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Electrical insulation characteristics of CO_2 and CO_2 gas mixtures under non-uniform electric field

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Abstract: Since SF_6 gas has been specified as one of the greenhouse gases, we attempt to develop new insulation gases or gas mixtures alternative to SF_6 gas for gas insulated switchgears (GIS). In this paper, we investigated partial discharge (PD) and breakdown (BD) characteristics of CO_2 gas and CO_2 gas mixtures as one of the promising candidates without using SF_6 gas. Experimental results revealed PD inception and BD strengths for different gas pressure and CO_2 content under lightning impulse voltage and ac high voltage application.

Introduction

Because of the environmental problem of SF_6 gas (global warming potential (GWP) = 23900) [1], the development of new insulation gases or gas mixtures alternative to SF_6 gas is strongly required. From the viewpoint of low GWP, toxicity, price and electronegativity, CO_2 gas and O_2 gas can be one of possible candidates without using SF_6 gas. Typical properties of CO_2 and O_2 gases are shown in Table 1, compared with those of N_2 and SF_6 gases [1-4]. Since the higher O_2 content may not be accepted for its oxidation and flammability, we focused on CO_2 gas and CO_2 gas mixtures as the SF_6 substitutes for the application to GIS.

This paper presents PD and BD characteristics of CO_2 gas and CO_2/O_2 gas mixtures for lightning impulse voltage and ac voltage application under non-uniform electric field. We measured 50% probability PD inception voltage $PDIV_{50}$ and BD voltage BDV_{50} for different gas pressure and CO_2 content, and discussed impulse ratio and PD inception electric field strength (PDIE) characteristics.

Experimental setup

Figure 1 shows the experimental setup. A rod-plane electrode system was placed in the experimental tank. The tip diameter of the rod was ϕ=5 mm, and the gap length of the rod-plane electrode was g=40 mm. The experimental tank was filled with CO_2 gas or CO_2/O_2 gas mixtures at the pressure P=0.1~0.4 MPa. Standard lightning impulse voltage and 60 Hz ac high voltage was applied to the rod electrode and generated PD and BD between the rod-plane electrodes. PD signals were detected by current pulses through a matching resistance and light intensity pulses were obtained through a photo multiplier tube (P.M.T.). The impulse $PDIV_{50}$ and BDV_{50} and their standard deviation were obtained by the up-and-down method. All experiments in this paper were carried out under room temperature.

Table 1: Properties of gases [1-4].

	CO_2	O_2	N_2	SF_6
Molecular weight	44.01	32.00	28.01	146.06
Ecr [kV(mm bar)$^{-1}$]	3.01	3.26	3.29	8.9
Boiling point [K]	194	90	77	209
Ionization potential [eV]	13.7	12.2	15.6	15.8
GWP	1	0	0	23900

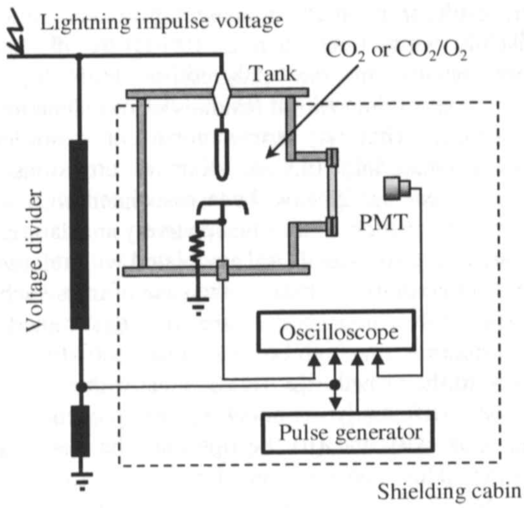

Figure 1: Experimental setup.

