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Integrated Experimental and Simulation Investigation of Breakdown Voltage Characteristics Across Electrode Configurations in SF_6 Circuit Breakers

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Abstract: This study investigates the breakdown voltage characteristics in sulfur hexafluoride (SF_6) circuit breakers, employing a novel approach that integrates both experimental investigations and finite element simulations. Utilizing a sphere-sphere electrode configuration, we meticulously measured the relationship between breakdown voltage and electrode gap distances ranging from 1 cm to 4.5 cm. Subsequent simulations, conducted using COMSOL Multiphysics, mirrored the experimental setup to validate the model's accuracy through a comparison of the breakdown voltage-electrode gap distance curves. The simulation results not only aligned closely with the experimental data but also allowed the extraction of detailed electric field strength, electric potential contours, and electric current flow curves at the breakdown voltage for gap distances extending from 1 to 4.5 cm. Extending the analysis, the study explored the electric field and potential distribution at a constant voltage of 72.5 kV for gap distances between 1 to 10 cm, identifying the maximum electric field strength. A comprehensive comparison of five different electrode configurations (sphere-sphere, sphere-rod, sphere-plane, rod-plane, rod-rod) at 72.5 kV and a gap distance of 1.84 cm underscored the significant influence of electrode geometry on the breakdown process. Moreover, the research contrasts the breakdown voltage in SF_6 with that in air, emphasizing SF_6's superior insulating properties. This investigation not only elucidates the intricate dynamics of electrical breakdown in SF_6 circuit breakers but also contributes valuable insights into the optimal electrode configurations and the potential for alternative insulating gases, steering future advancements in high-voltage circuit breaker technology.

Keywords: SF_6 circuit breaker; Breakdown voltage; Electrode configurations; COMSOL simulation; Electrical insulation

1. Introduction

Sulfur hexafluoride (SF_6) is widely used in high-voltage circuit breakers due to its superior insulating and arc-quenching properties. This literature review focuses on the breakdown voltage characteristics of SF_6

circuit breakers, integrating experimental and simulation studies to explore the impact of different electrode configurations and gap distances.

Extensive experimental studies have been conducted to understand the dielectric breakdown of SF_6 under various conditions. Lin *et al.* demonstrated the dynamic dielectric strength of mixed gases, showing SF_6's robustness under different electrical stresses [1,2]. Experimental setups often vary electrode gap distances and configurations to measure breakdown voltages accurately, providing critical insights into SF_6's behavior under high voltage conditions. Jiang *et al.* analyzed dielectric breakdown properties for different electrode configurations and gap distances, revealing the crucial role of electrode shape and spacing in determining breakdown voltage [3]. Additionally, studies have examined the performance of SF_6 mixtures, such as sulfur hexafluoride and nitrogen (SF_6-N_2) and sulfur hexafluoride and carbon dioxide (SF_6-CO_2), under various voltage conditions, further illustrating SF_6's effectiveness as an insulating gas. The effectiveness of SF_6 in maintaining high breakdown voltages compared to air and other gases has also been highlighted in studies by Guo *et al.* and Xiao *et al.* [4,5].

Simulations using software like COMSOL Multiphysics have become indispensable for predicting the breakdown voltage characteristics of SF_6 circuit breakers. Ou *et al.* utilized numerical simulations to explore the development of streamer discharge in SF_6, providing detailed electric field distributions and potential contours that closely align with experimental results [2]. Such simulations validate experimental findings, ensuring data reliability and accuracy.

The configuration of electrodes significantly influences the breakdown voltage in SF_6 circuit breakers. Different geometries, such as sphere-sphere, sphere-rod, and rod-rod, exhibit distinct breakdown characteristics. Studies by Okubo *et al.* and Xiao *et al.* have shown that electrode shape and spacing critically impact the breakdown voltage, with sphere-sphere configurations often providing the highest breakdown voltages due to uniform electric field distribution [6,7]. Further investigations by Geng *et al.* and Liu *et al.* have explored the effects of various electrode configurations on the electric field distribution and breakdown voltage, contributing to the optimization of circuit breaker designs [8,9].

