Insulation Characteristics of Gas Mixtures including Perfluorocarbon Gas

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ABSTRACT

This paper describes discharge properties of N_2 and CO_2-based gas mixtures including a perfluorocarbon (PFC) gas such as CF_4, C_3F_8 and c-C_4F_8 under non-uniform field. The mixture ratio between a base gas of N_2 or CO_2 and the additive PFC gas was fixed as 9:1; namely, 90%N_2/10%PFC or 90%CO_2/10%PFC gas mixture. The PFC gases have even smaller global warming potential (GWP) than SF_6 gas and have good insulation properties as SF_6 gas. Thus, PFC gas mixture is expected to be a SF_6 substitute without highly pressurizing the gas over the conventional pressure of 0.5 to 0.6 MPa. In this study, in order to compare the partial discharge (PD) inception voltage V_{PD} and breakdown voltage V_B properties between N_2 and CO_2-based gas mixtures, as well as between the additive gas of PFC and SF_6 gas, we investigated these properties of the gas mixtures with a needle to plane electrode under ac high voltage application. The gas pressure was changed from 0.1 to 0.6 MPa. As a result, it was found that V_{PD} and V_B characteristics of N_2 and CO_2-based gas mixtures differed considerably, especially the gas pressure dependence of V_B (so-called the N shape characteristics). V_B characteristics of N_2-based gas mixture including c-C_4F_8 proved to be excellent within the test conditions over the wide gas pressure region, showing the maximum breakdown voltage. In terms of V_{PD} properties, CO_2-based gas mixture had an advantage over N_2-based gas mixture due to higher V_{PD}. Furthermore, we discussed the synergy effects of V_{PD} and V_B for N_2 and CO_2-based gas mixtures using the index R_n which was defined to quantify the degree of the effect. R_n for CO_2-based gas mixture was higher than that of N_2-based gas mixture.

Index Terms — **SF_6 gas, perfluorocarbon (PFC) gas, partial discharge, breakdown voltage, non-uniform field.**

1 INTRODUCTION

SINCE SF_6 gas has excellent insulation and arc-quenching properties, it has been widely used as insulation media for gas insulated switchgear (GIS) and gas insulated transmission line (GIL). However, SF_6 gas is a potent green house gas with global warming potential (GWP) as large as 23,900. Thus, the decrease in the use of SF_6 gas and the development of the alternative gas having much lower GWP are required [1-3]. From this point of view, a lot of experimental and numerical studies have been made on gas mixtures which are composed of a small amount of an electronegative gas such as SF_6 and a perfluorocarbon (PFC) gas, mixed with a buffer gas like N_2, CO_2 and air as a base gas to avoid the gas pressure to be extremely high over 1.0 MPa [1-9]. High pressure gas requires quite a thick tank wall and it could compel GIS to need highly cost and weight, in addition, the equipments with over 1.0 MPa pressured gas are severely regulated in Japan. PFC gas has the advantage of GWP, which is one order of magnitude smaller than that of SF_6, and the dielectric strength is almost same as that of SF_6 [3, 4, 6-8]. So far, the authors have investigated insulation properties of CO_2/N_2/SF_6 ternary gas mixtures under non-uniform as well as uniform field by applying ac and standard lightning impulse voltages [9]. Using the same experimental setup and techniques, discharge properties of N_2 and CO_2-based gas mixtures including PFC gas can be investigated.

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In this study, in order to discuss the difference in PD inception voltage V_{PD} and breakdown voltage V_B characteristics not only between N_2 and CO_2-based gas mixtures, but also between the additive gas of PFC and SF_6 gas, we experimentally investigated V_{PD} and V_B characteristics of these gas mixtures under non-uniform field by ac high voltage application. Synergism effect of SF_6 gas mixture could be observed remarkably with only 2% to 10% proportion of SF_6 [10]. In the experiment of this study, from this reason, the mixture ratio of a base N_2 or CO_2 gas to the additive PFC or SF_6 gas was fixed as 9:1, *i.e.*, 90%N_2/10%PFC or 90%CO_2/10%PFC gas mixture. We used CF_4, C_3F_8 and c-C_4F_8 gases as an additive PFC gas. Additionally, the synergy effects on V_{PD} and V_B for these gas mixtures were discussed by introducing the index R_n that is defined to quantify the degree of the effect.

