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Flashover characteristics of G-11 at different cryogenic temperatures

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Abstract. The feeder busbar joint system is an important component in the International Thermonuclear Experimental Reactor (ITER) project. The insulation materials for the feeder busbar joint play a crucial role in both mechanical support and high voltage insulation. The G-11 block, which is a kind of industrial high-pressure, glass-reinforced epoxy laminates, has been chosen for the feeder busbar joint as insulation and mechanical support. The electrical characteristics of the G-11 depend significantly on temperature. As the feeder system works at the temperature of 77K, to ensure safe operation, the DC flashover voltage is required to be studied in a cryogenic environment. In this work, DC flashover characteristics of the G-11 at both room and cryogenic temperatures have been investigated using a self-developed test system. The results show that the surface flashover voltage rises as the flashover times increase. In addition, results indicate that the flashover voltage of the G-11 depends on orientations and it increases as the temperature decreases.

1. Introduction

Cryogenic insulation materials require excellent mechanical, thermal and electrical performance at both room and cryogenic temperatures [1]. It is well known that the G-11 has excellent mechanical performance [2] and thus it has been a commonly used structure supporting material for cryogenic equipment. For cryogenic insulation applications, they are often exposed to vacuum and extreme low temperature environments. For example, the ITER Feeder busbar joint is an important component which connects the high temperature superconducting current leads to the magnet terminals. G-11 blocks were chosen as the joint material to smooth the joint regions in the ITER project [3]. To ensure safety, the electrical performance of the G-11 is required to be experimentally studied at low temperature.

Surface flashover occurs when material fails to support a significant voltage gradient. Failure of solid insulation may cause permanent damage of component as well as equipment [4]. Surface flashover voltage of cryogenic insulation materials has been investigated at both room and cryogenic temperatures in previous research. For example, Sauers et al. [5] investigated the flashover voltage of the G-10 which is similar to the G-11 at cryogenic temperature using self-made equipment and they revealed that the flashover voltage at 90K is lower than that at room temperature. However, the surface flashover voltage at lower temperature is limited. In this work, DC flashover voltage of the G-11 film was tested in vacuum at three different temperatures, i.e., 293K, 77K and 9K. In addition, the effect of orientation on the flashover voltage was investigated at different temperatures and the results were discussed.

2. Experiments and materials

The sample chamber was cooled with a G-M cryocooler, as showed in figure 1, which provided a vacuum and tunable cryogenic environment for the test sample. The vacuum was obtained by a mechanical pump and then a turbo-molecular pump. The vacuum degree was checked by an ionization vacuum gauge and a resistance vacuum gauge. A G-M cryocooler (EASYCOOL. KDE415, 1.5W@4.2K) was selected as the cold source. The material mechanically attaches to the second cold head via a cold plate. Two radiation shields were attached to the two cryocooler cold heads. Temperatures was measured by several Rh-Fe resistance thermometers. The temperature of the copper plate and the material were monitored. The lowest temperature of the material was 9K and the temperature of the cold plate was 4.2K. The temperature gradient is considered to be result of the thermal conductance resistance of the Apizon grease, the test material, and the cold plate, which limits the lowest temperature.

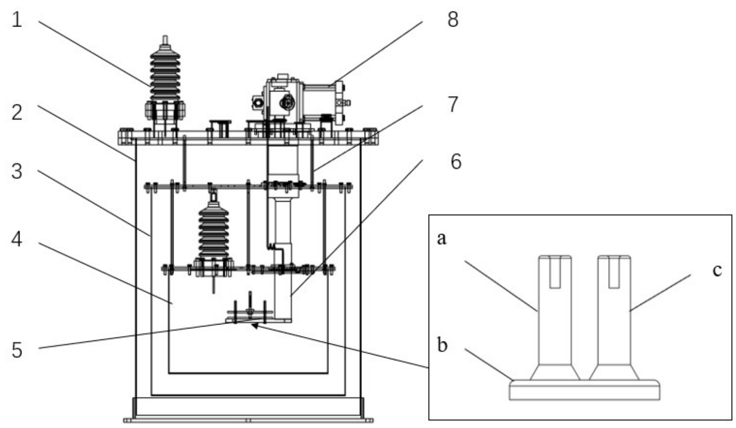


Figure 1. Schematic of the sample chamber. (1) feedthrough; (2) vacuum chamber; (3) the first thermal radiation shield; (4) the second radiation shield; (5) electrodes; (7) mechanical support and (8) GM cryocooler; (a) cathode; (b) copper plate and (c) anode