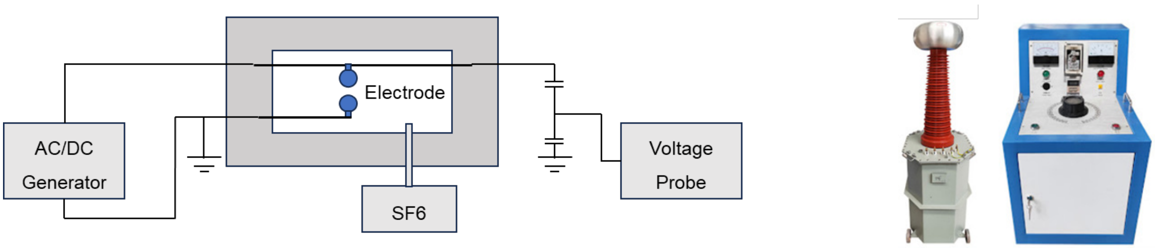
In addition to SF_6, researchers have investigated the breakdown voltage characteristics of alternative insulating gases. For example, the arc interruption performance of CO_2 and the use of SF_6-N_2 mixtures have been explored as potential substitutes for SF_6. Guo *et al.* highlighted CO_2's potential as a viable alternative, while other studies by Krämer *et al.* and Ito *et al.* emphasized the environmental benefits of mixed gases without compromising performance [4,10,11]. Environmental considerations have driven research into eco-friendly alternatives like green gas for grid (g^3), which offers equivalent dielectric strength to SF_6 while significantly reducing environmental impact. Studies by Zhou *et al.* have supported the viability of these alternatives in high-voltage applications [12]. SF_6 is a potent greenhouse gas, and its environmental impact has led to research into more sustainable alternatives. Studies by Kapetanovic and Jia *et al.* have examined the use of SF_6-N_2 and SF_6-CO_2 mixtures, which offer reduced environmental impact while maintaining high-insulating properties [13,14]. The push for greener alternatives is driving innovations in gas insulation technology, balancing performance with environmental sustainability.

This paper advances prior research to deepen understanding of SF_6 gas dielectric breakdown in high-voltage applications, particularly under non-homogeneous fields and varying gaps. Through experiments and simulations using COMSOL Multiphysics, this study explores SF_6's breakdown characteristics, focusing on electrode geometry and gap distances, and demonstrates its superior insulation properties compared to air. The research, utilizing sphere-sphere electrode configurations and varying gap distances, highlights the impact of electrode geometry on breakdown and the superior insulation of SF_6.

2. Methodology

2.1. Experiment

In the experimental setup illustrated in **Figure 1**, a sphere-sphere electrode configuration was placed within a sealed chamber filled with SF_6 gas, sourced from an SF_6 gas pump. This configuration was then connected to an alternating current/direct current (AC/DC) generator to facilitate the application of electrical potential across the electrodes. The differential in electric potential between the two electrodes was meticulously recorded using a voltage probe. The testing apparatus, depicted in **Figure 1(b)**, was acquired from Hezhong Electric Equipment, capable of generating voltages up to 150 kV at power frequency. For this experiment, the SF_6 gas was maintained at a pressure of 0.15 MPa. Both sphere electrodes, utilized in the setup, boasted a diameter of 4 cm, ensuring uniformity in the experimental conditions.

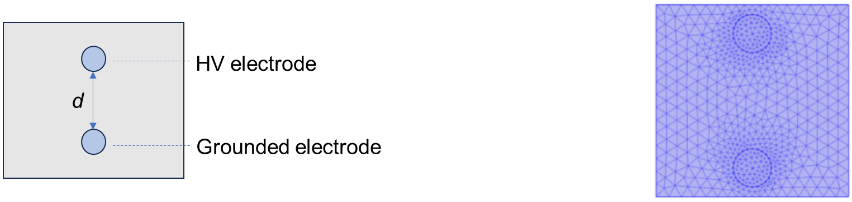


(a) (b)

Figure 1. (a) A schematic drawing of the schematic experiment setup (b) Test machine

2.2. Simulation

To complement the experimental investigation, a detailed finite element simulation was conducted using COMSOL Multiphysics software. The simulation began with the creation of a two-dimensional model representing the sphere-sphere electrode configuration within a chamber filled with SF_6 gas, as shown in **Figure 2**. The geometrical dimensions, including the 4 cm diameter of the sphere electrodes and the variable gap distances ranging from 1 cm to 4.5 cm, were precisely replicated as per the experimental design. The geometry domain was discretized using a triangular mesh to ensure detailed and accurate representation of the geometry for the finite element analysis.



