Breakdown Voltage of CO₂ at Temperatures around 4000 K and in Range from 300 to 700 K

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The breakdown voltage of high temperature CO₂ was measured at temperatures around 4000 K and in the temperature from 300 to 700 K at an absolute pressure of 0.1 MPa. A voltage was applied to the high temperature CO₂ through a set of two rod electrodes made of stainless steel with a diameter of 2 mm. The gap length between the electrodes was adjusted to be of 1 mm. The breakdown voltage of the hot CO₂ proved to decrease in inverse proportion to the increase in temperature, in the range from 300 to 700 K. Further increase in temperature of the CO₂ reduced the breakdown voltage more markedly. For example, at 4000 K the breakdown voltage was measured to be of 55 V. This breakdown voltage is only 1.1% of that at room temperature.

Keywords: breakdown voltage, high temperature gas, dielectric breakdown, thermal-ignition breakdown

1. Introduction

In circuit breakers, high temperature gas is generated by the arc established between contacts during current interruption. The high temperature gas remains between the contacts of the circuit breaker or may flow between metallic parts impressed with voltage. This voltage application might lead to the formation of an electrical discharge through the hot gas⁽¹⁾. To improve the performance of the circuit breakers, the critical conditions for forming the arc discharge should be investigated. However, the data are scarce on the related phenomena.

In case of high temperature gas with a high electrical conductivity, the transformation to the arc discharge is considered to result from the thermal-ignition breakdown due to Joule-heat in the gas. In relatively low temperature gases with less electrical conductivity, the transformation from the hot gas to the arc discharge is considered to be caused by the dielectric breakdown. Until now, we have investigated the breakdown voltage of high temperature CO₂ with a high electrical conductivity, in terms of the conductance of the gas⁽²⁾⁽³⁾. We focused on the CO₂, because CO₂ is expected to be alternative arc-quenching gas to SF₆⁽⁴⁾⁽⁵⁾.

The present paper summarizes the measurement result for the breakdown voltage in high-temperature CO₂ and air at temperatures around 4000 K and in the range from 300 to 700 K at an absolute pressure of 0.1 MPa. Firstly, whereas the

thermal breakdown of high temperature gas with high electrical conductivity was investigated in terms of the conductance as mentioned above, the temperature of the gas was evaluated from the conductance and found to be around 4000 K. This evaluation allowed us to discuss the breakdown voltage of the hot gas in terms of the temperature. Secondly, the dielectric breakdown voltage was measured for hot gas with temperatures from 300 to 700 K.

2. Temperature around 4000 K

2.1 Experimental Setup

2.1.1 Generation of high temperature gas Although the experimental setup and procedure were already described in a previous paper⁽³⁾, the detailed procedure is described in the present paper. As shown in Fig. 1, this setup had an arc chamber for generating hot gas and a testing chamber. The inner space of the chamber for producing hot gas had a thickness of 10 mm, sandwiched by two plates of polytetrafluoroethylene (PTFE). The electrodes in the chamber were made of graphite. Before the beginning of experiments on CO₂, not only the chamber for generating hot gas but also the testing chamber were filled with CO₂ at an absolute pressure of 0.1 MPa.

An alternating current with a frequency of 50 Hz was supplied during half a cycle to the graphite electrodes in the arc chamber from a 1600 μ F capacitor bank through a 6.5 mH reactor to produce an arc discharge. The discharge heated the gas that filled the chamber. The arc chamber had a PTFE tube 15 mm long with a cross-section of 10 $\times$ 10 mm² on the top in order to eject the hot gas to the testing chamber. Whereas the arc chamber was sandwiched by the PTFE plates, the arc established in the chamber and the hot gas ejected from this

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Fig. 1. Experimental setup for measurement of breakdown voltage in high temperature gases

chamber presumably seem to be free from PTFE-vapor contamination. The detailed explanations will be described in section 5.3.