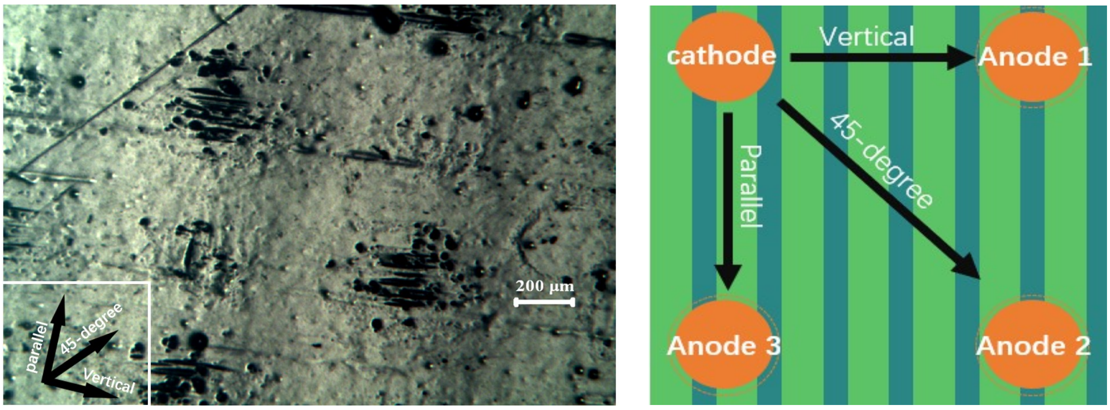
The electrodes were made of copper and the shape was designed according to the IEC Guide [6]. The gap between the two electrodes is 5mm. The material was mounted on the electrode by screw threads.

A DC high voltage power supply (Tianjin Dongwen, DW-P104-2ACF2, 100kV) was used to apply high voltage to the material surface. The voltage was measured by the combination of a divider (Wuhan Huading, FRC-100, 1000:1) and a digital oscilloscope (Rigol, DG1000Z, 1GS/s, 50MHz) with a high-voltage probe (UNI-T, UT-V23, 100:1, 100MHz). The signal was collected by oscilloscope when the surface flashover occurs. The sample was tested with a voltage ramp of 200 V/s. Each sample was tested at least 10 times with an interval of 2 minutes at each test temperature.

The G-11 film (Beijing Friend Group, 0.3 mm in thickness), was cut into the same pieces (50 mm in length, 50 mm in width). The specimens were washed in an ultrasonic cleaner with alcohol and dried in a vacuum oven before test. The surface condition was studied using an optical microscope (Shanghai Optical Instrument Factory, 10XB-PC, 2048×1536). To investigate the effect of the orientation, three orientations were chosen to test the value of flashover voltage, which are indicated in figure 2(b). The three orientations are parallel to the glass-fiber, normal to glass fiber and a 45-degree angle respectively.

3. Results and discussions

As shown in figure 2(a), the surface of the G-11 has regular bulges. The bulges are lines of glass fiber covered with epoxy resin. Also, there are some glass fibers without epoxy on the top of the surface. Glass fiber cloth (7628 type E-glass) used in G-11 is made by tightly interweaving the wrap and fill glass yarn, the difference in the fibric density of the wrap and fill makes the bulges only have one orientation. The bulges are illustrated through the light green and dark green blocks in figure 2(b).

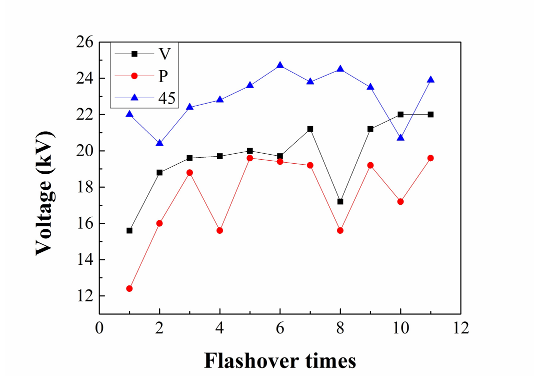


(a) (b)

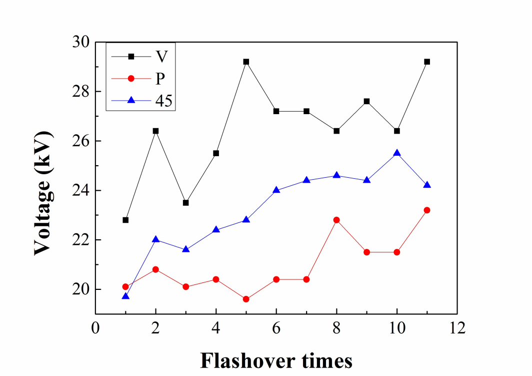
Figure 2. (a) the surface morphology of G-11 and (b) schematic diagram of three orientations

After test in cryogenic environment, the surface of the G-11 between the two electrodes did not show a clear breakdown path. The flashover voltage was affected by gas layer and the triple junction area. Figure 3 shows the test results of the flashover voltage of the G-11 at three different temperatures and in different orientations. The results show that flashover voltages fluctuate and rise as the flashover time increases. The first low values of flashover can be explained by the distorted electrical field. After the conditioning process, the uniform electric field is smoothed, then form a relatively stable and higher flashover voltage [4]. The flashover voltages in three orientations at 293K, 77K and 9K are shown in figure 3(a-c). The results show that flashover voltages in vertical orientations are higher than those in parallel orientations at all three temperatures. However, the flashover voltages in the direction of

45-degree angle are the highest at the temperature of 293K, and lower than vertical orientation at the temperature of 77K and 9K. The difference is smallest at 9K and biggest at 77K among three orientations which indicates that the effect of orientation of the G-11 is slight at extreme low temperature. Temperature also affects the flashover voltage of the G-11. As show in figure 3(d-f), the results show that the flashover voltage increases as the temperature decreases in every orientation. However, the difference between 77K and 293K is not obvious in 45-degree angle orientation.