2 EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows schematic diagram of experimental setup to investigate discharge properties of the gas mixtures including a PFC gas under non-uniform field. Tested gas mixtures consist of a PFC gas such as CF_4, C_3F_8 and c-C_4F_8 and a base gas of N_2 or CO_2. Specifications of each component gas are listed in Table 1. The mixture ratio of each component gas was decided by the pressure ratio of each gas at room temperature. The mixture ratio of a base gas to a PFC gas was fixed as 9:1; *i.e.* the mixture rate of a PFC gas was 10%. Prior to use for experiment, the gas mixtures were left for 24 h after mixing. A needle to plane electrode system made of stainless steel was mounted in a pressure chamber. The tip radius of the needle electrode was 500 μm and the gap length between electrodes was maintained as 10 mm in all experiments. Note that the electric non-uniform coefficient of this system is 14.5.

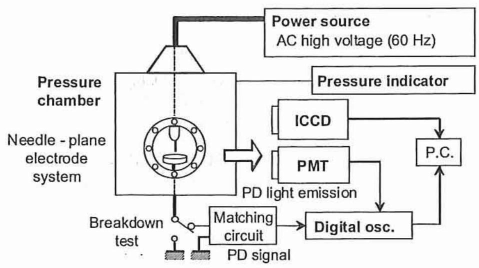


Figure 1. Experimental setup.

Table 1. Specifications of component gases used experiments [4.5].

Gas	GWP (100 years)	Vapor pressure (MPa)	Boiling temperature (°C)	Relative sterength*1
CF_4	6,500	*2	- 128	0.43
C_3F_8	7,000	0.78 (21.1°C)	- 38	0.93
c-C_4F_8	8,700	0.29 (24.3°C)	- 8	1.3 - 1.4
SF_6	23,900	2.28 (21.1°C)	- 64	1.0
N_2	-	*3	-196	0.40
CO_2	1	5.75 (21.1°C)	-79	0.37

*1)Uniform field, *2)Compressed gas at room temperature, *3)Critical temperature -147.1°C. N_2 can not be liquefied at temperatures higher than this.

V_{PD} and V_B characteristics of the gas mixtures were investigated by applying ac high voltage (60 Hz) to the needle electrode in the gas pressure range from 0.1 to 0.6 MPa. PD signal was detected with a digital oscilloscope (1GHz, 4Gs/s) through an impedance matching circuit connected between the plane electrode and earth ground [9]. When V_B was measured, the matching circuit was removed and the plane electrode was directly grounded for protecting the electronic devices. PD light emission intensity and image were measured by PMT (Photomultiplier Tube) and ICCD (Intensified Charge-coupled Devices) camera, respectively.

3 EXPERIMENTAL RESULTS

3.1 DISCHARGE PROPERTIES OF UNITARY PFC AND BUFFER GAS

Figure 2 shows positive V_{PD} (V_{PD}+) and V_B characteristics of SF_6, N_2 and CO_2 as a function of gas pressure [9]. Although not showing in Figure 2, experimental results revealed that negative V_{PD} (V_{PD}-) for these gases were lower than V_{PD}+. It is obvious from Figure 2 that V_B of N_2 linearly increases with gas pressure due to inherent nature of the non-electronegative gas. On the other hand, V_Bs of SF_6 and CO_2 do not show the linearity to the gas pressure but the well-known *N* shape characteristics, which are caused by the corona stabilization effect. The electronegative gases, i.e., SF_6 and CO_2, are easy to ionize negatively. Since the electrons are known to attach to molecules in electronically excited states with higher probability than to molecules in the ground electronic states, the ionized molecules would contribute to an enhancement in the breakdown voltage [1, 2]. Both V_{PD}+ and V_B increase in order of N_2, CO_2 and SF_6. The results for N_2 and CO_2 differ from those obtained under the uniform field as listed in Table 1 [4, 5]. Namely, dielectric strength of N_2 is larger than that of CO_2 under uniform field. One reason for this difference in V_{PD}+ seems to come from the detection sensitivity of PD current signal through the impedance matching circuit shown in Figure 1.

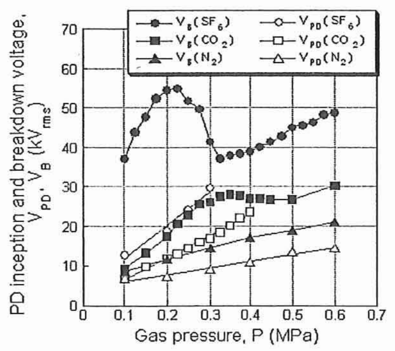


Figure 2. Positive V_{PD} and V_B characteristics of unitary gases of N_2, CO_2 and SF_6 gas [9].

