

Analysis of direct current surface flashover from high vacuum to atmospheric pressure

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1. Introduction

Surface flashover is an electrical discharge phenomenon that occurs along the surface of insulators under high voltage application. Enhancing insulator strength is essential for securing performance reliability in high voltage devices such as high power microwave (HPM). Therefore, enhancing insulator strength is essential, and prior work has explored surface treatment, coatings, shape modifications, temperature control to improve dielectric performance [1-3].

Despite these efforts, flashover behavior remains sensitive to gas inventory and operating pressure. Liu et al. showed that, beyond the above treatments, hot pressing and solvent casting applied to PEI (polyetherimide) can intentionally vary the amount of gas desorbed from the dielectric, enabling analysis of breakdown-voltage dependence on pressure[4]. In parallel, Schnyder et al. measured breakdown voltages as a function of pressure for different gas species, underscoring the role of the gaseous environment [5]. In this study, we developed an apparatus capable of measuring breakdown voltage by air pressure. And we investigated the pressure dependence of the surface-flashover voltage of PEEK and MC901 insulators.

2. Experimental Setup

This section describes the DC surface flashover chamber design and method to derive flashover voltage depending on gas pressure.

2.1 DC surface flashover chamber design

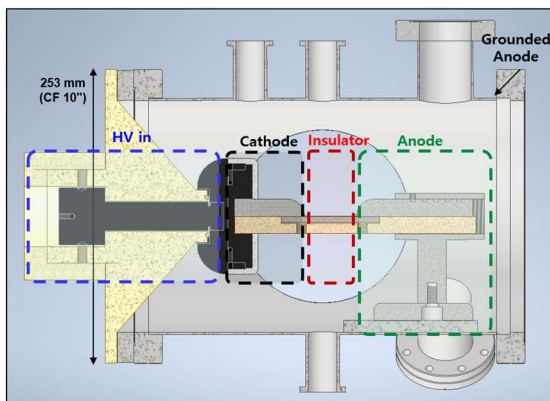


Fig. 1. Schematic diagram of Vacuum chamber

Figure 1 illustrates the structure of the vacuum chamber used for DC surface flashover experiments. The HV in feedthrough supplies high voltage from the power source, passes through the cathode-insulator-anode stack, and returns to the chamber wall at ground potential. Because the wall is grounded, a conical insulator was installed to prevent contact with the HV feedthrough and to increase creepage distance.

The electrodes use a finger type geometry. The cathode has a dome in contact with the finger, and the dome exterior is anodized aluminum. The finger has a curvature radius of 15 mm and is made of 304 stainless steel. The anode can move forward and backward, and the cathode-insulator-anode assembly is rotatable, which facilitates imaging from multiple viewing angles and enables 3D reconstruction from conventional 2D images. The gap between the electrodes was set to 2.5 mm, and PEEK and MC901 were used as the insulating materials.

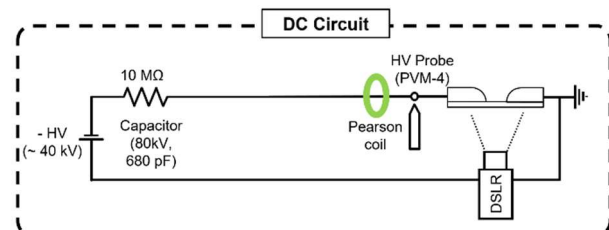


Fig. 2. Schematic of DC power circuit

Figure 2 shows the DC voltage application circuit connected to the vacuum chamber. We used a -40 kV power supply, while voltage and current were measured with a PVM-4 and a Pearson coil. The bandwidth of both instruments was about 140 MHz. For imaging, a DSLR camera was used with ISO 200 and an exposure time of 10 s.

2.2 Method to derive flashover voltage depending on gas pressure

We determined the flashover voltage as a function of pressure by sweeping from high vacuum (1×10^{-5} Torr) to atmospheric pressure (7.6×10^2 Torr) and partitioning the range into 23 set points. At each pressure, we recorded ten flashover voltages while alternating the sweep direction between descending (atmosphere to high vacuum) and ascending (high vacuum to atmosphere). The interval between successive shots was approximately 1 min, which was sufficient for

stabilization of gas desorbed from the insulator and of the surrounding ambient gas.