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Experimental results

PDIV and BDV characteristics

The CO_2 content dependence of positive impulse $PDIV_{50}$ and BDV_{50} in CO_2/O_2 gas mixtures at P=0.1 MPa is shown in Fig. 2, where the results in CO_2/N_2 gas mixtures [5] are included. The error bars show the standard deviation of $PDIV_{50}$ and BDV_{50}. $PDIV_{50}$ in CO_2/O_2 and CO_2/N_2 gas mixtures is almost the same at any CO_2 content, due to the similar critical electric field (E_{cr}) as listed in Table 1. BDV_{50} in CO_2/O_2 gas mixtures decreased with the increase in CO_2 content, whereas BDV_{50} in CO_2/N_2 gas mixtures slightly increased with the increase in CO_2 content. In other words, BDV_{50} in $CO_2$50%/$O_2$50% gas mixtures is higher than that in pure CO_2 gas as well as that in pure N_2 gas. These results can be attributed to the 4 times larger cross-section of electron attachment in O_2 gas than that in CO_2 gas [6].

The O_2 content dependence of positive impulse $PDIV_{50}$ and BDV_{50} in CO_2/O_2 gas mixtures at P=0.1 MPa is shown in Fig.3, together with those in N_2/O_2 gas mixtures [5]. BDV_{50} in CO_2/O_2 and N_2/O_2 gas mixtures increased with the increase in O_2 content, which can also be interpreted by the large cross-section of electron attachment in O_2 gas. Therefore, BDV_{50} in CO_2/O_2 and N_2/O_2 gas mixtures can be dominated by the electron attachment property of O_2 gas at 0.1 MPa.

Figure 4 shows positive impulse $PDIV_{50}$ and BDV_{50} as a function of gas pressure in pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures. $PDIV_{50}$ in both gases were proportional to the increase in the gas pressure, whereas BDV_{50} in pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures exhibited nonlinear characteristics against the gas pressure. BDV_{50} is increased by corona stabilization effect. However, at high gas pressure, PD type tends to change from streamer PD to leader PD, and this brings about the great reduction of BDV_{50} because leader PD propagates long length [7]. Thus, the BDV_{50} characteristics have local maximum around the gas pressure at streamer-to-leader transition. Gas pressure at local maximum of the BDV_{50} in $CO_2$50%/$O_2$50% gas mixtures is lower than that in pure CO_2 gas. This result may be caused by PD in $CO_2$50%/$O_2$50% gas mixtures being changed to leader discharge even at lower gas pressure than that in pure CO_2 gas because of limited residual charges after PD by suppressed PD expansion. Residual charges are more limited with the increase in gas pressure and the limited residual charges make easy to enhance the electric field strength at the tip of PD.

Figure 5 shows positive ac PDIV and BDV as a function of gas pressure in pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures. Being different from the results under lightning impulse voltage application, BDV in $CO_2$50%/$O_2$50% gas mixtures is much higher than BDV in pure CO_2 gas at P=0.15 MPa. As O_2 gas suppressed PD expansion, residual charges in $CO_2$50%/$O_2$50% gas mixtures may be limited at the tip of rod electrode and bring about higher corona stabilization effect than that in pure CO_2 gas. Thus, corona stabilization effect as a sum of PD that has been generated until BD made large difference between in pure CO_2 gas and in $CO_2$50%/$O_2$50% gas mixtures. Also, by comparing BDV(ac) with BDV(impulse), we can find that gas pressure at the local maximum of BDV is the same at P=0.2 and 0.15 MPa, respectively. The higher corona stabilization in CO_2/O_2 gas mixtures than that in pure CO_2 gas may be attributed to the higher electron attachment property of O_2 gas.

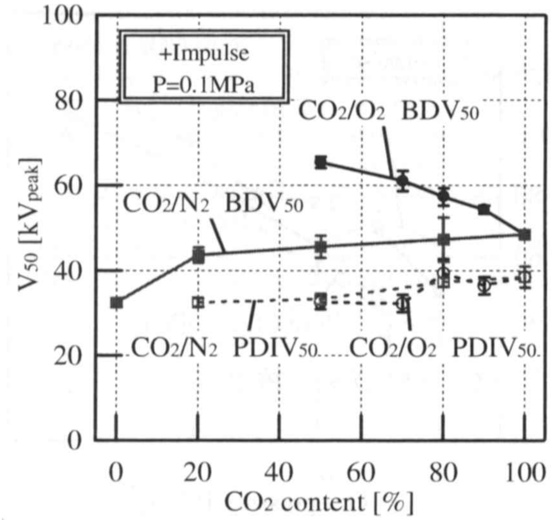

Figure 2: Positive impulse $PDIV_{50}$ and BDV_{50} as a function of CO_2 content in CO_2/O_2 and CO_2/N_2 gas mixtures.

