ELECTRODE AREA EFFECTS OF ELECTRICAL BREAKDOWN IN HIGH-PRESSURE CO_2

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Abstract: SF_6 gas is a widely used insulation medium in Gas Insulated Switchgear (GIS) because SF_6 has high insulation and interruption performance. Recently, the development of GIS using a substitute gas for SF_6 has been strongly demanded from the viewpoint of environmentally friendly concepts. We are paying attention to CO_2 gas as a substitute for SF_6. In this paper, we investigate the electrode area effects of electrical breakdown in electrode area range of 0.2 cm^2 – 2000 cm^2 with high-pressure CO_2 gas up to 0.9MPa-absolute. BD characteristics in various electrode configurations are summarized based on streamer discharge criteria to discuss area effects. Finally, we evaluate electrode area effects quantitatively for positive/negative impulse voltage and AC voltage.

1 INTRODUCTION

A Gas Insulated Switchgear (GIS) applying SF_6 gas as insulation and interruption medium is widely used in high-voltage power transmission and distribution (T&D). However, SF_6 has a high global warming potential (GWP=23900), and was specified as an emission-restricted gas at COP3 in 1997. Recently, from a view point of environmentally friendly concepts, development of GIS using a substitute for SF_6 gas has been strongly demanded.

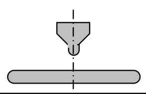
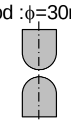
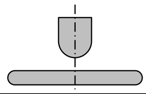
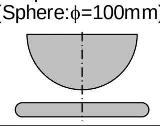
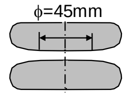
We are paying attention to CO_2 gas as a substitute for SF_6, and are continuing to investigate its insulation and interruption characteristics[1]-[3]. Generally, it is well known that the electrode area effects of electrical breakdown (BD) are very important characteristics when we design GIS. However electrode area effects have not been quantitatively investigated in CO_2 gas.

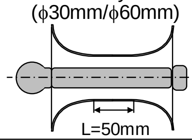
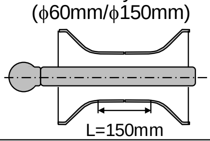
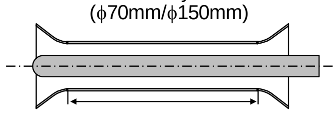
In this paper, we investigate electrode area effects with high-pressure CO_2 gas up to 0.9MPa in the range of a high-voltage electrode area of 0.2cm^2 – 2000 cm^2. To compare characteristics, electrode area effects in SF_6 gas were also investigated. First, we discuss the influence of electric field distribution on BD in CO_2 and SF_6 gas because we change the electrode configuration (electric field distribution) to investigate the electrode area effects. Finally, BD characteristics in various electrode configurations are summarized based on streamer discharge criteria and we evaluated the electrode area effects quantitatively in high-pressure CO_2 gas.

2 EXPERIMENTAL SETUP

Table.1 shows the electrode configuration (a)-(h) we use for investigating electrode surface area effects[4]. Coaxial cylinder, plane-plane, sphere-

Table 1. Electrode configuration for investigating area effects.

	(a)	(b)	(c)	(d)	(e)
Electrode Configuration	Rod-Plane (Rod :ϕ=10mm) 	Rod-Rod (Rod :ϕ=30mm) 	Rod-Plane (Rod :ϕ=30mm) 	Sphere-Plane (Sphere:ϕ=100mm) 	Parallel Plane (Plane :ϕ=100mm) 
	gap=15mm	gap=5mm	gap=15mm	gap=15mm	gap=10mm
Non-uniform factor (Emax/Eave)	3.01	1.11	1.71	1.20	1.01
Electrode surface roughness	HV: Rz=15μm Ground: Rz=1.5μm	HV: Rz=15μm Ground: Rz=1.5μm	HV: Rz=15μm Ground: Rz=1.5μm	HV: Rz=15μm Ground: Rz=1.5μm	HV: Rz=7μm Ground: Rz=7μm

	(f)	(g)	(h) [4]
Electrode Configuration	Coaxial cylinder (ϕ30mm/ϕ60mm) 	Coaxial cylinder (ϕ60mm/ϕ150mm) 	Coaxial cylinder (ϕ70mm/ϕ150mm) 
	gap=15mm	gap=45mm	gap=40mm
Non-uniform factor(Emax/Eave)	1.44	1.68	1.86
Electrode surface roughness	HV: Rz=15μm Ground: Rz=1.5μm	HV: Rz= less than25μm Ground: Rz=10μm	HV: Rz= less than25μm Ground: Rz=less than25μm

plane, rod-rod, and rod-plane electrode were used to change the electrode surface area. This table also shows non-uniform factor (maximum electric field Emax/average electric field Eave) and electrode surface roughness at the high-voltage side and ground side. Electrode material of (a)-(d), (f)-(h) was aluminium, (e) was brass.