(a) (b)

Figure 2. (a) The two-dimensional geometry model created in COMSOL Multiphysics (b) The finite element model

To thoroughly investigate the impact of electrode configurations on electric breakdown, the simulation extended to include various electrode setups: sphere-sphere, rod-rod, sphere-rod, rod-plane, and sphere-plane as shown in **Figure 3**.

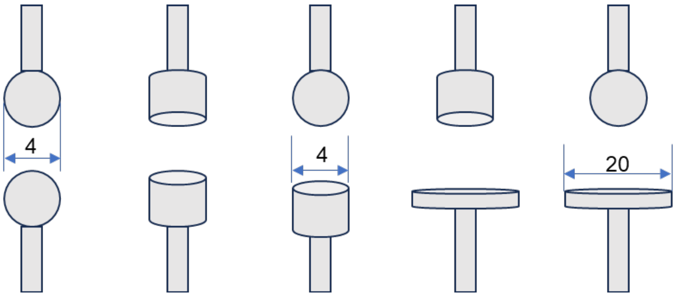


Figure 3. A schematic drawing of different electrode configurations: sphere-sphere, rod-rod, sphere-rod, rod-plane, and sphere-plane

The electrical properties of the materials were crucial for accurate simulation. Specifically, the relative permittivity (dielectric constant) of SF_6 was set to 1.002, and for air, it was set at 1, with the breakdown electric field strength in SF_6 considered to be 89 kV/cm, and in air, 30 kV/cm. The AC/DC module of COMSOL Multiphysics was utilized to simulate the electric field distribution, potential difference, and current flow within the setup for the range of electrode gap distances and configurations. Incremental application of potential difference across the electrodes was performed until electric breakdown was observed in the model. The simulation's scope included analyzing electric field strength, potential contours, and current flow paths at critical points leading to breakdown, especially at a constant voltage of 72.5 kV and varying electrode gap distances up to 10 cm.

3. Results

The primary objective of our research was to compare the breakdown voltage in an SF_6 circuit breaker as a function of the electrode gap distance, using both experimental methods and finite element simulation. The experimentally measured and simulated breakdown voltages across electrode gap distances ranging from 1 cm to 4.5 cm are presented in **Figure 4**.