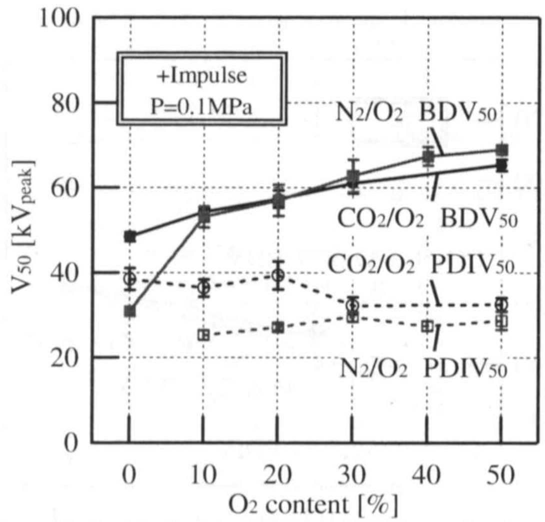

Figure 3: Positive impulse $PDIV_{50}$ and BDV_{50} as a function of O_2 content in CO_2/O_2 and N_2/O_2 gas mixtures.

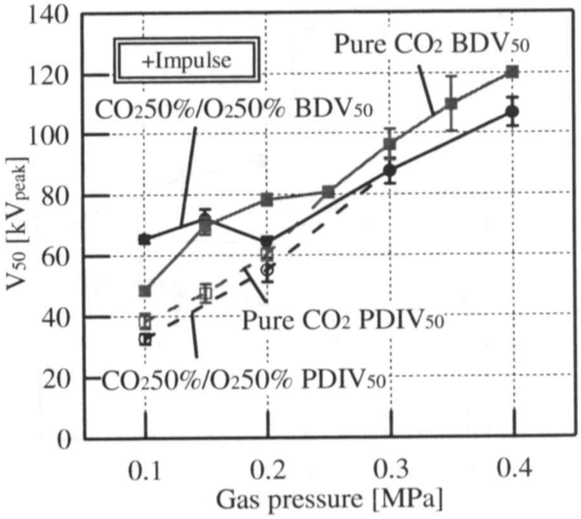

Figure 4: Positive impulse $PDIV_{50}$ and BDV_{50} as a function of gas pressure in pure CO_2 gas and CO_2 50% /O_2 50% gas mixtures.

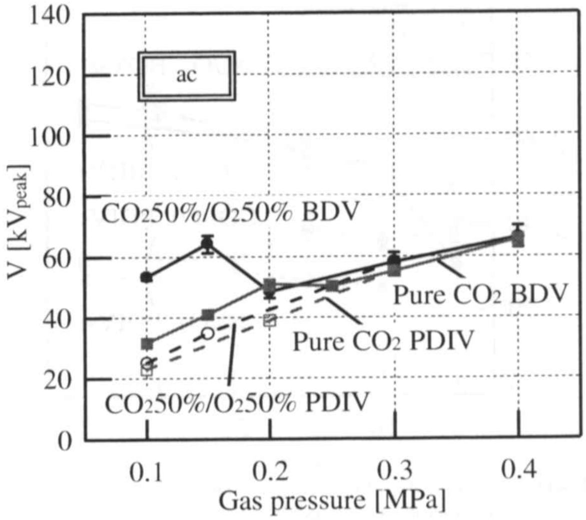

Figure 5: Positive ac PDIV and BDV as a function of gas pressure in pure CO_2 gas and CO_2 50% /O_2 50% gas mixtures.

