component is voltaflexpreg 11E061) and its width is 25 mm and thickness is 0.45 mm. The voltaflexpreg 11E061 is a flexible three ply combination material consisting of glass cloth, polyimide-film-glass cloth and is made of both sides with epoxy. The thickness of polymide film in the voltaflexpreg 11E061 is 0.05 mm. Besides, voltaflexpreg 11E061 has high electrical and mechanical strength and shows good adhesive properties against metallic surface that was mentioned from the isovalta company. As shown in Fig. 1, the structure of pre-preg insulation sample was KK structure (K = dry isovalta pre-preg tape and one KK layer's thickness is $0.5 \times 2 = 1$ mm). Six KK layers of half overlapping pre-preg tapes are flatly wrapped on the surface of a stainless steel die, then the insulation layers were pressed by stainless steel die to control its thickness. Finally, the insulation with the die was heat up to 100 °C for 8 h. The pre-preg insulation samples are shown in (a), (b) and (c) of Fig. 1. The low temperature mechanical behavior of isovalta pre–pre insulation material have been tested (Standards followed for the mechanical tests is ASTM D3039/D3039 M-95a [11]), as shown in Table 1. For ITER's procurement arrangement [12], the tensile strength of insulation material

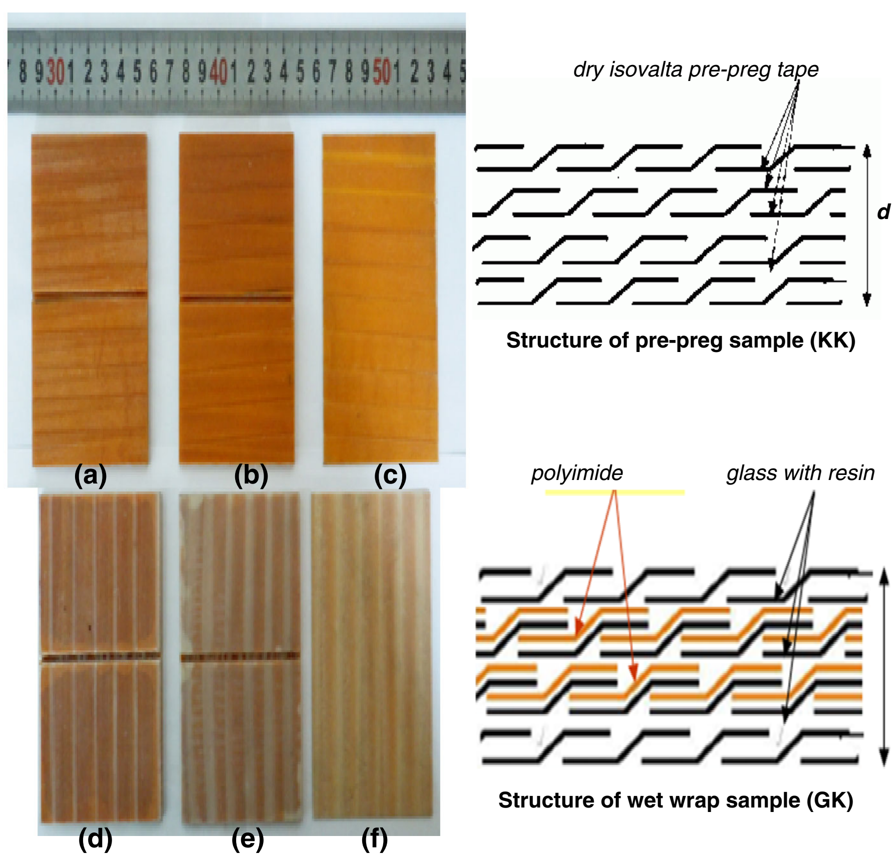

Fig. 1 The samples of two types of insulation

Table 1 Mechanics behavior of the two type insulation

Sample code	Tensile strength (MPa)		Shear strength (MPa)	
	80 K	298 K	80 K	298 K
Isovalta pre-preg insulation				
1	510	245	35	17
2	560	305	36	19
3	475	300	44	17
4	485	285	37	19
5	520	245	32	20
Mean value	510	276	36.8	18.4
Wet wrap insulation				
Mean value	563	350	28.7	17

at 80 K need to high than 500 MPa, and the requirement of shear strength is about 30 MPa. The mechanical properties test results indicated this type pre-preg insulation material meet the requirements of at 80 K.

