Breakdown Characteristic of N\textsubscript{2}-CO\textsubscript{2} Gas Mixtures under AC and DC Test Voltages

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Abstract. This study provides fundamental knowledge on the breakdown properties of N\textsubscript{2}-CO\textsubscript{2} gas mixture with a ratio of 20:80, 50:50, and 80:20. The gas mixtures were tested under HVAC and HVDC voltages with 1 bar (abs) pressure. The plane-plane and needle-plane electrodes were used with gap lengths between 0.5 cm to 2.5 cm. It is found that the breakdown voltage of N\textsubscript{2}-CO\textsubscript{2} mixture increased with the increased of CO\textsubscript{2} content. The breakdown voltage is also affected by the increment of gap distance for both electrode geometrics; plane-plane to represent the uniform field and needle-plane as the non-uniform field. The gas under uniform field configuration has a higher ability to withstand higher voltage levels compared under non-uniform field configuration. However, the non-uniform field provides a very high electric field intensity, which implies very high electric field stress. By increasing the percentage CO\textsubscript{2} in N\textsubscript{2}-CO\textsubscript{2} mixture, the insulation strength can reach about 64% that of pure SF\textsubscript{6} gas at the 0.1 MPa.

1. Introduction
In 1997, six kinds of gases including sulphur hexafluoride (SF\textsubscript{6}) were labelled as a potent greenhouse gas by the Kyoto Protocol during the United Nations Framework Convention on Climate Change (UNFCCC) [1],[2]. However, the usage of the SF\textsubscript{6} gas is widely used without any limitation due to the strong economic implication worldwide. The effect of the longtime excessive usage, for example in 100 years, may increase the percentage of global warming of SF\textsubscript{6}. Therefore, it is demanded that developed countries should limit the industrial application of SF\textsubscript{6}, or completely stop its usage by 2020 [3],[4].

Many researchers have investigated alternative gases to replace SF\textsubscript{6}, but till now any of the gases could not entirely substitute SF\textsubscript{6}. Conventional or natural gases, mainly refer to the nitrogen (N\textsubscript{2}), carbon dioxide (CO\textsubscript{2}), and air can be the main alternative gases [5]. Although the dielectric strength of these gases is far less than SF\textsubscript{6}, they can fundamentally solve the greenhouse effect without compromising the good qualities of pure SF\textsubscript{6} [6],[7]. Since the conventional gases are significantly weaker in dielectric properties, efforts have been made to enhance the dielectric strength through an admixture.

Previous studies have shown that the CO\textsubscript{2} mixed with air give the highest dielectric strength compared with other natural gas admixtures. It is due to the influence of nitrogen in air [8]. To accurately obtain the dielectric strength of the conventional gas mixtures, this study focused on the breakdown characteristics of N\textsubscript{2}-CO\textsubscript{2} under HVAC and HVDC test voltages. The insulation properties of the gas mixture were analysed under various electric field arrangement and gap distance.
2. Experimental Setup
This section shows some of the experimental setup used for the laboratory works.

2.1. HVAC and HVDC Test Setup
The single-phase test transformer operated at 50 Hz with coupling winding for cascade connection is used to produce HVAC. The test transformer provides a maximum voltage of 100 kV (rms), and the capacitance of the capacitor divider for measurement of AC voltage is 100 pF.

The silicon-type rectifiers consist of 100 kΩ protective resistor and 25 nF smoothing capacitor were used to generate HVDC test voltage. The smoothed DC voltage was then be measured by voltage division in measuring resistor.

2.2. Pressure Vessel
The gas mixtures were tested inside a pressure vessel made of Plexiglas. Figure 1 shows the structure of the pressure vessel used for the testing. The height of the vessel from the floor is approximately 800 mm with a radius of 90 mm, and the thickness of the vessel wall is 5 mm.

A linear actuator has been attached inside the vessel for varying the gap length between the high voltage electrode and the ground electrode.

2.3. Electrode Configurations
There are two main electrode configurations used in this study, which are plane-plane and needle-plane. The plane electrode has a diameter of 90 mm, and the needle electrode has a 45° angle with the edge radius of 0.5 mm. Figure 2 shows the dimensions of a needle-plane electrode configuration.

All the electrodes used are made of aluminium. The high voltage electrodes are stationary; while the ground electrodes are vertically moveable in the range of 5 to 25 mm using a linear actuator.