Impulse ratio

As described in the previous section, BDV of electronegative gases under non-uniform electric field is affected by the corona stabilization effect after the PD inception, so that impulse ratio of BDV (impulse BDV_{50} / ac BDV) is complicated and no longer explained by only V-t characteristics. Thus, we focused on the impulse ratio of PDIV (impulse $PDIV_{50}$ / ac PDIV) in order to understand the discharge mechanism under non-uniform electric field.

From Fig. 4 and 5, we can obtain gas pressure dependence of the impulse ratio of PDIV and BDV in pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures as shown in Fig.6. The impulse ratio of PDIV tends to increase with the gas pressure, which means that the lack of initial electrons become remarkable due to the shrinkage of critical volume around the tip of rod electrode. The higher impulse ratio of pure CO_2 gas than that of CO_2/O_2 gas mixtures might be related to the difference in generation characteristics of initial electrons in both gases.

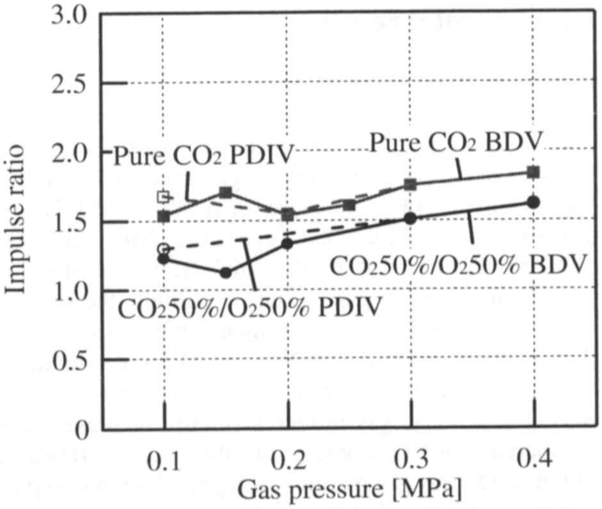

Figure 6: Impulse ratio of PDIV and BDV as a function of gas pressure in pure CO_2 gas and CO_2 50% /O_2 50% gas mixtures.

PDIE characteristics

Figure 7 shows positive impulse and ac PDIE as a function of gas pressure in pure CO_2 gas. PDIE represents the maximum electric field strength at the tip of rod electrode calculated by simulation (CSM). PDIE is much higher than E_{cr}, which may be attributed to the fact that PD inception needs a certain distance for electron avalanche to develop into streamer discharge. In other words, the electric field strength at the tip of rod electrode should be higher than E_{cr} at the tip of streamer at PD inception and propagation.

PDIE divided by E_{cr} at each gas pressure are shown in Fig. 8, for positive impulse and ac voltage as a function of gas pressure in pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures. PDIE/E_{cr} decreased as the gas pressure increased, which can be interpreted by the shorter PD propagation length at the higher gas pressure.

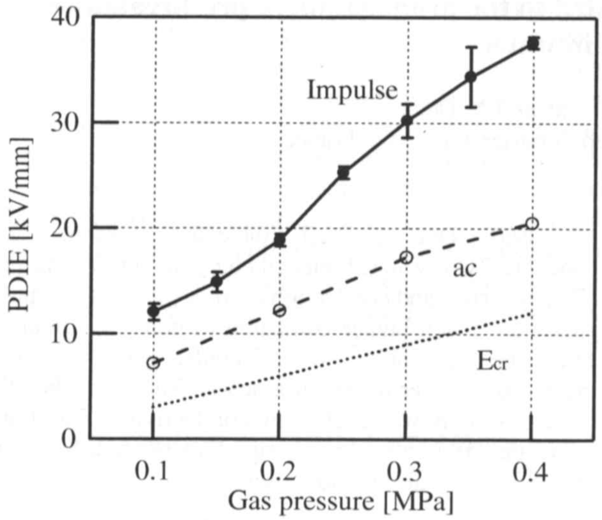

Figure 7: Positive impulse and ac PDIE as a function of gas pressure in pure CO_2 gas.