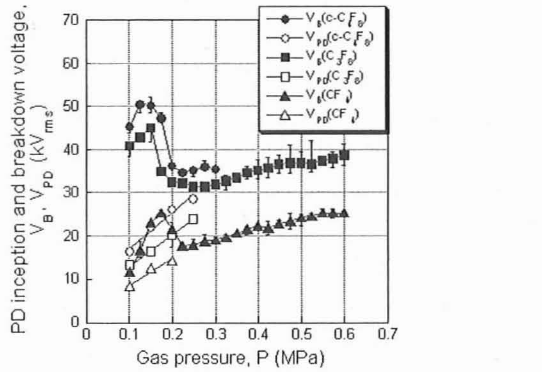


Figure 3. Positive V_{PD} and V_B characteristics of unitary PFC gases of CF_4, C_3F_8 and c-C_4F_8.

Figure 3 depicts schematic gas pressure dependence of V_{PD}+ and V_B for unitary PFC gases of CF_4, C_3F_8 and c-C_4F_8. These voltage characteristics for c-C_4F_8 were measured below 0.3MPa to avoid liquefying the gas. The N shape characteristics of V_B are confirmed in all PFC gases like SF_6 and CO_2 gas shown in Figure 2. V_{PD}-s for PFC gases were also found to be lower than V_{PD}+. Here, let us define the maxima and minima in a V_B vs P curve as V_{Bm} and V_C', and also define the corresponding gas pressures as P_m and P_C', as shown in Figure 4, respectively [9]. These parameters as well as V_{PD}+ and V_{PD}- at 0.2 MPa of the tested unitary gases shown in Figures 2 and 3 are listed in Table 2. V_{PD}+ as well as V_B rise in order of CF_4, C_3F_8 and c-C_4F_8, which is the same order as for the case under the uniform field listed in Table 1. Particularly, it should be noticed that the normalized V_{PD}+ and V_{PD}- for C_3F_8, c-C_4F_8 and N_2 against SF_6 listed in Table 2 are nearly equal to the normalized strength under the uniform field (Table 1). On the other hand, the normalized V_Bs for these gases listed in Table 2 do not agree with the relative strength under the uniform field because of the influence of the space charge by PD. This result shows that V_{PD} is closely related to the dielectric strength under the uniform filed. It is also found from Table 2 that P_m for PFC gas appears at lower gas pressure than that for SF_6. Figure 5 shows molecular weight dependences of V_{PD}+, V_{PD}- and V_B at 0.1 MPa for all tested gases. This result indicates that V_{PD} and V_B increase with the molecular weight, and the difference between V_B and V_{PD}; *i.e.* corona stabilization effect, also increases with the molecular weight.

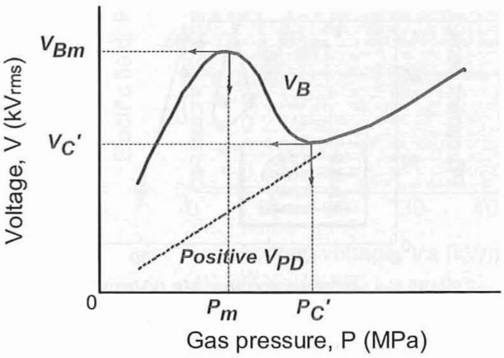


Figure 4. Definition of V_{Bm}, V_C', P_m and P_C' in the N shape characteristics of V_B vs P curve.

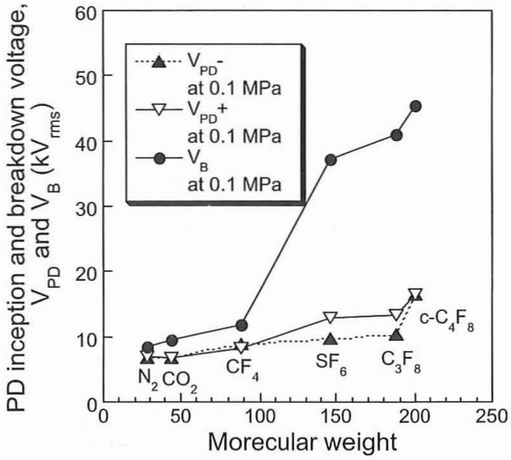


Figure 5. Molecular weight dependence of insulation properties of each unitary gas shown in Figures 2 and 3.

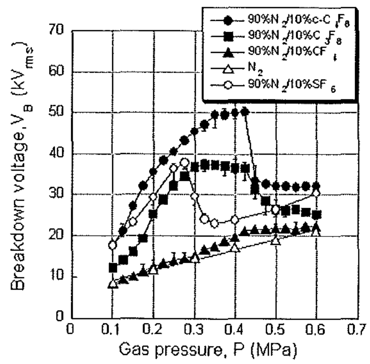
Table 2. Specifications of PFC gases shown in Figures 2 and 3. V_{PD}, V_{Bm} and V_C' are relative values to that of SF_6.