CO_2 gas pressure was set at 0.7 MPa and 0.9 MPa-absolute. To compare characteristics, we set the pressure of SF_6 at 0.3 MPa-absolute. Positive and negative standard lightning impulses (1.2/50μs) were applied repeatedly based on the up-down method to evaluate BD characteristics. We calculated the 50% BD field strength E_{-Imp} and E_{+Imp} from 40 times BD for impulse voltage applications. In the case of an AC voltage, BD field strength E_{AC} was determined from an average value of 5-20times BD. During voltage applications, BD voltage did not change as a conditioning and deconditioning effect.

3 EXPERIMENTAL RESULTS

3.1 Effects of electric field distribution on BD

First, we discuss the influence of electric field distribution on BD in CO_2 to evaluate electrode area effects under various electrode configurations. Figure 1 shows the fundamental characteristics of gaseous dielectrics what show the relationship between reduced field E/p and effective ionization coefficient $(\alpha-\eta)/p$ of CO_2 and SF_6[5]-[8]. From this figure, in the case of SF_6, the slope of the effective ionization coefficient line is very steep around Ecr(electric field for which effective ionization coefficient $(\alpha-\eta)/p=0$). However, in CO_2, the slope of the effective ionization coefficient is gentle around Ecr.

This means that BD characteristics might be decided by Ecr in SF_6 gas, however, in the case of CO_2, a higher electric field or a wider electric field range are necessary for discharge formation. Thus, this implies that BD field strength under high non-uniformity indicates a higher value than that under low non-uniformity in CO_2. This characteristic is very important when evaluating electrode surface

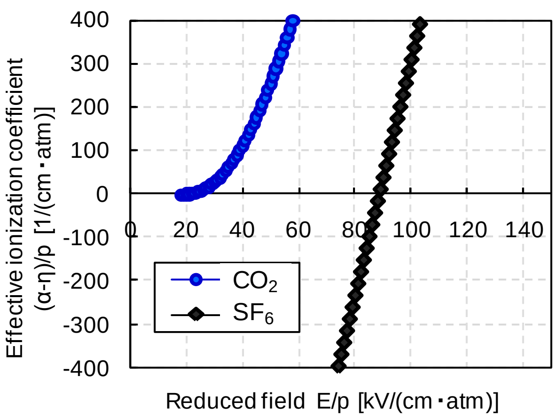


Figure 1: Relationship between E/p and $(\alpha-\eta)/p$ for CO_2 and SF_6

area effects because we change the electric field distribution to change the electrode area as mentioned above.

Electrode configurations (a) ϕ=10 mm-d=15 mm, (c) ϕ=30 mm-d=15 mm, (d) ϕ=100 mm-d=15 mm were used to discuss the influence of electric field distribution on BD. Gap length of these electrode configurations is 15 mm constant. Figure2 shows the electric field distribution from high-voltage side to ground voltage side on the central axis in electrodes (a), (c), (d) with 100 kV applied at high-voltage electrode. This figure also shows average field Eave (100 kV/1.5 cm). Non-uniform electric field factor (Emax/Eave) of electrodes (a) is 3.01, (b) is 1.71, and (d) is 1.20.