Figure 1. Pressure vessel.  
Figure 2. Needle-plane electrode configuration.
3. Results and Discussion
The results demonstrate the breakdown voltage for both plane-plane and needle-plane configurations under HVAC and HVDC voltages. It is observed by varying the gap distance at various mixture ratios. The influence of electric field uniformity on the breakdown characteristic of N$_2$-CO$_2$ mixtures also been discussed in this section.

3.1. Breakdown Characteristics of N$_2$-CO$_2$ mixture
Figure 3(a) and Figure 3(b) show the breakdown characteristics for the plane-plane and the needle-plane configurations, respectively. The figures consist of breakdown voltage under HVAC and HVDC with different gap distance for a various ratio of N$_2$-CO$_2$ gas at 1 bar (abs) pressure.

By observing the result, the breakdown voltages increased with the increment of the gap length. It is obvious that the gas has a higher ability to withstand high voltage under plane-plane electrodes compared to the needle-plane electrode for both test conditions. The AC breakdown performance of 20%N$_2$ + 80%CO$_2$ in plane-plane configuration has a higher value of 32.6% compared to the needle-plane at 1 cm gap distance. However, as the gap length increased to 2.5 cm, the breakdown voltages at all N$_2$-CO$_2$ mixture ratio give the same values in the plane-plane electrode. In the case of needle-plane...
Figure 3. Breakdown characteristics of various N$_2$-CO$_2$ ratios under (a) HVAC, and (b) HVDC tests. The electrode, the breakdown voltage at 20%N$_2$ + 80%CO$_2$ showed a linear increment as the gap length increases above 1.5 cm. Therefore, the effect of the gap distance of an electrode is more significant by using higher concentration of CO$_2$ in N$_2$-CO$_2$ mixture. The growth trend of breakdown values for 50:50 and 80:20 ratio of N$_2$-CO$_2$ mixtures was similar, especially under AC test voltages.

To further investigate the performance of N$_2$-CO$_2$ gas mixture, the mixing ratio of each gas was varied. The effect of CO$_2$ content in N$_2$-CO$_2$ gas mixture at 1 cm gap under HVAC and HVDC test voltages are shown in Figure 4. The highest breakdown value is noticeable in the gas mixture consists of 80%CO$_2$ compared to the other mixture ratio, particularly under the uniform gap configuration. It provides the dielectric strength of 1.6 times compared to N$_2$ or CO$_2$ as a single gas and can reach to 64% when compared to SF$_6$. However, there is a less significant difference in the breakdown voltage at 50:50 mixture ratio due to the same dielectric properties of N$_2$ or CO$_2$ as a single gas.

![Figure 4: Effect of CO$_2$ concentration in N$_2$-CO$_2$ mixtures under HVAC and HVDC test.](image)

3.2. Electric Field Uniformity on Breakdown Characteristics of N$_2$-CO$_2$ mixture

In this section, the behaviour of the electric field was analysed using FEMM, a finite element analysis software. The data from the experimental tests was applied to obtain the maximum electric field (E$_{max}$) against various gap distances. Thus, the electric field utilisation factor (η) can be calculated for both plane-plane and needle-plane electrode configurations.

Figure 5 shows an example of the location of E$_{max}$ for 1 cm gap under HVAC test at 50:50 mixture ratio. As expected, the high field stress was identified along the edge of the high voltage electrode.

![Figure 5: E$_{max}$ for N$_2$-CO$_2$ (50:50) mixture at 1 cm gap for (a) plane-plane, and (b) needle-plane configuration under HVAC test.](image)
with the red color region. The $E_{\text{max}}$ for plane-plane configuration is significantly lower than the needle-plane electrode. The value of $E_{\text{max}}$ for the plane-plane electrode in Figure 5(a) is 73.97 kV/cm while for the needle-plane electrode is 158.40 kV/cm as in Figure 5(b).

Figure 6 shows the $E_{\text{max}}$ curve for both electrode arrangements with three different ratios under HVAC and HVDC tests, respectively. By comparing the $E_{\text{max}}$ for both electrode configuration, needle-plane configuration has the highest value of $E_{\text{max}}$ with the lowest breakdown values. This is due to the sharp edge of the needle electrode. The $E_{\text{max}}$ value for plane-plane configuration at 20:80 under HVAC test voltage is about 75.76 kV/cm, while the $E_{\text{max}}$ for needle-plane is 53% higher at about 159.80 kV/cm. The value of $E_{\text{max}}$ decrease with the increase in breakdown voltage. The simulation results also indicate that the maximum field strength decreased slightly with the increased of the electrode gap.