Mixed gas	V_{PD} + at 0.2 MPa	V_{PD} - at 0.2 MPa	V_{Bm}	P_m (MPa)	V_C'	P_C' (MPa)
CF_4	0.76	0.84	0.46	0.175	0.47	0.225
C_3F_8	1.08	1.02	0.82	0.15	0.85	0.25
c-C_4F_8	1.40	1.24	0.92	0.125	0.93	0.225
SF_6	1.0	1.0	1.0	0.225	1.0	0.325
N_2	0.40	0.42	-	-	-	-
CO_2	0.63	0.65	0.51	0.35	0.72	0.5

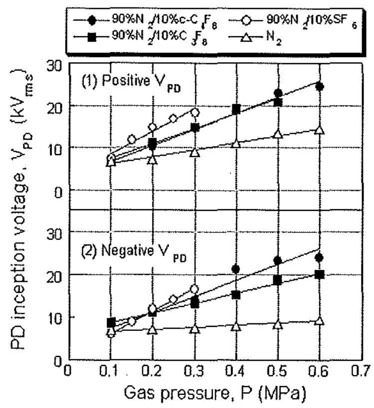
3.2 DISCHARGE PROPERTIES OF N_2/PFC AND CO_2/PFC GAS MIXTURES

V_{PD} and V_B of 90%N_2/10%PFC and 90%CO_2/10%PFC gas mixtures as a function of the gas pressure are shown in Figures 6 and 7, respectively. V_{PD} for N_2/CF_4 gas mixture could not be measured because V_{PD} was close to V_B. Although V_B vs P curves of both N_2/PFC and CO_2/PFC gas mixtures indicate the N shape characteristics, V_B vs P curves for N_2/PFC gas mixtures quite differ from those for CO_2/PFC ones; that is, V_{Bm} for N_2/PFC gas mixtures, particularly including C_3F_8 and c-C_4F_8, appears at higher gas pressures than that for CO_2/PFC ones. Also, we can say that the N shape curves of V_B for CO_2/PFC gas mixture seem to be similar with that for CO_2/SF_6 one, while those for N_2/PFC gas mixture differs from that for N_2/SF_6 one as mentioned above. This relation is also confirmed quantitatively in Tables 3 and 4, which list the parameters of the gas mixtures shown in Figures 6 and 7. It should be noted that P_m for the PFC gas mixtures shifts to higher gas pressure compared with pure PFC gas.

Some differences in V_{PD} properties between N_2/PFC and CO_2/PFC gas mixtures were also confirmed in Figures 6 and 7. Namely, V_{PD} for CO_2/PFC gas mixtures are generally higher than that for N_2/PFC ones, and difference between

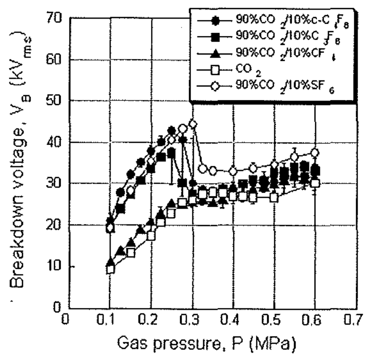


(a) Breakdown voltage.

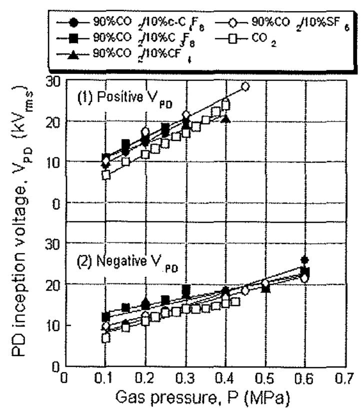


(b) Positive and negative PD inception voltage.

Figure 6. Discharge properties of 90%N_2/10%PFC gas mixtures.



(a) Breakdown voltage.



(b) Positive and negative PD inception voltage.

Figure 7. Discharge properties of 90%CO_2/10%PFC gas mixtures.

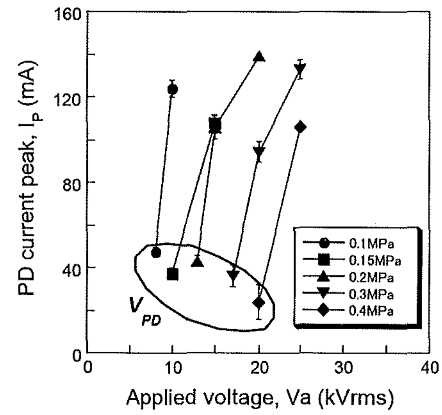
V_{PD}+ and V_{PD}- for CO_2/PFC gas mixtures seems to be slightly larger than that for N_2/PFC ones; *e.g.* V_{PD}+ of N_2/c-C_4F_8 gas mixture is identical to the V_{PD}-. Thus, from the viewpoint of V_{PD}, CO_2/PFC gas mixtures have an advantage over N_2/PFC ones due to higher V_{PD} although the peak value of the PD current pulses of CO_2/PFC gas mixtures generated during the positive half cycle indicates higher value than that of N_2/PFC ones as shown in Figure 8. Corona stabilization effect gives larger PD current with V_a

Table 3. Parameters of 90%N_2 gas mixtures shown in Figure 6.