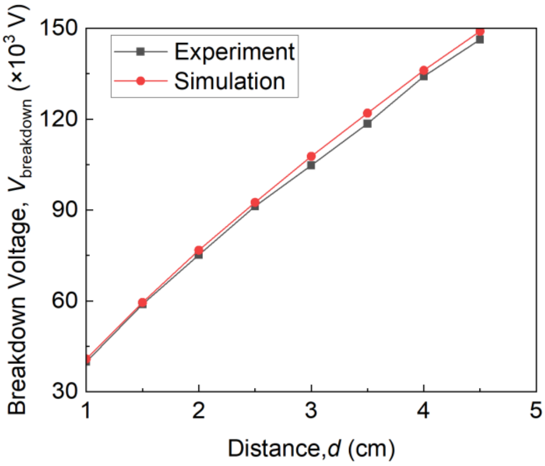
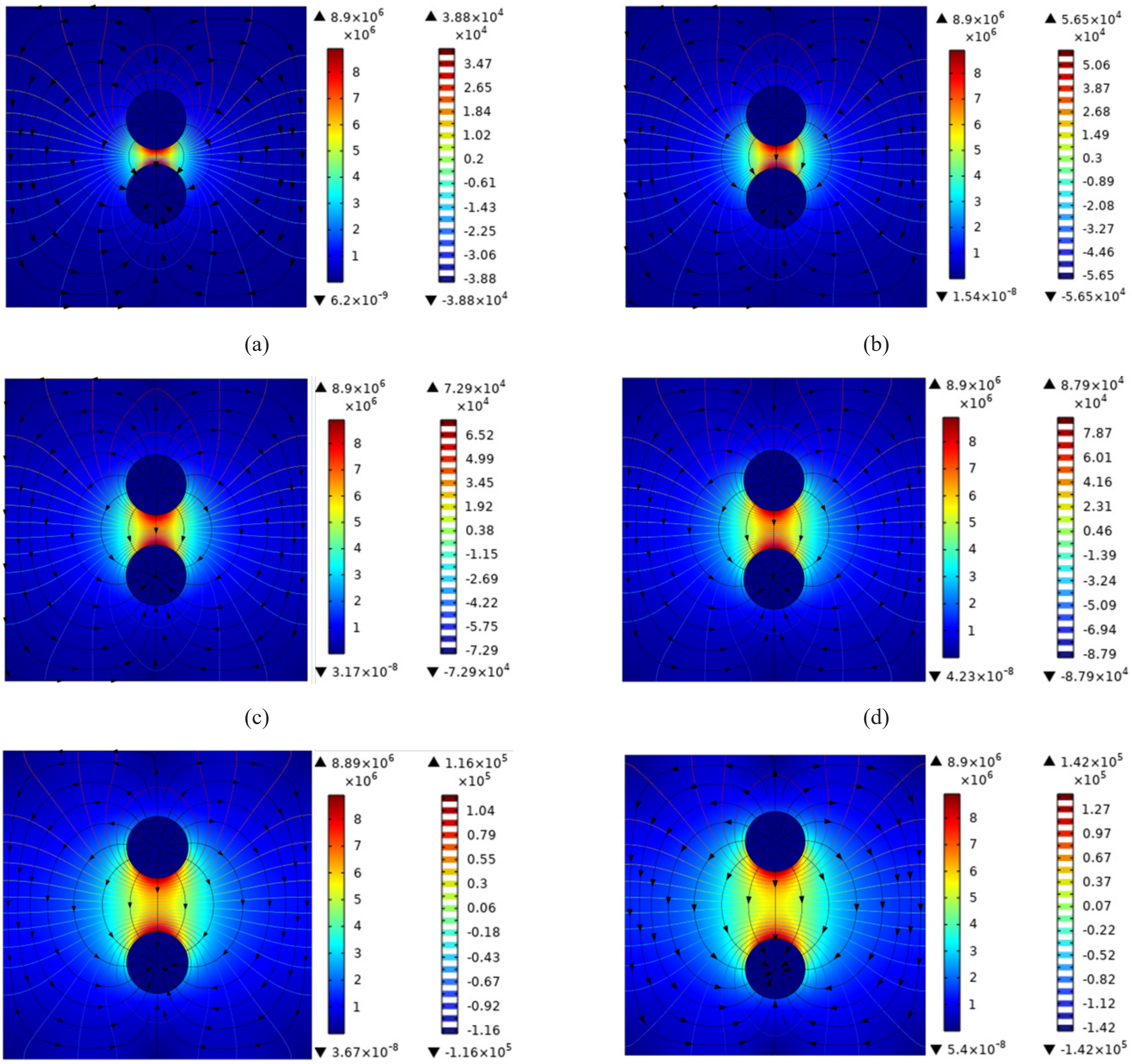


Figure 4. The breakdown voltage of sphere-sphere configuration in SF_6 circuit breaker from experiment and simulation

The experimental data showed a clear linear correlation between the breakdown voltage and the electrode gap distance, confirming classical Paschen's Law. The breakdown voltage increased from 39.8 kV at a 1 cm gap to 146 kV at 4.5 cm. Similarly, COMSOL Multiphysics simulations closely matched the experimental data, with breakdown voltages ranging from 40.8 kV at 1 cm to 149 kV at 4.5 cm. The strong agreement between the experimental and simulated data validates the simulation model as a reliable predictive tool for electrical breakdown in SF_6 circuit breakers. **Figure 5** illustrates these simulations, showing changes in electric field strength, potential, and current flow at gap distances from 1 to 4.5 cm.