Figure 3(a) (b) shows the relationship between non-uniform factor and 50% BD field strength E_{-Imp} of negative impulse voltage in CO_2 0.9 MPa and SF_6 0.3 MPa. BD field strength was standardized

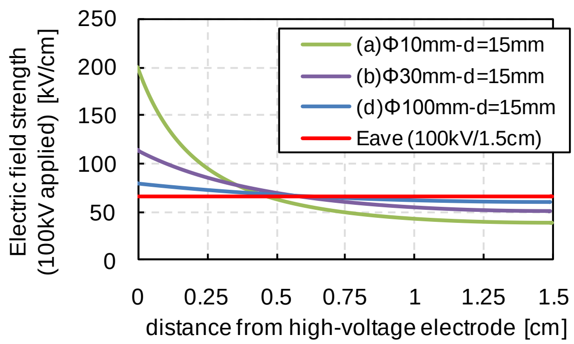


Figure 2: Electric field distribution on central axis

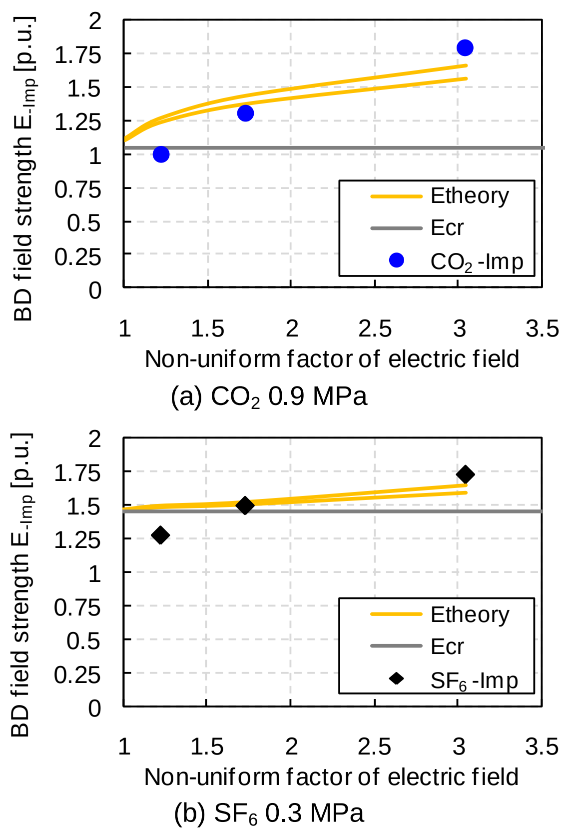


Figure 3: BD field strength E_{-Imp} as a function of non-uniform factor of electric field

by E_{-Imp} under the electrode configuration (d) ϕ=100 mm-d=15 mm in CO_2 0.9 MPa. Critical field Ecr and theoretical BD field strength Etheory are also indicated. In this paper, Etheory is calculated from streamer criterion equation (1), and constant value k is applied as follows –CO_2: k=13~20.5, SF_6: k=10.5~18 [9].

$$\int_{x2}^{x1} (\alpha-\eta)dx = k \cdots\cdots\cdots\cdots\cdots (1)$$

From this figure, in the case of CO_2, E_{-Imp} increases about 80% with an increase of non-uniform factor in the range of 1.20 – 3.01. However, in the case of SF_6, E_{-Imp} increases only 30% when changing non-uniformity. This result shows a similar tendency to Etheory calculated with streamer criteria as we expected. In addition, experimental results for positive impulse voltage and AC voltage shows same the characteristics.

As mentioned above, we clarify the relationship between non-uniformity of electric field distribution and BD field strength in CO_2 and SF_6, reveal that BD characteristics of CO_2 strongly depend on electric field distribution.

3.2 Electrode area effects on BD

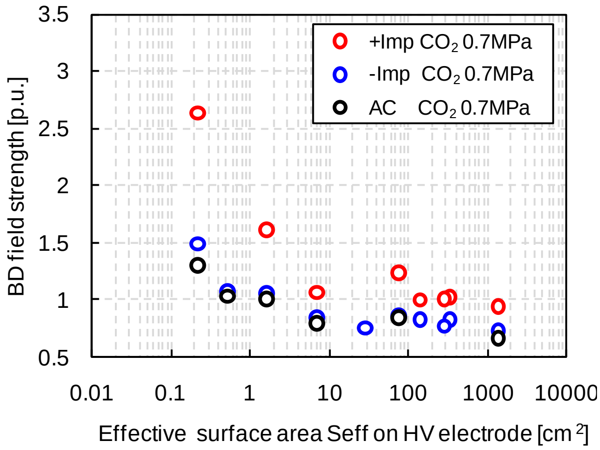
Evaluating electrode area effects of BD is very important when designing a GIS. We investigate electrode area effects in CO_2 up to 0.9 MPa in the range of electrode areas of 0.2cm^2 – 2000cm^2.