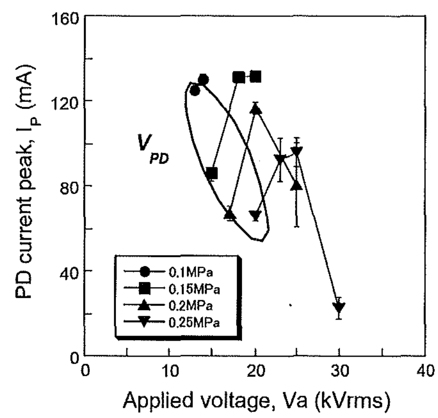
Mixed gas	V_{PD}+ at 0.2 MPa	V_{PD}- at 0.2 MPa	V_{Bm}	P_m (MPa)	V_C'	P_C' (MPa)
CF_4	-	-	0.57	0.45	0.94	0.55
C_3F_8	0.76	0.94	0.99	0.35	1.14	0.525
c-C_4F_8	0.69	0.95	1.33	0.425	1.40	0.5
SF_6	1.0	1.0	1.0	0.275	1.0	0.35

Table 4. Parameters of 90%CO_2 gas mixtures shown in Figure 7.

Mixed gas	V_{PD}+ at 0.2 MPa	V_{PD}- at 0.2 MPa	V_{Bm}	P_m (MPa)	V_C'	P_C' (MPa)
CF_4	0.92	1.31	0.57	0.25	0.78	0.35
C_3F_8	0.95	1.20	0.84	0.25	0.83	0.3
c-C_4F_8	0.84	0.87	0.96	0.25	0.86	0.35
SF_6	1.0	1.0	1.0	0.30	1.0	0.40



(a) 90%N_2/10%PFC gas mixtures.



(b) 90%CO_2/10%PFC gas mixtures.

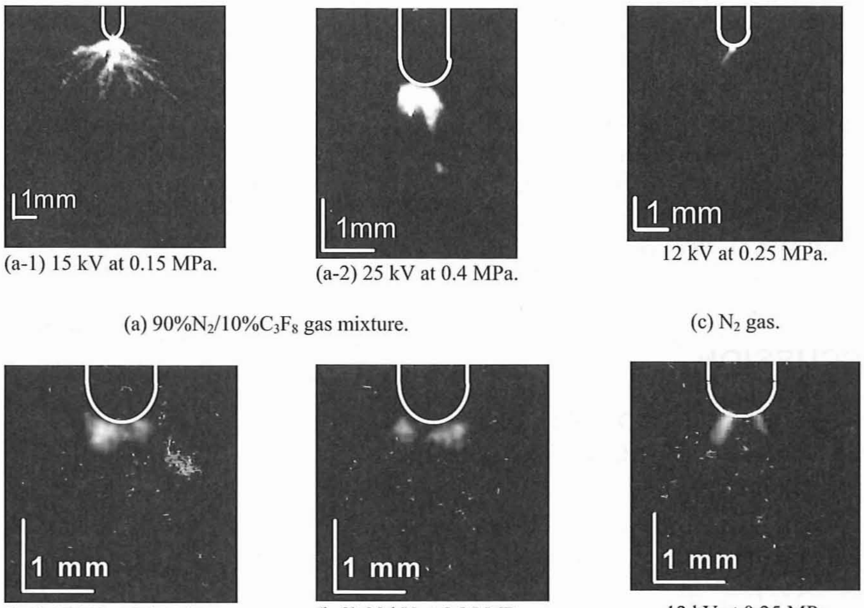
Figure 8. Applied voltage dependence of the peak value of PD current pulses during the positive half cycle for different gas pressures.

in Figure 8 but for CO_2/PFC gas mixture, some data points with higher gas pressure show decline trend with V_a where the gas pressure correspond to the range of being shift to the no corona stabilization region.

3.3 PARTIAL DISCHARGE LIGHT EMISSION PROPERTIES OF N_2/PFC AND CO_2/PFC GAS MIXTURES

As an example of difference in PD properties between N_2/PFC and CO_2/PFC based gas mixture, we observed PD light emission images of 90%N_2/10%C_3F_8 and 90%CO_2/10%C_3F_8 gas mixtures.