Breakdown voltages were extracted using a two-parameter Weibull analysis. The cumulative distribution is given by $F(V; \alpha, \beta) = 1 - \exp[-(\frac{V}{\alpha})^\beta]$, where α (kV) is the scale parameter corresponding to the 63.2% quantile, and β is the shape parameter that reflects the spread of the data. Linearization yields $Y = \ln[-\ln(1 - F)] = \beta X - \beta \ln \alpha$ with $X = \ln V$; this Y value is used on the Weibull probability axis.

3. Results & Discussion

3.1 Flashover voltage according to pressure

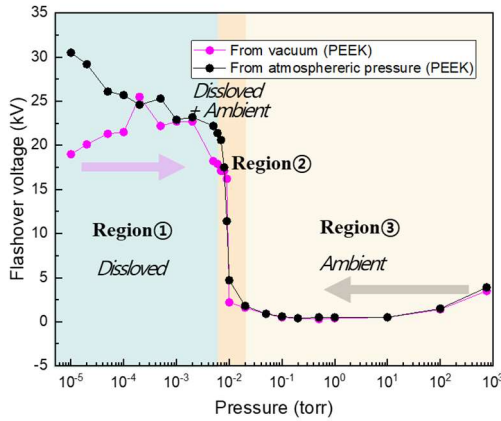


Fig. 3. Flashover voltage of PEEK depending on gas pressure

Figure 3 shows the flashover voltage of the PEEK insulator as a function of pressure. The pressure range is divided into three regions. Region 1 (1×10^{-5} – 5×10^{-2} Torr) exhibits relatively high breakdown voltages. Region 2 is near 1×10^{-2} Torr, where the breakdown voltage drops rapidly as pressure increases. Region 3 (2×10^{-2} – 7.6×10^2 Torr) exhibits relatively low breakdown voltages. Hysteresis is observed in Region 1, whereas Regions 2 and 3 seems like Paschen curve.

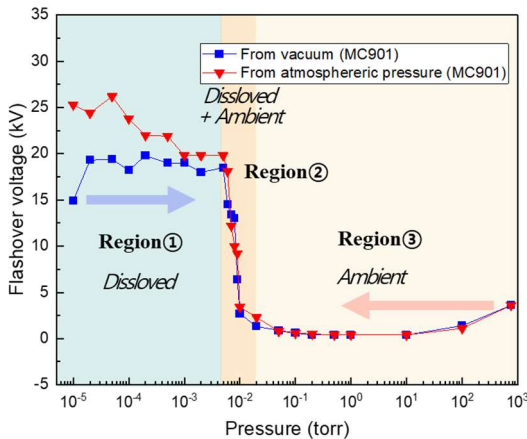


Fig. 4. Flashover voltage of MC901 depending on gas pressure

Figure 4 shows that MC901 exhibits an overall profile similar to that of PEEK. From the two datasets, we find that, in high vacuum, the breakdown voltage for a given insulator depends on the sweep direction. When sweeping from high vacuum to atmosphere, the breakdown voltage increases slightly as the pressure rises from 1×10^{-5} to 2×10^{-5} Torr, then remains approximately constant with further increases. In contrast, when sweeping from atmosphere to high vacuum, the breakdown voltage in Region 1 increases as the pressure decreases. Near the transition from Region 2 to Region 1, the flashover voltage increases by up to approximately 30%, which we attribute to dielectric conditioning. Regions 2 and 3 exhibit broadly similar breakdown voltages regardless of sweep direction. Prior studies indicate that Region 1 is dominated by dissolved gas, Region 2 by a coexistence of dissolved and ambient gases, and Region 3 by ambient gas; together, these observations suggest that the conditioning effect is governed primarily by dissolved gas. Furthermore, because Regions 2 and 3 show a trend consistent with the Paschen curve, the dominant mechanism in these regions is gas breakdown rather than vacuum breakdown.