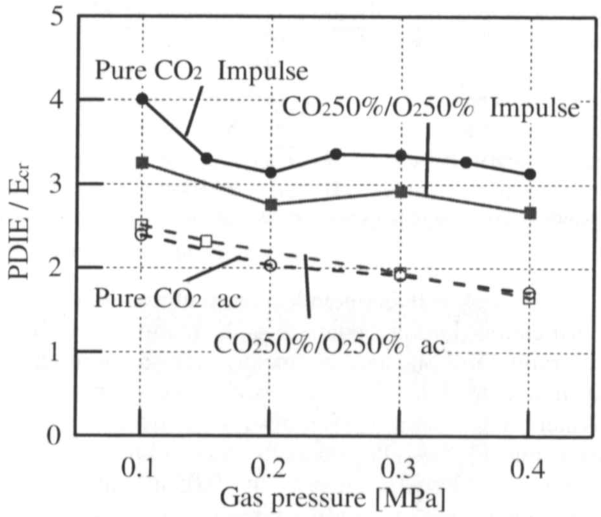

Figure 8: Positive impulse and ac PDIE / E_{cr} as a function of gas pressure in pure CO_2 gas and CO_2 50% /O_2 50% gas mixtures.

Conclusions

We investigated the impulse and ac PD and BD characteristics under rod-plane electrode system in CO_2 gas and CO_2/O_2 gas mixtures as the SF_6 substitutes. The main results obtained in this paper are summarized as follows:

(1) BDV_{50} in CO_2/O_2 gas mixtures increased with CO_2 content due to that O_2 gas has high cross-section of electron attachment.

(2) PD in $CO_2$50%/$O_2$50% gas mixtures may change to leader discharge at lower gas pressure than that in CO_2 gas for limited residual charges after PD by suppressed PD expansion.

(3) The lack of initial electron became more remarkable as gas pressure increased in pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures under rod-plane electrode system.

(4) PDIE is much higher than E_{cr} in all condition due to that PD inception needs a certain distance for electron avalanche to develop into streamer discharge. And the difference between PDIE and E_{cr} was smaller as gas pressure increased in both pure CO_2 gas and $CO_2$50%/$O_2$50% gas mixtures.

References

[1] Intergovernmental Panel on Climate Change (IPCC), "Climate Change 1995: The Science of Climate Change—Contribution of Working Group I to the Second Assessment Report of the IPCC", p.121, 1996.

[2] R. D. Hake, Jr. and A.V. Phelp: "Momentum-Transfer and Inelastic-Collision Cross Sections for Electron in O_2, and CO, and CO_2", *Physical Review,* Vol.158, No.1, pp.70-84, 1967.

[3] G. Biasiutti, "Homogeneous Field Breakdown Strength Characteristics of Some Dielectric Gases", *Gaseous Dielectrics III,* pp.174-182, 1982.

[4] Th.Aschwanden: "Swarm Parameters in SF_6/N_2 Mixtures Determined from a Time Resolved Discharge Study", *Gaseous Dielectrics IV* , pp.24-33, 1984.

[5] J. Deng, N. Hayakawa, T. Ueda and H. Okubo, "Impulse Partial Discharge and Breakdown Characteristics of Rod-Plane Gaps in N_2/O_2 and N_2/CO_2 Gas Mixtures", *14th International Conference on Gas Discharges and their Applications,* Vol.1, No.C45, pp295-298, 2002.

[6] L. G. Christophorou and L. A. Pinnaduwage: "Basic Physics of Gaseous Dielectrics", *IEEE Transactions on Electrical Insulation,* Vol.25, No.1, pp.55-74, 1990.

[7] H.Saitoh, K.Morita, T.Kikkawa, N.Hayakawa and H.Okubo:"Impulse Partial Discharge and Breakdown Characteristics of Rod-plane Gaps in N_2/SF_6 gas mixtures", IEEE Transactions on Dielectrics and Electrical Insulation, Vol.9, No.4, pp.544-550, 2002.

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