The glass fiber tape with epoxy resin and the polyimide film are chose as the composite materials for wet wrap insulation samples. The epoxy resin system is selected from EAST insulation materials and ASIPP have all the intellectual property right of the formula of this type resin system [7, 8]. The glass fiber tape is made of boron-free E glass, with the width of 25 mm and the thickness of 0.2 mm. The width of polyimide tape is 20 mm, 20 % less than the glass tape, which forms the bonding between layers and allows the wicking of the fiber glass. The thickness of polyimide tape is 0.05 mm. As shown in Fig. 1, the structure of wet wrap insulation sample was GK structure (G = glass fiber tape, K = polyimide tape and one half overlapping GK layer's thickness is $(0.2 + 0.05) \times 2 = 0.5$ mm). The GK structure layers were also solidified on stainless steel die to process the insulation samples but it has not been heated. The wet wrap insulation samples are shown in (d), (e) and (f) of Fig. 1.

In order to ease the experiment antitheses and reduce the experimental errors, all of the pre-preg insulation and wet wrap insulation samples were processed to be 60 mm in width, 180 mm in length, and 5 mm in thickness. In addition, for more study of the low-temperature electrophysical performance between the two types insulation, some of the samples were processed with an artificial fissure, the width of which was 2 mm and the depth of which was 1 mm.

Experimental Equipment

The high voltage Paschen test under low gas pressure and low temperature condition can measure the performance of superconducting insulation easily and effectively [13]. That's the reason why the Paschen test needs to be implemented in all the high potential components that was required by ITER international organization.

An experimental equipment of insulation breakdown discharge that can provide a low temperature and low pressure environment has been built up in December 2011 in ASIPP. The sketch of the experimental equipment is shown in Fig. 2. The discharge of various types insulation sample can be measured in different cryogenic temperature and vacuum condition.

The experimental platform includes two parts, namely, a three-tier experimental Dewar flask and a high-voltage test system, as shown in Fig. 2. The three-tier experimental Dewar flask consists of a vacuum test container, liquid nitrogen cooling Dewar and an outer adiabatic vacuum Dewar. The high voltage test system is mainly composed of cathode and anode, upper and lower epoxy support board,

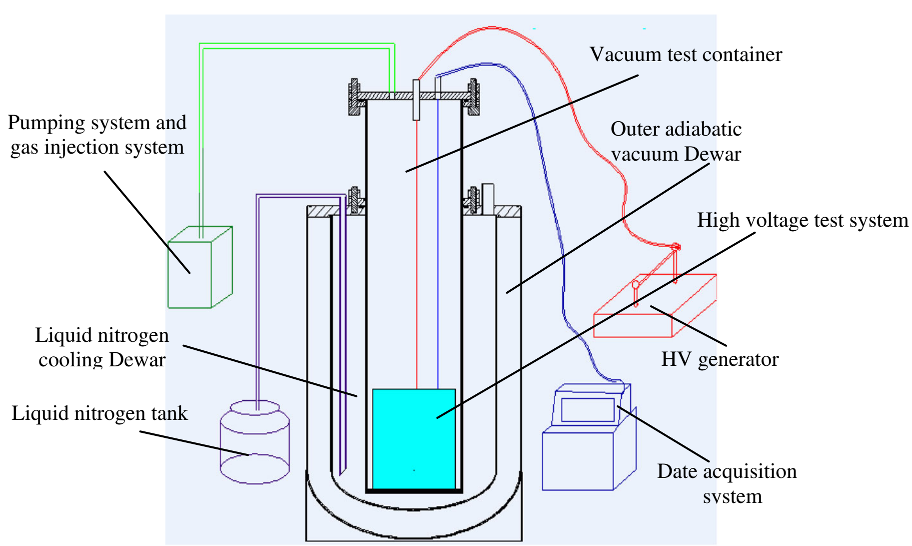

Fig. 2 The sketch of the experimental equipment framework

polyimide insulation layer and copper support plate which is used for heat exchange. Among them, the cathode board was connected with leakage current test system and temperature test system. In addition, temperature sensors (PT1000 platinum resistance temperature sensors) were pasted on copper cathode plate surface and insulation sample surface to monitor the temperature.