(a) (b)

(c) (d)

(e) (f)

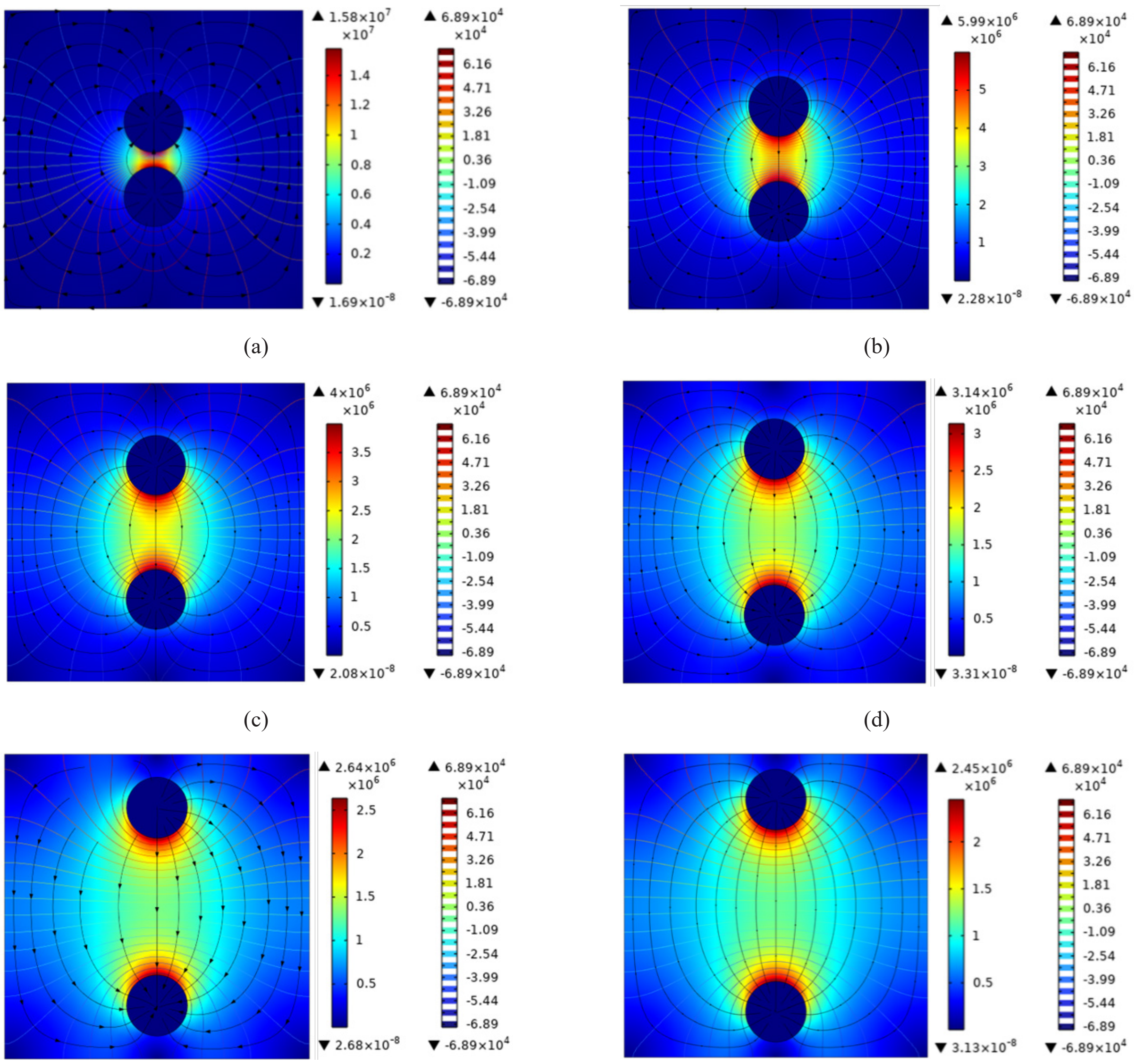
Figure 5. The electric field strength, potential distribution, and current flow within a sphere-sphere electrode setup in an SF_6 circuit breaker environment at varying gap distances of (a) 1 cm (b) 1.5 cm (c) 2 cm (d) 2.5 cm (e) 3.5 cm (f) 4.5 cm

