Understanding Surface Flashover in Helium Gas Cooled High Temperature Superconducting Devices

A Al-Taie1,2,3, P Cheetham1,2, C H Kim2, C Park4, L Graber5 and S V Pamidi1,2
1 Florida A&M University - Florida State University College of Engineering, Tallahassee, FL 32310, USA
2 Center for Advanced Power Systems, Florida State University, Tallahassee, FL 32310, USA
3 University of Technology, Baghdad, 10066, Iraq
4 Department of Electrical and Computer Engineering, Mississippi State University, Mississippi State, MS 39762
5 Georgia Institute of Technology, Atlanta, GA 30332, USA
aha16b@my.fsu.edu

Abstract. Surface flashover voltage on solid insulators in gas cooled superconducting power devices is studied. The relationship between the surface flashover voltage and the dielectric strength of the gas media is established. Analysis of the data on surface flashover voltage measurements on cylindrical samples made of high-pressure fiberglass laminate (G10) in three different gas media with varying dielectric strength and pressure showed a positive correlation between the surface flashover voltage and the dielectric strength of the gas both at room temperature and 77 K. The positive relationship, however, is not linear. The results suggest that using gas media with higher dielectric strength, employing higher pressure, and lowering temperature in HTS power devices lead to higher surface flashover voltages and higher operating voltages because surface flashover is usually the limiting voltage in devices that use solid support structures and possess voltage gradients.

1. Introduction
High temperature superconducting (HTS) devices enable higher current densities and efficiencies compared to their conventional counterparts. For some applications, the required operating temperature is less than 50 K, and gaseous helium (GHe) is a potential cryogen. These applications include devices that use MgB2 as the superconductor, and for HTS motors, generators, and magnets which operate with a higher internal magnetic field and require the lower operating temperature to achieve the necessary high current density [1]. To achieve high power ratings in the MW range, HTS devices need to operate at medium voltage between 5-20 kV. The cryogen is a part of the electrical insulation system of HTS devices, and the low dielectric strength of GHe limits the operating voltage of GHe cooled HTS devices [2], [3]. Our research over the last few years has focused on understanding the intrinsic dielectric properties of GHe and developing insulation materials and designs to increase voltage ratings of GHe cooled HTS devices [4]. We discovered that adding less than 7 mol% of hydrogen to GHe significantly increases its intrinsic dielectric strength without flammability concerns [5], [6]. It is now necessary to understand how this improvement translates to improved voltage ratings of GHe cooled HTS devices. The limiting voltage rating for an HTS device is not expected to be intrinsic breakdown in the gas medium, but instead through other mechanisms such as partial discharge and surface flashover, which occur at significantly lower voltages than the intrinsic breakdown.

Surface flashover is a phenomenon of electrical breakdown along the interface between the conductor and two electrical insulation materials with different electrical properties. The mechanisms which dictate
surface flashover vary depending on whether an ac or dc voltage is applied. For ac voltages, surface flashover is typically dependent on the permittivity of the insulation materials and the electric field enhancement caused by the geometry. The permittivity of insulation materials plays a significant role in the field distribution under AC fields, and the temperature does not largely influence permittivity. However, under DC fields, the conductivity of insulation materials, which varies with temperature, governs the field distribution. Our previous work on gas mixtures shows that the intrinsic breakdown of a gas is a function of density and is independent of operating temperature [7]. To enable the potential of the dielectric design of HTS prototype devices to be verified at room temperature instead of at cryogenic temperature, it is necessary to confirm whether surface flashover is a function of gas density, but not a function of temperature. The ability to validate the dielectric integrity of HTS devices at room temperature instead of cryogenic temperature will lead to substantial cost savings, rapid prototype development, and collection of statistically significant data.

The purpose of the experiments conducted for this study is to understand the effect of the dielectric strength of the gas medium on the surface flashover voltage and to see if the temperature has any effect on the phenomenon. Three different gas media were investigated, which include research grade helium (GHe) with 99.9999% purity, 4 mol% hydrogen + 96 mol% GHe, and nitrogen gas (GN2). These gases have varying dielectric strength, and comparisons can be made between the gases. The 4 mol% H2 helium-based gas mixture and GN2 are stronger than GHe in dielectric strength at room temperature. For the same particle density, GN2 has 6.7 times the dielectric strength of GHe. That means under the same conditions of electric field, gap distance, pressure, and temperature, GN2 should have a breakdown voltage 6.7 times to that of GHe [8], [9]. Additionally, 4 mol% H2 helium-based gas mixture has 80% higher dielectric strength than GHe [5], which means the gas mixture is 1.8 times stronger than pure helium. Accordingly, GN2 is 3.7 times stronger than 4 mol% H2 helium-based gas mixture. It is important to understand if the ratios between the gases for intrinsic breakdown hold true for surface flashover. Surface flashover involves a different mechanism compared to intrinsic breakdown. As surface flashover is expected to be the limiting voltage rating for HTS power devices, it is necessary to understand the relationship between the dielectric strength of the gas insulating medium and the surface flashover voltage and to assess the practical benefits of incorporating helium-gas mixtures with enhanced dielectric strength.