Figure 3 is the experimental equipment and the sketch of the high voltage test system. The radius of anode is 9 mm and the size of cathode is 10 mm × 60 mm. The insulation sample was cooled by the liquid nitrogen which absorbed heat through the bottom stainless steel plate of the vacuum test container, the copper support plate and the cathode (copper material), and ultimately the insulation sample was cooled to a certain temperature at 80 K. The pumping system and gas injection system can provide a testing gas pressure condition which swept from 0.001 to 1000 Pa continuously and cryogenic insulation condition. The vacuum test container pressure was reached to 0.2 Pa firstly by the pumping system, and then using gas injection system to control the pressure continuously, such as 0.1, 1, 100 Pa and so on. The maximum output voltage and current of the DC high voltage generator is 100 kV and 3 mA. The leakage current can be measured during test of which the accuracy is 0.1 μA.

Results and Discussion

Due to the insulation sample was in the vacuum test container, it was unable to determine directly whether the breakdown was caused by the material destruction or by the flashover. The cause of breakdown was regarded as material destruction on the base of GB/T1408.1-1999 standard [14] which was formulated and promulgated in China. When the breakdown occurred, high voltage would be applied on the insulation sample again, and if the second breakdown voltage is far below than the fist time breakdown voltage. The insulation sample's breakdown can be considered to be caused by material damage rather than flashover.

(1) Results of two types of insulation sample of 1 mm thickness.

R.J. Meats [15] had done some research on the breakdown characteristics of helium at very low pressure. The discharge tends to be more easily caused by the active helium. Hoshino. M [16] had studied on the high voltage breakdown characteristic of cryogenic helium. The results indicated that the breakdown voltage of cryogenic helium is much lower than of air under same condition. Besides, inner local discharge may easy take place if helium penetrates into the air hole or flaw of solid insulation. The accumulation of local discharge will lastly bring on insulation breakdown. In addition, although Paschen law is used to study on pure gas discharge mostly, it is introduced to predict the breakdown voltage of small air hole or microcrack of solid insulation [17]. The minimal breakdown voltage of helium is maintained at 150–200 V.

The 80 K high voltage discharge test results of the two types of 1 mm thickness insulation sample are showed in Fig. 4. All the samples' thickness is equivalent to 1 mm (one is 2 mm thickness with a fissure of 1 mm depth, while the other is just 1 mm thickness without fissure). Both of the two type insulation's breakdown voltages decrease with increasing pressure (helium). In addition, high permeability of helium (especially under the condition of frequent fluctuation of the pressure) may play an important role on the failure of the insulation structure [18]. It can be considered that the increasing helium pressure may play a catalytic role on the aging and breakdown process of cryogenic superconducting insulation materials in this experiment.

For the wet wrap insulation sample of 1 mm thickness (2 mm thickness with a fissure of 1 mm depth), the measured breakdown voltage is in the range from 23.2 to 18.9 kV at high vacuum region (from 0.001 to 0.1 Pa) and from 18.7 to 15.4 kV at low vacuum region (from 1 to 30,000 Pa), while for the wet wrap insulation sample of

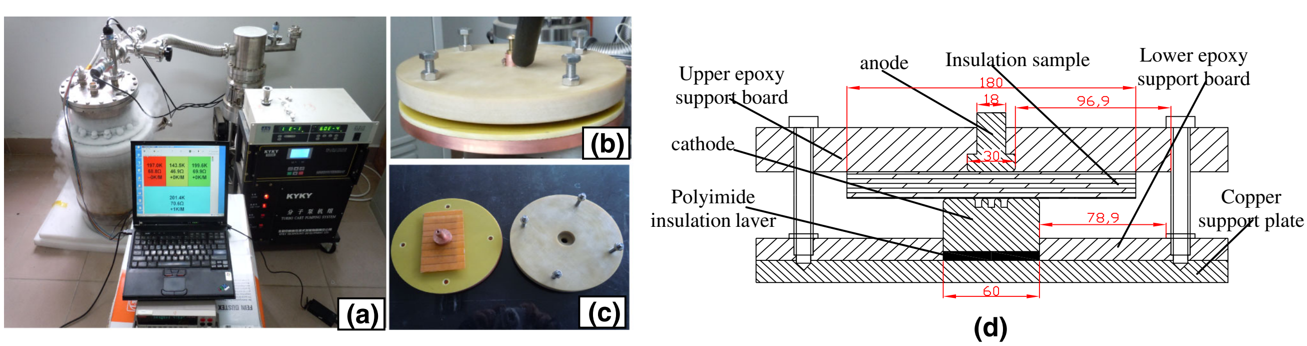

Fig. 3 The experimental equipment **a** part of the experimental test platform, **b** high-voltage test system, **c** components of the high-voltage test system, **d** the sketch of the high voltage test system