At a 1 cm gap distance, the electric field strength is highly concentrated between the electrodes, with a rapid decrease outward, and the potential distribution is relatively uniform, directing most current flow directly between the electrodes. As the gap increases to 1.5 cm and 2 cm, the electric field spreads wider, the potential gradient becomes more pronounced, and current dispersion slightly increases. At 2.5 cm, the electric field spreads further and less intensely between the electrodes, with a steeper potential gradient and more dispersed current flow. At 3.5 cm and 4.5 cm, the electric field distribution broadens and intensifies less between electrodes, with a significant gradient in potential and widespread current flow, showing a transition from a concentrated to a more evenly distributed electric field as the gap widens.

4. Discussion

4.1. Electric field strength with gap distance

Figure 6 illustrates the electric field intensity, potential distribution, and current flow patterns at a fixed voltage of 72.5 kV for various electrode gap distances in an SF_6 circuit breaker model.



(a) (b)

(c) (d)

(e) (f)

Figure 6. The electric field strength, potential distribution, and current flow within a sphere-sphere electrode setup at a fixed voltage of 72.5 kV for different electrode gap distances in an SF_6 circuit breaker model at (a) 1 cm (b) 3 cm (c) 5 cm (d) 7 cm (e) 9 cm (f) 10 cm

Figure 6 shows the electric field at a 1 cm gap displaying peak concentration between the electrodes, with a steep potential gradient and densely packed current flow lines, indicating a strong localized field conducive to breakdown. As gaps increase to 3 cm and 5 cm, the electric field spreads more evenly, with a less steep potential and broader current distribution. At gaps of 7 cm and 9 cm, the field's intensity and the potential gradient decrease, with current flow covering a wider area, reducing localized breakdown likelihood. At a 10 cm gap, shows the most distributed electric field, the flattest potential gradient, and the most dispersed current flow, indicating the lowest electric stress and breakdown propensity. The trend shows that as gap distance increases, electric field distribution becomes more even, potential gradients flatten, and current flow extends across a broader area.

Figure 7 illustrates the variation in maximum electric field strength as the electrode gap distance is increased from 1 to 10 cm.

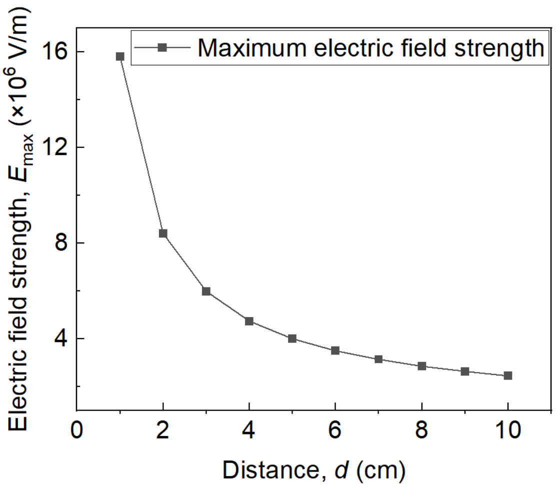


Figure 7. The variation in maximum electric field strength as the electrode gap distance increased from 1 to 10 cm

Figure 7 illustrates the variation in maximum electric field strength (E_{max}) as a function of the electrode gap distance (d) in SF_6 circuit breakers. The relationship is an inverse correlation, where the maximum electric field strength decreases as the electrode gap distance increases from 1 cm to 10 cm. This trend indicates the classical behavior described by Paschen's Law, which states that the breakdown voltage is a function of the product of pressure and gap distance.

At smaller gap distances (1–2 cm), the electric field strength is significantly high, reaching up to 16×10^6 V/m at a 1 cm gap. This high electric field strength is due to the concentrated potential difference over a small distance, resulting in a stronger field. As the gap distance increases, the electric field strength diminishes, decreasing sharply initially and then more gradually. By 10 cm, the electric field strength reduces to approximately 2×10^6 V/m. This reduction is due to the dispersion of the electric field over a larger distance, leading to a less intense field between the electrodes.