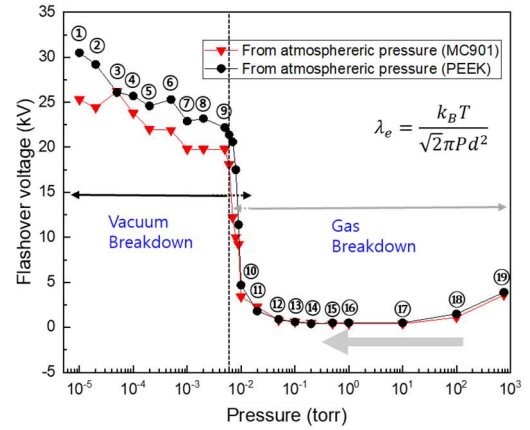


Fig. 5. Flashover voltage of MC, PEEK depending on gas pressure

Figure 5 shows an overlay of the breakdown voltages for PEEK and MC901 during a pressure sweep from atmospheric pressure to high vacuum. As noted above, the transition points between regions are nearly identical and the overall profiles are similar. To examine the discharge behavior at each labeled point in greater detail, the corresponding images are provided below.

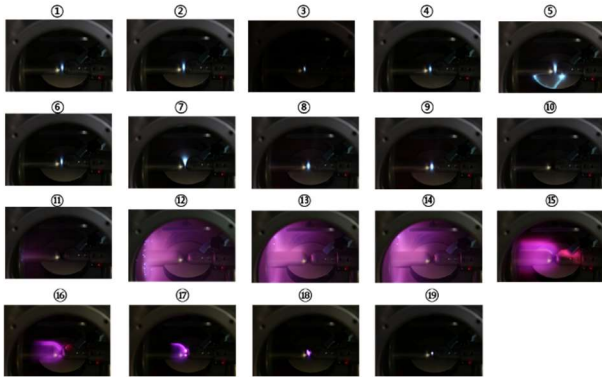


Fig. 6. Flashover image of PEEK depending on gas pressure

We observed that points 1–9 correspond to discharges occurs along with insulator surface. Beginning at point 10, the discharge no longer follows the surface; instead, it bridges between the cathode dome and the anode shown in Figure 1. This transition indicates that around point 9 the discharge enters the gas-breakdown regime, consistent with the left branch of the Paschen curve. With pressure fixed, increasing the effective discharge distance moves the operating point toward the Paschen minimum. As a result, breakdown between the dome cathode and the anode becomes more favorable than along the finger. Point 13 corresponds to the Paschen minimum. From point 14 onward, the behavior follows the right branch, and the discharge path shortens. As pressure increases, the electron mean free path decreases and the plasma contracts spatially. At atmospheric pressure, the discharge again appears along the insulator surface.

4. Conclusions

In this study, a DC surface flashover device was developed and the flashover voltage by air pressure was measured from 1×10^{-5} to 7.6×10^2 torr. The discharge voltage according to the pressure was largely divided into three areas: Region 1, in which a relatively high discharge voltage, conditioning and hysteresis are observed in a high vacuum, Region 2, in which gas breakdown begins with a sharp drop in discharge voltage, and Region 3, in which gas discharge is dominant. If the pressure control order was changed, the flashover voltage in Region 1 was changed, and the conditioning effect was up to 30%. The imaging results show that as the pressure increases, a flow discharge between the cathode and the anode of the discharge path appears between the finger type electrodes, and then returns to the discharge between the finger type electrodes. This supports that it is consistent with Paschen curve.

Acknowledgements

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REFERENCES

- [1] I. I. Kalyatskii and G. M. Kassirov, "An Investigation of Pulse Flashover of Some Solid Dielectrics in Vacuum", *Sov. Phys. Tech. Phys.*, Vol. 9, pp. 1137–1140, (1964).
- [2] M. Mounho, C. Fuksa, R. Clark et al., "Statistical characterization of high voltage vacuum surface flashover with gapped and ungapped anodes," *Phys. Plasmas* 31, 080701 (2024).
- [3] Y. Ohki and K. Yahagi, "Temperature Dependence of Surface Flashover Voltage of Polyethylene in Vacuum", *J. Appl. Phys.*, Vol. 46, pp. 3695–3696 (1975).
- [4] Zeng, Jiakai, et al. "Diverse effects of gases on surface flashover in a wide pressure range from atmospheric to near vacuum pressure." *Journal of Applied Physics* 132 (2022).
- [5] Schnyder, R., A. A. Howling, D. Bommottet, and Ch. Hollenstein. "Direct current breakdown in gases for complex geometries from high vacuum to atmospheric pressure." *Journal of Physics D: Applied Physics* 46 (2013).