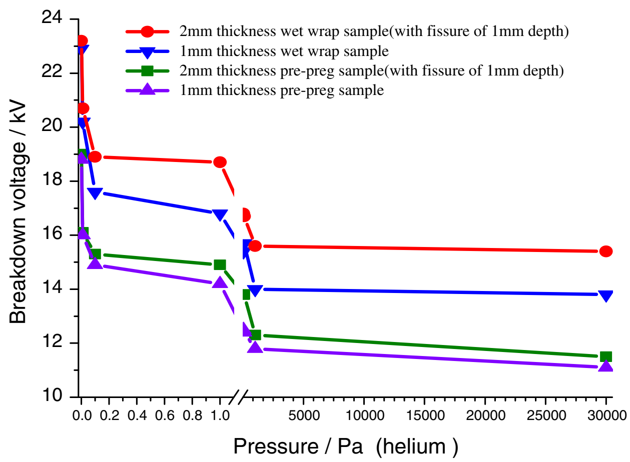

Fig. 4 Results of two types of insulation sample of 1 mm thickness

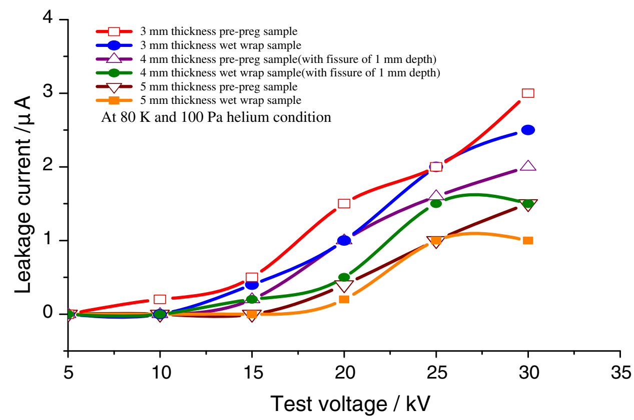

Fig. 5 Change trend of leakage current at 80 K under 100 Pa helium condition (two types of insulation sample of 3 and 5 mm thickness)

1 mm thickness (without fissure), the breakdown voltage is in the range from 19 to 15.3 kV at high vacuum region and from 14.9 to 11.5 kV at low vacuum region. Compared with the sample which is just 1 mm thickness without fissure, it can be considered that the dielectric strength of such sample with 1 mm-depth fissure was reinforced lie in the fact that the fissure may be filled with helium. Furthermore, the fissure which was filled with helium is equivalent to increasing the thickness of solid insulation although the minimum Paschen breakdown voltage is much lower than other gases (such as nitrogen and air) under the same condition.

For the pre-preg insulation samples of 1 mm thickness, the change trend of breakdown voltage was found to be similar to that measured for the wet wrap insulation sample of 1 mm thickness. As shown in Fig. 4, it can be found that the dielectric strength of the pre-preg insulation samples of 1 mm thickness is about 18 % lower than of the wet wrap insulation under same condition. Both of the dielectric strength of the two types of insulation sample ranges from 11 to 23 kV/mm at 80 K helium condition.

(2) Results of two types of insulation samples of 3 and 5 mm thickness.

In this work, the insulation samples were separately processed to be 3 mm (one is 4 mm thickness with a fissure of 1 mm depth, while the other is just 3 mm thickness without fissure) and 5 mm in thickness. The experimental results shown that all of the wet wrap insulation samples' leakage currents at different test voltages (limited to 30 kV) and pressures are kept <20 μA at 80 K, the maximum leakage current is just 6 μA. Similarly to the wet wrap insulation samples' test results, no significant large leakage current of the pre-preg insulation samples was measured under various voltages and pressures at 80 K. Besides, there are no obviously relationship between the leakage current and the helium pressure. Figure 5 is the results at 80 K under 100 Pa helium condition of the two types of 3 mm thick and 5 mm thick insulation samples. It was a typical change trend of leakage current at 80 K under different test voltages and helium pressures condition. However, it can be concluded that the property of the two type insulation samples of 3 and 5 mm thickness didn't change obviously at 80 K under different helium pressures, no defect and crack generated after the high voltage tests, so there are no breakdown phenomenon happened during all the tests. Both of the two types of insulation sample of 3 and 5 mm thickness can withstand 30 kV under various helium pressures at 80 K.