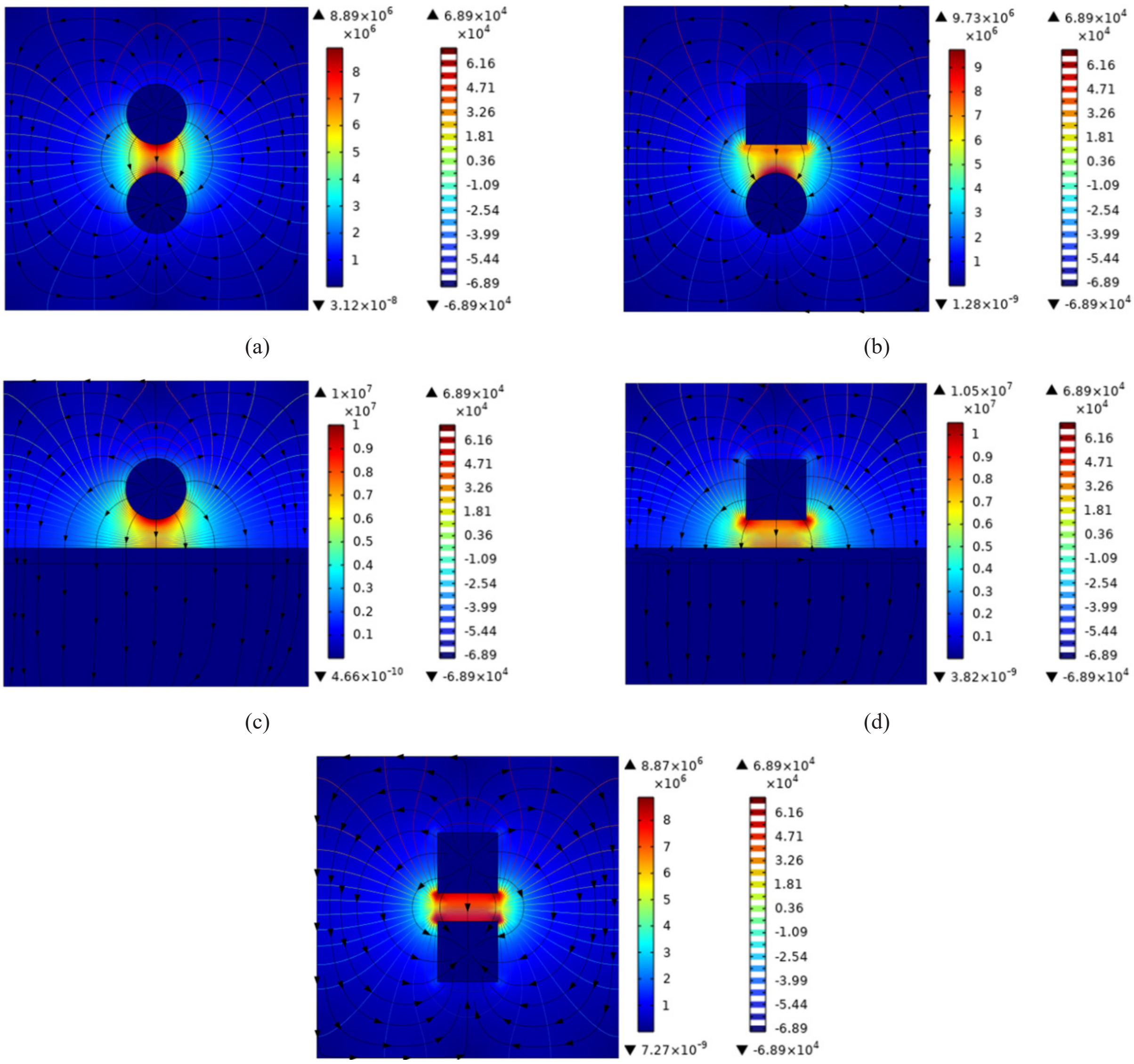
4.2. Electric field strength with different configurations

Figure 8 depicts the simulation results for the electric field intensity, potential distribution, and current flow patterns at a critical voltage of 72.5 kV and a gap distance of 1.84 cm, which has been identified as the critical distance for electric breakdown in a sphere-sphere electrode configuration within an SF_6 environment.