![Diagram](image)

(a)

![Diagram](image)

(b)

**Figure 6.** Maximum electric field of various $\text{N}_2$-$\text{CO}_2$ ratios under (a) HVAC, and (b) HVDC test.

The relationship between the $E_{\text{max}}$ and the electrical breakdown can define the uniformity of the electrode configuration between the high voltage electrode and the ground electrode. Table 1 shows
the field utilization factor (\( \eta \)) for 20:80 N\(_2\)-CO\(_2\) mixture. The electric field utilisation factor (\( \eta \)) can be defined as the ratio of the average electric field (\( E_{av} \)) to the maximum electric field (\( E_{max} \)) [9].

From Table 1, it can be observed the field utilization factor for plane-plane electrode is higher (Table 1(a)) than needle-plane electrode (Table 1(b)). Higher field utilization factor implies more uniform field configuration. In this case, electric field within plane-plane electrode is more uniform as compared to needle-plane electrode. As in Figure 3, higher content of CO\(_2\) in N\(_2\)-CO\(_2\) mixture provides better performance under non-uniform field configuration. However, Figure 7 shows that the uniformity of the plane-plane electrode reduced as the gap distance increased. It is due to the \( E_{max} \) occur on the curve edge of the plane electrode. Therefore, IEC used the sphere gap as the calibration device since it gives a more uniform field while maintained the linearity even increase the gap distance [10].

Table 1. Field utilisation factor (\( \eta \)) for 20:80 N\(_2\)-CO\(_2\) mixture in (a) plane-plane, and (b) needle-plane electrode under HVAC test.

(a)

| Gap distance (cm) | Breakdown voltage (kV) | \( E_{max} \) (kV/cm) | \( E_{ave} \) (kV/cm) | \( \eta = \frac{E_{ave}}{E_{max}} \) |
|------------------|-----------------------|------------------------|-----------------------|-------------------------------|
| 0.5              | 21.78                 | 80.82                  | 43.56                 | 0.54                          |
| 1.0              | 33.15                 | 75.76                  | 33.15                 | 0.44                          |
| 1.5              | 40.60                 | 70.44                  | 27.07                 | 0.38                          |
| 2.0              | 44.54                 | 63.88                  | 22.27                 | 0.35                          |
| 2.5              | 47.54                 | 58.36                  | 19.02                 | 0.33                          |

(b)

| Gap distance (cm) | Breakdown voltage (kV) | \( E_{max} \) (kV/cm) | \( E_{ave} \) (kV/cm) | \( \eta = \frac{E_{ave}}{E_{max}} \) |
|------------------|-----------------------|------------------------|-----------------------|-------------------------------|
| 0.5              | 15.66                 | 173.70                 | 31.32                 | 0.18                          |
| 1.0              | 22.36                 | 159.80                 | 22.36                 | 0.14                          |
| 1.5              | 24.38                 | 134.30                 | 16.25                 | 0.12                          |
| 2.0              | 32.14                 | 147.30                 | 16.07                 | 0.11                          |
| 2.5              | 41.45                 | 167.50                 | 16.58                 | 0.10                          |
4. Conclusion
Overall, the breakdown characteristics of N₂-CO₂ as a natural gas admixture has been studied in different field uniformities under AC and DC test voltages. The plane-plane electrode configuration was used to represent the more uniform field condition, while the needle-plane correspond to the non-uniform field. The gas pressure was fixed at 1 bar (abs), and the N₂-CO₂ gas was varied to three mixture ratio: 20:80, 50:50 and 80:20. Meanwhile, the effect of gap distance for the breakdown test was analysed in the range of 0.5 cm to 2.5 cm. From the results, it was found that by increasing the gap distance, the breakdown value will be increased. The AC and DC breakdown voltage of 20%N₂ + 80%CO₂ is higher than other mixture ratios, especially under plane-plane configuration. The insulation strength of 20%N₂ + 80%CO₂ (57.12 kV/cm) can reach about 64% of that pure SF₆ (89 kV/cm) at 0.1 MPa. On the other hand, the highest E_max was found in the needle-plane electrode with the lowest breakdown voltage. It also found that the highest field utilisation factor (η) implies more on uniform field electrode arrangement compared to the non-uniform field configuration.

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