Conclusion

A new low-temperature high-voltage experimental platform has been developed which might be suitable for the electrical properties test of superconducting insulation materials under low temperature and helium environment. The dielectric performance of both pre-preg cryogenic insulation and the wet wrap cryogenic insulation were studied. The experimental results are as following:

(a) For both of the two types insulation samples of 1 mm thickness (with and without fissure), the breakdown voltages decrease with increasing pressure (helium) at 80 K. The dielectric strength of the pre-preg insulation samples of 1 mm thickness is about 18 % lower than that of the wet wrap insulation under same condition. Both of the dielectric strength of the two type insulation is in the range from 11 to 23 kV/mm at 80 K helium condition.

(b) Both of the two type insulation samples of 3 and 5 mm thickness can withstand 30 kV under various helium pressures at 80 K.

(c) From this work, the pre-preg insulation appears to withstand 30 kV at 80 K helium condition if its thickness exceeds 3 mm. It can be used as an option for cryogenic superconducting insulation but further work is required to determine the operation under much worse working condition.

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References

1. P. Osmokrovic, M. Vujisic, K. Stankovic, A. Vasic, B. Loncar, Mechanism of electrical breakdown of gases for pressures from 10^{-9} to 1 bar and inter-electrode gaps from 0.1 to 0.5 mm. Plasma Sources Sci. Technol. **16**, 643–655 (2007)
2. E. Husain, R.S. Nema, Analysis of Paschen curves for air, N2 and SF6 using the Townsend breakdown equation. IEEE Trans. Electr. Insul. **EI-17**(4), 350–353 (1982)
3. H. Eichhorn, K.H. Schoenbach, Paschen law for a hollow-cathode discharge. Appl. Phys. Lett. **63**(18), 2481–2483 (1993)
4. Zhixiong Wua, Hao Zhang, Properties of radiation stable, low viscosity impregnating resin for cryogenic. Cryogenics **51**(6), 229–233 (2011)
5. K. Bittner-Rohrhofer, K. Humer, H. Fillunger, R.K. Maix, H.W. Weber, Mechanical behavior of the ITER TF model coil ground insulation system after reactor irradiation. Cryogenics **42**(11), 697–704 (2002)
6. D.P. Ivanov, I. Anashkin. B. Kolbasov. Reliability of force cooled superconducting magnets for fusion. IEEE Trans. Appl. Supercond. **22**(3), (2012)
7. Y. Song, L. Kun, X. Huang, Status of design and R&D for ITER feeder system procurement in China. IEEE Trans. Appl. Supercond. **22**(3), 4800404 (2012)
8. X. Huang, K. Yuntao Song, High voltage test of ITER feeder components under Paschen condition. IEEE Trans. Appl. Supercond. **22**(3), 7701004 (2012)
9. Z. Jinxing, S. Yuntao. Experimental Study on Paschen tests of ITER current lead insulation. 8th General Scientific Assembly of the Asia Plasma and Fusion Association (APFA2011)
10. H. Fengnian, W. Weihan, Electrical breakdown of vacuum insulation at cryogenic temperature. IEEE Trans. Electr. Insul. **25**(3), 557–562 (1990)
11. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. ASTM committee on standards. D 3039/D 3039 M-95a
12. ITER Annex to Design Requirements and Guidelines Level 1. Structural Material Database: Article 3 Non-metallic Materials Database & Specifications: N 11 FDR 26 01-07-04 R 0.1
13. H. Scheller, H. Langenberg, Paschen testing on W7-X coils and components in the BNN test facility. IEEE Trans. Appl. Supercond. **16**(2), 759–762 (2006)
14. Methods of test for electric strength of solid insulating materials—tests at power frequencies. GB/T 1408.1-1999
15. R.J. Meats, Pressurised-helium breakdown at very low temperatures. IEEE Proc. Inst. Electr. Eng. **119**(6), 760–765 (1972)
16. M. Hoshino, T. Satowe. Breakdown characteristics of plane electrodes having spacers in cryogenic gaseous helium. Conference on Electrical Insulation and Dielectric Phenomena, Annual Report: 451–454 (1995)
17. P. Carazzetti, H.R. Shea, Electrical breakdown at low pressure for planar microelectromechanical systems with 10- to 500-μm gaps. J. Micro. Nanolithogr. MEMS MOEMS **8**(3), 031305 (2009)
18. Y. Xiao-Li, Y. Xiao-Yong, Z. Shi-Xi, Preliminary study on insulation design of electrical device in helium for high temperature gas-cooled reactor. At. Energ. Sci. Technol. **45**(40), 426–429 (2011)