(a)



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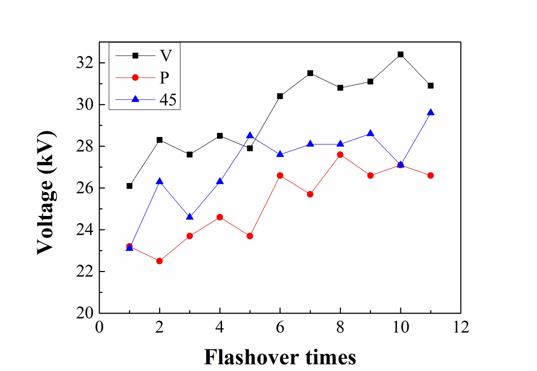
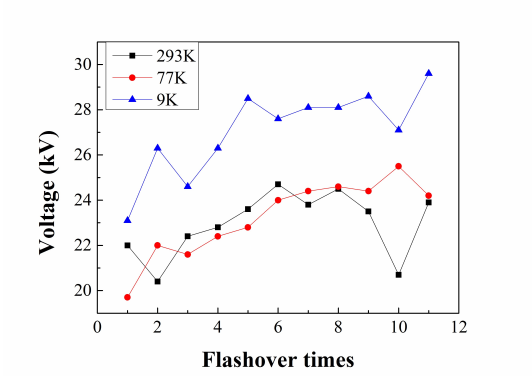
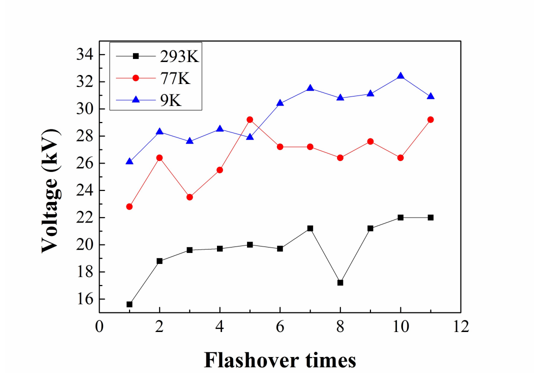


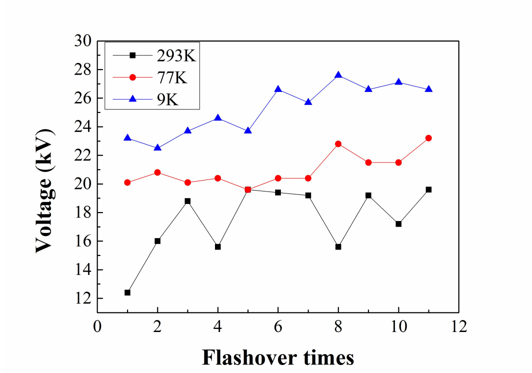
(c)



(d)



(e)



(f)

Figure 3. Flashover strength of the G-11 with different orientations and temperatures: (a) Flashover voltages at 293K, (b) Flashover voltages at 77K, (c) Flashover voltages at 9K, (d) Flashover voltages in 45-degree angle, (e) Flashover voltages in vertical and (f) Flashover voltages in parallel

The extreme low temperature and the regular bulges inhibit the intermediate electron cascade along the surfaces. The electron emission from the triple junction of the G-11, electrode and vacuum [4] needs more energy when the temperature of the material and the electrodes is low. In addition, the bulges change the path of the electron. Some of the secondary electrons need more energy to strike again the surface. Compared to the parallel orientation, the form of electron avalanche is harder due to the bulges which increase the reflection of electrons, as shown in figure 4. Therefore, the surface flashover voltage increases.

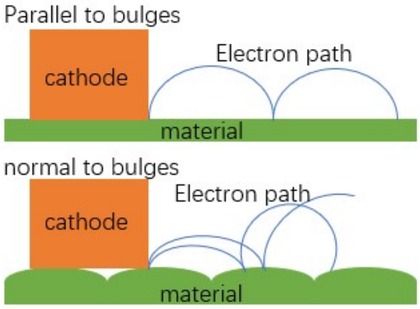


Figure 4. Flashover process in different orientations

4. Summary

The surface of the G-11 film was investigated with an optical microscope and the surface flashover voltage was tested at three temperatures and in three orientations. The G-11 has a natural structure of bulges surface for resisting surface flashover. It was observed that the flashover voltages increased as the temperature decreased and depended on orientations. The flashover voltages at every test temperature increased when the electrodes were vertical to the surface orientation. The results indicated that choosing a proper orientation can inhibit flashover effectively in practical applications.

Acknowledgments

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