Figures 9a to 9d display photos of PD light emission images of 90%N_2/10%C_3F_8 and 90%CO_2/10%C_3F_8 gas mixtures together with N_2 and CO_2 unitary gas at (1) 0.15 MPa and around (2) P_m. All of the photos were taken by an accumulated exposure time of 20 μs near the phase angle of 90deg. of the alternating voltage, *i.e.* positive peak. As shown in these photos, PD light emission images reflect that of the base gas. Namely, PDs of CO_2/C_3F_8 gas mixture emit light in such a way that the light wraps the tip of the needle electrode irrespective of the gas pressure as in Figure 9b. On the other hand, in the low pressure range below P_m of



(a-1) 15 kV at 0.15 MPa. (a-2) 25 kV at 0.4 MPa.

(a) 90%N_2/10%C_3F_8 gas mixture.

12 kV at 0.25 MPa.

(c) N_2 gas.

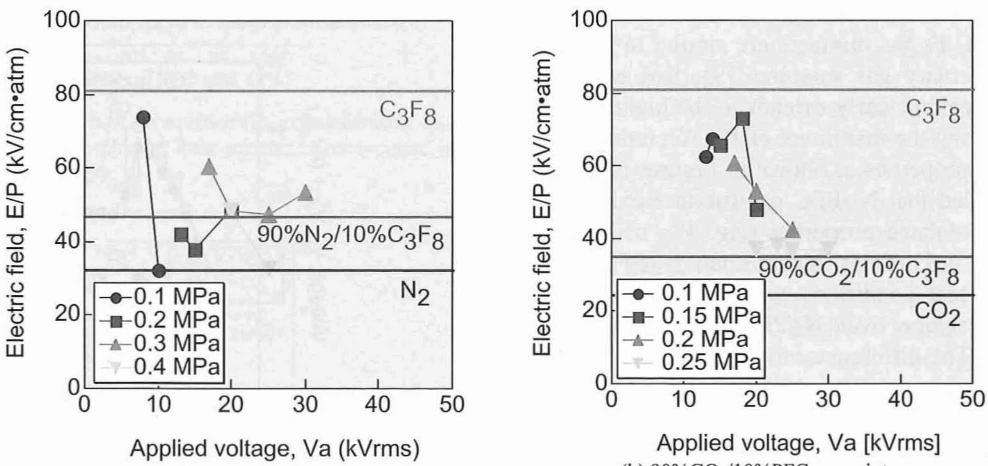
(b-1) 18 kV at 0.15 MPa. (b-2) 30 kV at 0.25 MPa.

(b) 90%CO_2/10%C_3F_8 gas mixture.

12 kV at 0.25 MPa.

(d) CO_2 gas.

Figure 9. PD light images for tested gas mixtures.



(a) 90%N_2/10%PFC gas mixtures. (b) 90%CO_2/10%PFC gas mixtures.

Figure 10. Applied voltage dependence of the reduced electric field strength calculated at the tip of the PD light emission images for different gas pressures. The three lines in each figure represent the reduced critical field of each gas.

the N_2/C_3F_8 gas mixture, tree-like PD light emission pattern is observed as in Figure 9a-1 which is characterized by the N_2 unitary gas as in Figure 9c. In the high pressure region above P_m, filamentary light characterized by leader discharges appears out of the light surrounding the needle tip as in Figure 9a-2.

Here, we indicated the applied voltage dependence of the reduced electric field strength calculated at a position where the PD stops. The space charge effect was not considered throughout the calculation. The term "critical field" in Figure 10 is defined as that the effective ionization coefficient is absolutely zero. The horizontal line in Figure 10a and 10b represents the reduced critical field strength for each gas. Note that PD in $90\%CO_2/10\%C_3F_8$ gas mixture develops up to the critical field of the mixture gas while PD in $90\%N_2/10\%C_3F_8$ gas mixture further develops to the critical field of the base gas (N_2). As the reduced critical field of N_2 is lower than that of $90\%CO_2/10\%C_3F_8$ gas mixture, these PD light emission development properties seem to result in lower V_{PD} of N_2/PFC gas mixtures compared with that of CO_2/PFC ones shown in Figures 6 and 7.

4 DISCUSSION

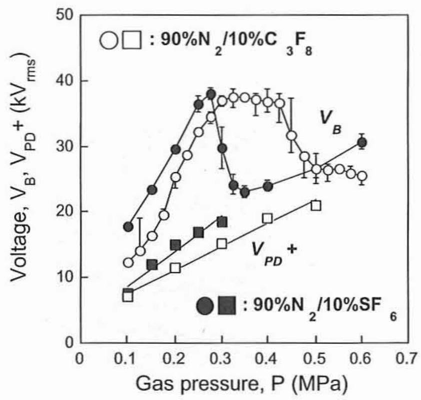
4.1 COMPARISON OF DISCHARGE PROPERTIES BETWEEN THE GAS MIXTURES INCLUDING PFC AND SF_6 GAS