Figure 4 shows the relationship between effective area on high-voltage electrode (Seff) and E_{-Imp}, E_{+Imp} and E_{AC} in (a) CO_2 0.7MPa, (b) CO_2 0.9 MPa. To compare the characteristics, experimental results of SF_6 indicate (c) SF_6 0.3 MPa. In the case of CO_2 gas, a discharge trace was observed on the surface area that has an 85% electric field of Emax in each electrode configuration, so its surface area was defined as Seff. On the other hand, in the case of SF_6, as reported already, the surface area with a 90% field of Emax was defined as Seff [10]-[12]. In this figure, BD field strength is standardized by E_{-Imp} under electrode configuration (d) ϕ=100 mm-d=15 mm in CO_2 0.9 MPa.

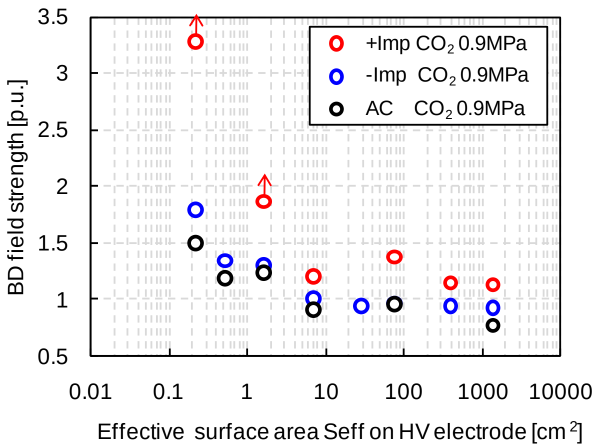
This figure shows electrode area effects for positive/negative impulse voltage and AC voltage. In particular, it appears that BD field strength tends to increase sharply in the small Seff in CO_2. This is because the electrode configuration with a small Seff has a higher non-uniformity of electric field, and the BD field apparently increases more than the influence of area effects as we mentioned Section 3.1. However, in the case of SF_6, such an increase was not seen remarkably.

We evaluate area effects by normalizing BD field strength with streamer criteria because Figure 4 including the influence of electric field distribution could not be applied for the evaluation. Figure 5 shows electrode area effects to which BD field is normalized Etheory calculated by streamer criteria (equation (1), constant value k is applied as follows –CO_2: k=13, SF_6: k=18) in (a) CO_2 0.7 MPa, (b) CO_2 0.9 MPa and (c) SF_6 0.3MPa.

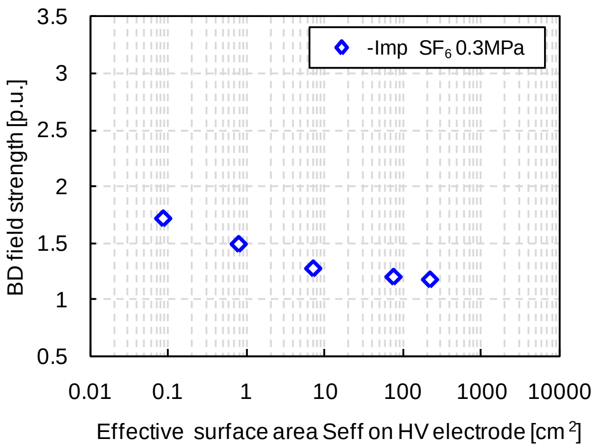
In the case of negative impulse voltage and AC voltage, electrode area effects appeared clearly because electrode surface conditions (field emission from cathode, electrode surface roughness(micro-protrusion) and contamination) on the high-voltage electrode decide BD characteristics. Rate of decrease by electrode