2.1.2 Measurement of breakdown voltage As illustrated in Fig. 1, a pair of probing electrodes was located inside the testing chamber at a distance of 15 mm from the exit of the PTFE tube in order to measure the breakdown voltage of the hot gas. The electrodes were made of stainless steel (SUS) with a diameter of 2 mm. The gap length between the electrodes was adjusted to be 1 mm. A circuit that provided dc-voltage was connected to these probing electrodes.

2.2 Experimental Procedure First a 600 μF capacitor shown in Fig. 1 was charged with dc-voltage ranging from 30 to 80 V, so that the dc-voltage was applied between the probing electrodes. The arc current with a peak value of 1 kA was supplied to establish the arc in the arc chamber and further to generate the high temperature gas. After leaving the chamber the hot gas arrived at the probing electrodes. The voltage applied to this electrodes caused a leakage current i to flow through the hot gas giving the Joule-heat. The time variations of the voltage v between the probing electrodes, the leakage current i , and the arc current i_{arc} were measured. In our experiment, we estimated the conductance of the hot gas with the equation below.

$$g = \frac{i}{v} \quad [\text{S}] \quad \dots \dots \dots (1)$$

Another experiment has been made to find out that the hot CO₂ ejected from the exit of the PTFE tube at a velocity of 20–38 m/s and that the air 35–62 m/s. However, these velocities were very slow, so being found to give little influence on a pressure at a location of the probing electrodes, on the basis of the Bernoulli's equations. Accordingly, the pressure at the position of the probing electrodes is considered to be equal to 0.1 MPa.

2.3 Experimental Results

2.3.1 Breakdown voltage in terms of the conductance of the gas Figure 2(a) shows the typical waveforms of the current i_{arc} supplied to the chamber, the voltage v between the probing electrodes, the leakage current i flowing through hot gas and the conductance g . These waveforms were obtained for hot CO₂, when the initial dc-voltage across the probing electrodes was adjusted to be 60 V. As seen in Fig. 2(a)(iv), after rising gradually within an elapsed time from 2 to 3 ms, the conductance augments abruptly around

(a) Applied voltage of 60 V

(b) Applied voltage of 50 V

Fig. 2. Typical waveforms obtained in the experiments for CO₂ with high temperature and high electrical conductivity

3 ms. Figure 2(a)(v) presents the conductance during the period from 3 to 3.5 ms. The sudden growth in the conductance is observed after the conductance reaches 0.9 mS at 3.3 ms. This rise in the conductance is considered to result from a thermal-ignition breakdown of the hot CO₂ between the probing electrodes. This method of determining the occurrence of thermal-ignition breakdown was already confirmed and used in previous works ⁽²⁾⁽⁶⁾⁽⁷⁾.

Figure 2(b) presents the waveforms obtained for the hot CO₂ and for the applied voltage to the probing electrodes of 50 V. As shown in Fig. 2(b)(iv), the conductance of the hot

Fig. 3. Breakdown voltage measured for CO₂ and air around 4000 K

CO₂ gradually grows to a peak of 0.6 mS at time of 5 ms. After reaching this low peak value, the conductance decayed with the passage of time and no sudden increase is observed. In other words, thermal-ignition breakdown did not occur.

The results of the experiments are shown in Fig. 3. Filled marks correspond to the cases where thermal-ignition breakdown occurred. These marks designate the conductance of the gas and the voltage just before thermal-ignition breakdown occurrence. Open marks correspond to the cases where no thermal-ignition breakdown occurred, denoting the peak conductance and the voltage applied to the gas. In Fig. 3 we can trace a critical line separating the cases whether the breakdown was observed or not. As a result, for gas with a certain conductance we can determine the minimum dc-voltage inducing breakdown. For example, for hot CO₂ with an electrical conductance of 1 mS, the breakdown voltage was 55 V. In case of air with the same conductance, the breakdown voltage was 50 V. It is also seen in Fig. 3(a) that whereas being measured under the same experimental condition, the conductance fluctuates from 0.25 to 3 mS. Further, the minimum breakdown voltage is almost independent of the conductance in this range. Similar independence is also seen for air shown in Fig. 3(b).