Based on the results in Figures 6 and 7, we compared V_B and V_{PD} characteristics of the gas mixtures including PFC gas with those including SF_6 gas. In CO_2-based gas mixtures, V_B of CO_2/c-C_4F_8 gas mixture only exceeds that of CO_2/SF_6 gas mixture below 0.25 MPa, which corresponds to P_m of CO_2/c-C_4F_8 gas mixture. On the other hand, V_B of N_2/c-C_4F_8 and N_2/C_3F_8 gas mixtures exceeds that of N_2/SF_6 gas mixture in the whole gas pressure region tested and above 0.275 MPa corresponding to P_m of N_2/SF_6 gas mixture. As compared with Figures 11a to 11c, V_B characteristics of N_2/C_3F_8 gas mixtures are similar to those of the $CO_2/N_2/SF_6$ ternary gas mixtures [9]; that is, the corona stabilization region clearly extends to the higher gas pressures over P_m giving the maximum of V_B. According to these results and V_C' properties as shown in Figures 6a and 7a, it can be concluded that N_2/PFC gas mixture exhibits excellent breakdown voltage properties (*e.g.* V_{Bm} of N_2/c-C_4F_8 gas mixture is 1.33 times higher than N_2/SF_6 gas mixture) under the test conditions while CO_2/PFC gas mixture has the advantage over N_2/PFC gas mixture in terms of higher V_{PD}. The difference in V_B between N_2/PFC and CO_2/PFC gas mixtures may be attributed to the weaker electronegativity of N_2/PFC gas mixture which could reduce the shrinkage and heating of leader column and the activation of the streamer to leader transition [2] as well as the large electron scattering cross section of N_2 which is more likely to retard electrons [1], resulting in increase of V_B even at higher gas pressures.

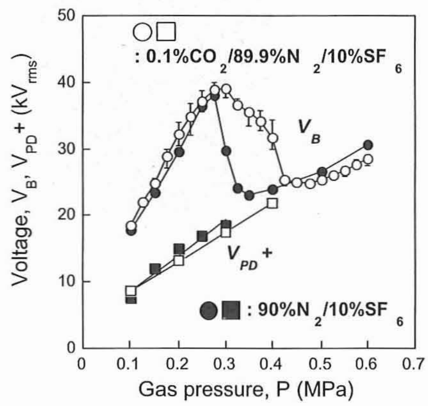
4.2 SYNERGY EFFECTS ON V_{PD} AND V_B

In order to compare the synergy effects on V_{PD} and V_B between the N_2 and CO_2-based gas mixtures including a PFC and SF_6 gas in Figures 6 and 7, we introduce the index R_n (%) to quantify the degree of the synergy effect [7,8]. The index R_n is defined as equation (1).

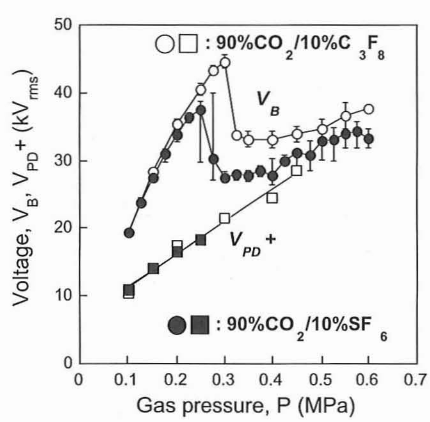
$$R_n = (V_S - V_r)/(V_1 - V_2) \times 100 \quad (1)$$



(a) Comparison between C_3F_8 and SF_6 gas in N_2-based gas mixture.



(b) Comparison between SF_6/CO_2 and SF_6 gas in N_2-based gas mixture.



(c) Comparison between C_3F_8 and SF_6 gas in CO_2-based gas mixture.

Figure 11. Difference in V_B vs P curves of N_2 and CO_2-based gas mixtures with C_3F_8 and SF_6 gas.

where the subscript " r " of V_r is the mixture rate of PFC or SF_6 gas, V_1 is measured V_{PD} of pure PFC or SF_6 gas (r = 100%) and V_2 is also measured V_{PD} of the base gas of N_2 or CO_2 (r = 0). V_r is V_{PD} at r% when it is assumed that V_{PD} changes linearly with the mixture rate r between V_2 and V_1, and V_S is measured V_{PD} at r% (r is 10% in this study). When the synergy effect on V_B will be discussed, we can use the similar scheme as given in Figure 12 by changing the parameters with the corresponding V_Bs.