Figure 8 illustrates various electrode configurations and their impact on electric field strength. In the sphere-sphere setup, the maximum field strength is 89 kV/cm, with a symmetrical, high-intensity distribution between the electrodes. The sphere-rod configuration shows a higher field strength of 97.3 kV/cm, intensified at the rod's tip, indicating a greater breakdown risk there. The sphere-plane disperses the field more, with a strength of 88.7 kV/cm, and a wider current spread reducing electrical stress. The rod-plane reaches the highest field strength at 105 kV/cm due to intense concentration at the rod's tip. Lastly, the rod-rod records a strength of 100 kV/cm, with a symmetric but intense field between the rods, underscoring the effect of electrode shape on field dynamics.

The result shows that electric field strength varies greatly with electrode shape, particularly at a critical

1.84 cm gap under 72.5 kV in an SF_6 environment. The rod-plane configuration, with the highest field strength of 105 kV/cm, is most susceptible to breakdown due to intense field concentration at the rod's tip. Conversely, the sphere-plane and sphere-sphere configurations show lower strengths around 88.7 kV/cm, indicating greater resistance to breakdown compared to other configurations.



(a) (b) (c) (d) (e)

Figure 8. Simulation results for the electric field intensity, potential distribution, and current flow patterns at a critical voltage of 72.5 kV and a gap distance of 1.84 cm

4.3. Breakdown voltage with insulating gas

Figure 9 presents a comparative analysis of the breakdown voltage as a function of the electrode gap distance in two different gaseous environments: sulfur hexafluoride (SF_6) and air.

For SF_6, the breakdown voltage linearly increases from approximately 40.8 kV at a 1 cm gap to 149 kV at a 4.5 cm gap, highlighting its robust insulating properties and high dielectric strength. In contrast, air shows a much lower and flatter breakdown voltage curve, starting from 13.8 kV at a 1 cm gap and only reaching about 50.2 kV at 4.5 cm, indicating its lesser insulating effectiveness. The significant disparity between SF_6 and air in these tests underscores SF_6's superiority as an insulator in high-voltage applications, essential for maintaining electrical integrity over various gap distances.

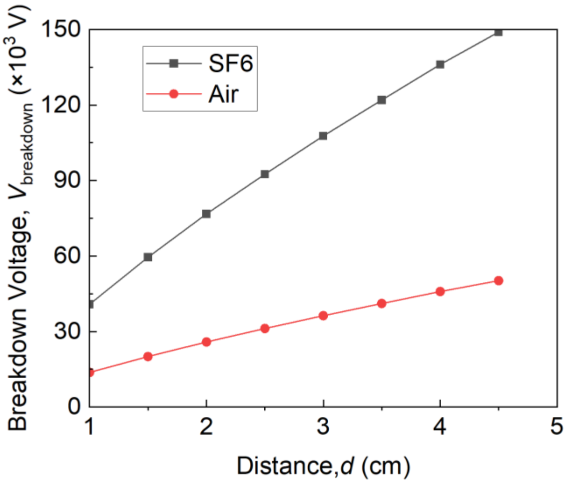


Figure 9. The breakdown voltage changes with the electrode gap distance in sulfur SF_6 and air environment

5. Conclusion

This comprehensive study, through experimental analysis and finite element simulation, has confirmed the linear relationship between breakdown voltage and electrode gap distance in SF_6 circuit breakers, aligning with Paschen's Law. The close match between experimental and simulated data validates our finite element model for predicting electrical breakdown. We found that electrode configuration significantly affects electric field distribution; the rod-plane setup was most prone to breakdown, while the sphere-plane showed the greatest resistance. The study highlights SF_6's superiority over air as an insulating medium, emphasizing the critical role of electrode geometry in the design and performance of high-voltage circuit breakers. This research enhances our understanding of electric breakdown in SF_6 systems and underscores the importance of electrode design in optimizing high-voltage electrical infrastructure.

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Disclosure statement

The authors declare no conflict of interest.

Author contributions

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Writing: Bo Guan

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