(a) CO_2 0.7 MPa



(b) CO_2 0.9 MPa

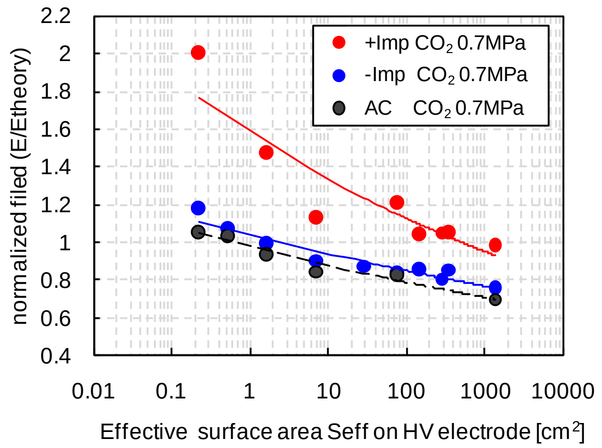


(c) SF_6 0.3 MPa

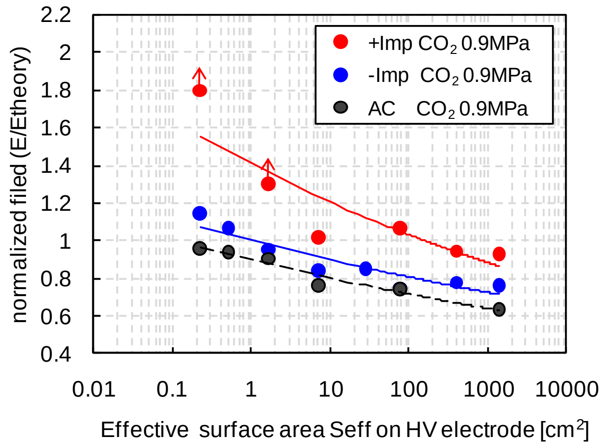
Figure 4: Electrode area effects in each gas

surface area in CO_2 0.7 MPa, 0.9 MPa and SF_6 0.3MPa was same level under these experimental conditions.

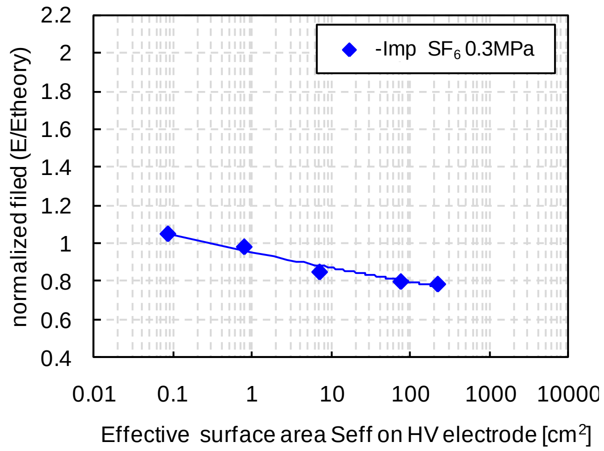
On the other hand, in the case of positive impulse, the relationship between surface area Seff and normalized BD field did not appear clearly, especially in the smaller Seff region. From past research, we found that the BD field in a positive impulse did not decrease when electrode surface roughness increased, which suggests that the BD characteristic was not influenced by surface conditions, so the relationship summarized by electrode surface area Seff in Figure 5 might not be clarified. We should summarize the experimental results by gas volume with a high electric field because the generation of initial electrons plays an important role in BD phenomena in the case of a positive impulse [13].



(a) CO_2 0.7 MPa



(b) CO_2 0.9 MPa



(c) SF_6 0.3 MPa

Figure 5: Electrode area effects in each gas (BD field were normalized by Etheory)

4 CONCLUSION

In this paper, we discuss electrode surface effects on electrical BD in the range of high-voltage electrode areas of 0.2 cm^2 – 2000 cm^2 in high-pressure CO_2. First, the influence of electric field non-uniformity on BD was investigated to evaluate area effects. Finally, to summarize BD characteristics based on streamer discharge criteria, we evaluated electrode area effects quantitatively. As a result, the following characteristics were revealed.

(1) E_{-Imp} of negative impulse in CO_2 0.9 MPa increases about 80% with an increase of non-uniform factor in the range of 1.20 – 3.01(gap length is 15 mm), however, E_{-Imp} in SF_6 0.3MPa increases only 30%. We suggest that this characteristic is explained by the relationship between reduced field E/p and effective ionization coefficient $(\alpha\text{-}\eta)/p$ of CO_2 and SF_6.

(2) Discharge trace in CO_2 gas was observed on the surface area that has an 85% electric field of Emax in each electrode configuration, so its surface area was defined as Seff. To take into consideration electric field non-uniformity, electrode area effect is summarized by normalizing BD field strength with streamer criteria.

(3) In the case of negative impulse voltage and AC voltage, electrode area effects appeared clearly because surface conditions on high-voltage electrode may decide BD characteristics. Rate of decrease due to electrode area effects in CO_2 0.7 MPa, 0.9 MPa and SF_6 0.3 MPa were the same under this experimental condition.

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