Figure 13 indicates R_n of V_{PD}+ at 0.2 MPa for N_2 and CO_2-based gas mixtures including c-C_4F_8, C_3F_8 and SF_6 gas. R_n for CF_4 gas mixtures is removed in the figure because V_S exceeded V_1; *i.e.* V_{PD} of the CF_4 gas mixture did not obey Takuma's equation [7,8]. Figure 13 indicates that R_n for CO_2-based gas mixtures is larger than that for N_2-based ones irrespective of the additive gas of PFC or SF_6 gas. This higher R_n of CO_2/PFC gas mixtures than N_2/PFC ones was also confirmed not only in other gas pressures at 0.15 and 0.25 MPa in our study, but also in other study on c-C_4F_8 gas mixtures measured with the sphere to plane electrodes [7,8]. R_n of V_{PD}+ increases in order of gas mixture including c-C_4F_8, C_3F_8 and SF_6 gas. It can be concluded from Figure 13 that the synergy effect on V_{PD}+ for CO_2-based gas mixtures is much larger than that for N_2-based ones, and in terms of the additive gas, those for the PFC gas is smaller than that for SF_6 gas.

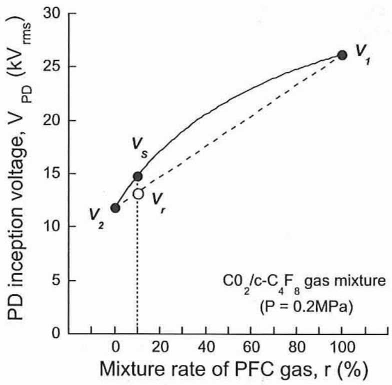


Figure 12. Parameters for index R_n of equation (1), explained using V_{PD} as an example. When R_n of V_B is estimated, these parameters are replaced with the corresponding V_B.

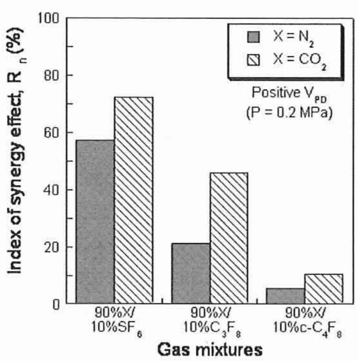


Figure 13. R_n of positive V_{PD} for different gas mixtures.

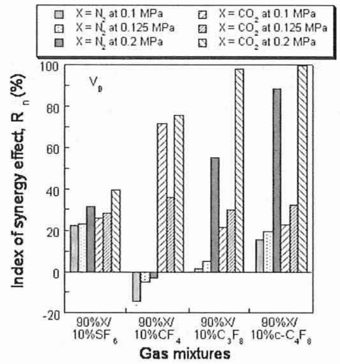


Figure 14. R_n of positive V_B for different gas mixtures.

Figure 14 shows R_n of V_B estimated at 0.1 and 0.125 MPa. These gas pressures were selected below P_m of unitary PFC gas to eliminate the corona stabilization effect as much as possible. It should be noted that only R_n for N_2/CF_4 gas mixture shows negative value, which means the "negative" synergy effect. In Figure 14, R_n of V_B for CO_2-based gas mixtures is larger than that for N_2-based ones. This result is similar with that for V_{PD}+ shown in Figure 13. Note that R_n of V_B at 0.2 MPa drastically rises to near 100% because V_B of the gas mixture becomes larger than that of the each unitary PFC gas. Consequently, the results in Figures 13 and 14 reveal that CO_2-based gas mixtures have an advantage in terms of the synergy effect on both V_{PD}+ and V_B as compared with N_2-based ones.

5 CONCLUSION

Electrical insulation and discharge properties of N_2 and CO_2-based gas mixtures including a PFC gas such as CF_4, C_3F_8 and c-C_4F_8 gas were experimentally investigated under non-uniform field with ac high voltage application. As a result, it was found that gas pressure dependence of V_B for both N_2/PFC and CO_2/PFC gas mixtures showed the N shape characteristics but their V_B vs P properties were different. V_B vs P properties of CO_2/PFC gas mixtures indicated the similarity of those of CO_2/SF_6 gas mixtures. V_B properties of N_2/PFC gas mixture were superior to those of CO_2/PFC ones because of the higher V_B properties and the wider corona stabilization region even under gas pressures over P_m. On the other hand, in terms of V_{PD}, CO_2/PFC gas mixtures had an advantage over N_2/PFC ones due to higher V_{PD} that might contribute to the development of a new PFC gas insulated power apparatus with corona free design. The advantage of CO_2/PFC gas mixtures was also found in the synergy effects on both V_{PD} and V_B, which were discussed by using the index R_n that quantifies the degree of the synergy effects. The synergy effect of CO_2-based gas mixtures was larger than that of N_2-based ones irrespective of the additive gas of the PFC (c-C_4F_8 or C_3F_8 gas) and SF_6 gas.

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