Experiments were conducted at room temperature and at 77 K in the same gas medium and solid surface combination. Surface flashover voltages were measured on samples with both ac and dc voltages at room temperature and 77 K to understand the influence of the dielectric strength of the gas medium on surface flashover voltage.

2. Experimental Setup

There is no standardized surface flashover experimental setup. In this study, a needle-plane arrangement was selected. The needle plan arrangement allows for surface flashover to occur in multiple radial paths due to its symmetry. The experimental setup was designed to ensure the electrodes remained in contact with the insulating specimen at both room and cryogenic temperatures. Previous surface flashover experiment setups have had issues with specimens becoming loose between electrodes due to the mismatch in coefficient of thermal expansion between the metal electrodes and the polymer-based insulator. The current experiment setup ensures that experimental results between room and cryogenic temperature can be easily compared to one another. A 12.4 cm diameter copper disc was fabricated from a copper sheet. A 12.7 mm circular hole at the center and four 6.35 mm circular holes separated by 90 degrees by the circumference were made on the copper disc by a waterjet. The centre hole was made to fit the cylindrical G10 samples, which was inserted through, and the other four holes were made to fit in the 6.35 mm threaded rods in the cylindrical G10 set that provides the structure for the setup. Cylindrical G10 samples of 12.7 mm in diameter and 15 mm in height were used as solid insulator samples. G10 is a commercially available glass reinforced epoxy which is compatible with cryogenic temperatures. A needle electrode having diameter of 2 mm with its tip placed on the center of the G10 sample was connected to the high voltage source through a bushing while the copper disc was connected to ground. The experimental arrangement of the sample and the electrode is shown in Figure 1 (a).

The upper circular surface of G10 specimen sits at a higher level than the copper disc by 3.4 mm, as shown in Figure 1 (b). The minimum total surface flashover path length between the tip of the needle
Electrode and the copper disc is the sum of the 6.35 mm radius and 3.4 mm vertical height of the cylindrical G10 insulator, which equals to 9.75 mm.

3. Measurements and Results for G10 in Different Gases

The three different gases were tested with G10 specimens to understand the relationship between the dielectric strength of the gas and the surface flashover voltage. Again, GN₂ was selected since it possesses higher dielectric strength compared to the other two gases, as discussed in the introduction.

At room temperature, the pressure levels used for GHe and 4 mol% H₂ helium-based gas mixture were 2.0, 1.5, 1.0 and 0.5 MPa. For GN₂ pressure levels of 2.0, 1.5, 1.0 and 0.5 MPa were also used, but in addition, the test was extended to lower pressure levels of 0.4, 0.3 and 0.2 MPa to have a wider pressure range, and accordingly wider gas mass density range. For the measurements at 77 K with GHe and 4 mol% H₂ helium-based gas mixture, the same pressure ranges were also used. For these two gases, besides the pressure levels of 2.0, 1.5 and 1.0 MPa at 77 K, lower pressure levels of 0.54, 0.4, 0.27 and 0.14 MPa were chosen to have the same gas densities at 2.0, 1.5, 1.0 and 0.5 MPa at room temperature, respectively. Pressure was monitored by CMM type of HEISE® dial pressure gauge of which accuracy is ±0.02 MPa.

AC measurements were performed using a Haefely high voltage test kit (100 kV/5 kVA AC, rms, 60 Hz). The DC measurements were performed using the Glassman high voltage source (100 kV/16 kW DC) since it has a stable DC voltage profile having 0.025% ripple factor and capability of limiting the output (discharge) current less than 3.2 mA (2% of its maximum). For both the AC and DC measurement, a ramp rate of approximately 300 V/s was applied until surface flashover occurred. Restricting the output current reduces the energy released during surface flashover, which enables more measurements to be taken before degradation of the sample occurs. Once degradation occurs on the sample by multiple experiments, measured surface flashover voltage was found more than 50% offset from the statistically meaningful average of the experimental value. With the limiting output current capability of the high voltage sources used in this study, degradation of the sample were not frequent or problematic.
Flashover voltage data obtained in the DC and AC measurements for room temperature and 77 K is shown in Figure 2. Each data point is an average of 5 measurements. The error bars in the figure show maximum and minimum flashover voltages obtained at each pressure level.

4. Discussion
The systematics of the results obtained are summarized below:

1. For all the cases studied, the DC surface flashover voltages are higher than the corresponding AC rms (60 Hz) surface flashover voltages for the same gas, temperature, and pressure combinations. Analysis of the surface flashover data obtained at 77 K to the previous obtained intrinsic dielectric strength of GHe and the 4 mol% H2 mixture demonstrates that the increase in DC surface flashover values is not solely based on representing the AC measurements in rms instead of peak voltage (Table 1).

2. Comparing the surface flashover voltage data of different gases studied, the 4 mol% hydrogen-helium mixture with higher dielectric strength resulted in higher surface flashover voltages compared to pure helium at all the pressures measured at room temperature.

3. For both pure GHe and 4 mol% hydrogen-helium mixture, the 77 K measurements resulted in higher flashover voltages than the corresponding room temperature values. The dielectric strength of a gas for a given pressure at 77 K is 3.7 times stronger to that at room temperature due to the increase of gas density by the same number.

4. Surface flashover voltages in GN2 are higher than those in pure helium or helium-hydrogen mixture. GN2 is 6.7 times stronger dielectric medium than pure helium [8].

Table 1. Intrinsic dielectric strengths for the various gases

| Pressure | GHe breakdown (kV) [5] | GHe Surface flashover (kV) | 4 mol% H2/ GHe Breakdown (kV) [5] | 4 mol% H2/ GHe Surface Flashover (kV) |
|----------|------------------------|---------------------------|-----------------------------------|-------------------------------------|
|          | 2 MPa                  | 1.5 MPa                   | 1 MPa                             | 0.5 MPa                             |
|          | AC DC                  | AC DC                     | AC DC                             | AC DC                               |
| GHe      | 73.8 105.4 57.6 82.7   | 41.2 57.0 23.4 29.5       | 132.5 200.7 110.6 158.9           | 19.4 39.9 18.1 37.0                 |
|          | DC                     |                            | DC                                | DC                                  |

From Table 1 it can be seen that for the intrinsic dielectric strength comparison between AC and DC measurement the DC measurements are higher by \(\sqrt{2}\). When the surface flashover data is compared between AC and DC voltages the DC measurements are between 1.8 – 2.7 times higher than the AC which is expected as AC and DC surface flashover are governed by different breakdown mechanisms. It should be noted that the DC voltage applied to the sample was done at a continuous ramp rate which may not have given sufficient time for space charge accumulation to influence the surface flashover voltage recorded. Table 1 also demonstrates the difference between intrinsic breakdown and surface flashover values. The experimental data on intrinsic breakdown taken from [5] was extrapolated to have the same gap distance (9.5 mm) as the surface flashover experiment. The significantly lower surface flashover values demonstrate why it is expected to be a limiting factor for HTS power devices.

5. The needle plane experimental setup has a non-uniform electric field which means that different surface flashover voltages are expected if a negative DC voltage is applied to the needle compared to what has already been obtained for a positive DC voltage. As a continuation of this study, we intend to complete surface flashover measurements utilizing a modified experiment configuration with a negative DC voltage applied on the needle. Collection of these data will give a greater level of understanding of surface flashover in GHe and GHe mixtures for varying waveforms.

Analysis of all the results shows that increasing the dielectric strength of the gaseous medium, either by using a stronger gas or by increasing the pressure or decreasing the temperature, increases the surface flashover voltage.

To present the relationship between the dielectric strength of the gas and the surface flashover voltage, Table 2 summarizes all the data of surface flashover in the three different gas media and two
different temperatures. All the values in Table 2 show relative strength of gas compared to GHe at room temperature by normalizing with GHe values at same pressure. Accordingly, the increase in DC and AC surface flashover voltages were compared to the increase in the dielectric strength of the gas medium.

Analysis of the data in Table 2 allows the conclusion that increasing the dielectric strength of the gaseous medium increases the surface flashover voltage. In other words, the surface flashover voltages correlate positively with the dielectric strength of the gas. However, the relationship is not linear. For example, increasing the dielectric strength 3.7 times does not yield an increase of 3.7 times flashover voltage. Additionally, the data in table show that DC surface flashover voltages are generally higher than the corresponding AC surface flashover voltage.

![Figure 2. (a) DC and (b) AC rms surface flashover voltages at various pressure levels.](image-url)
Table 2. Dielectric strength of various gases, normalized to GHe at room temperature and the corresponding surface flashover voltages

|                         | Both AC and DC Intrinsic Dielectric strength (ratio) [5], [8] | DC surface flashover AC surface flashover voltage (ratio) |
|-------------------------|---------------------------------------------------------------|----------------------------------------------------------|
| GHe at room temperature | 1                                                             | 1                                                        |
| H$_2$-He mixture at room temperature | 1.8                                                       | 1.3-1.7                                                   |
| GHe at 77 K             | 3.7                                                          | 1.6-1.7                                                   |
| H$_2$-He mixture at 77 K| 6.7                                                          | 2.0-3.1                                                   |
| GN$_2$ at room temperature | 6.7                                                       | 2.4-3.7                                                   |

5. Conclusion

The surface flashover is the lower limit of the performance of an insulation system when solid surfaces and electric field gradients are present. Surface flashover measurements were performed at room temperature and at 77 K on G10 cylindrical samples in three different gas media at two different temperatures. The three different gas media, two different temperatures, and several pressures were used to change the dielectric strength of the gas media over a wide range. Increasing the dielectric strength by changing the gas media, increasing the pressure, or lowering the temperature leads to an increase in the surface flashover voltage, but not linearly. The non-linearity of the relationship between the dielectric strength of the gas medium and the flashover voltage need to be further investigated. The results of this study suggest that for gas-cooled HTS power applications, it is useful to employ a gas medium with higher dielectric strength to push the surface flashover voltages to higher values. Similarly, use of high pressures or lower temperatures are also useful in pushing the surface flashover voltages to higher values.

6. References

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