2.3.2 Breakdown voltage in terms of the temperature of the gas Temperature is one of very important factors for indicating the state of high-temperature gas. Thereby, it is effective to evaluate the temperature from the measured conductance of the gas. Since being described in detail in

Fig. 4. Electrical conductivity of high-temperature CO₂ and air as a function of temperature at a pressure of 0.1 MPa

Ref. (7), the procedures (1) and (2) for evaluating the temperature from the conductance are explained in brief.

- (1) From the conductance g , the electrical conductivity σ of the gas was derived using the following expression:

$$\sigma = g \frac{L}{S}, \dots \dots \dots (2)$$

where L is a gap length between the probing electrodes. The quantity S is an equivalent cross-section of the area through which the current passes and was estimated to be $1.44 \pi \times 10^{-6} \text{ m}^2$ for electrodes 2 mm in diameter with a gap length of 1 mm⁽⁷⁾.

- (2) Figure 4 presents the electrical conductivity of high-temperature CO₂ and air as a function of the temperature at a pressure of 0.1 MPa. Using this characteristic curve of the electrical conductivity against the temperature, the temperature was determined from σ derived in the procedure (1).

Figure 3 also presents the determined temperature as horizontal axis. As found in Figs. 3(a) and (b), for instance, the conductance of 1.0 mS for CO₂ and air corresponds to 4100 K and 3500 K, respectively.

A conductance of 1 mS was selected as a representative value. The reason is given below. As seen in Fig. 3(a), the temperature corresponding to the conductance in the range from 0.25 to 3 mS is in the range from 3800 to 4500 K and this temperature range is as low as 700 K. In the other words, the variation in the representative conductance causes no significant change in the evaluated temperature. In addition, as found from Fig. 3(a), the temperature corresponding to the conductance of 1 mS is 4100 K for the CO₂ case, thus being an average value in the temperature range from 3800 to 4500 K. Similar facts are obtained for air case shown in Fig. 3(b).

Above considerations lead to the result that the breakdown voltage of 55 V was obtained for the CO₂ with the temperature of 4100 K and that the voltage of 50 V was obtained for air with 3500 K.

3. Temperature Ranging from 300 to 700 K

3.1 Experimental Setup Figure 5 illustrates the experimental setup to measure the breakdown voltage of gas with temperature ranging from 300 to 700 K. The setup had a thermostatic oven that heated the CO₂ gas or air to the desired

Fig. 5. Experimental setup for measurement of breakdown voltage in gas with temperature of 300 to 700 K

Fig. 6. Waveforms of the voltage v in the experimental setup shown in Fig. 5

temperatures and a circuit for applying voltage to the gas. The thermostatic oven was filled with gas at room temperature and atmospheric pressure of 0.1 MPa. As illustrated in Fig. 5, a pair of electrodes was located inside the thermostatic oven to measure the breakdown voltage of the hot gas. As in the experiment described above, the electrodes were made of SUS with a diameter of 2 mm. The gap length between the electrodes was adjusted to be 1 mm. No variation in the gap length was observed after heating the gas to the temperature of 700 K.

3.2 Experimental Procedure First, the CO_2 or air was heated inside the thermostatic oven to the temperature in the range of 300 to 700 K. Then, the $600\text{ }\mu\text{F}$ capacitor shown in Fig. 5 was charged with dc-voltage of 5.5 kV. When the switch SW was closed, the 100 pF capacitor started to be charged to 5.5 kV with a time constant of 1.0 msec. This voltage charged in the 100 pF capacitor was applied to the probing electrodes and to the hot gas through a $100\text{ k}\Omega$ resistor. The time variation of the voltage v applied between the electrodes was measured to find out the breakdown voltage of the hot CO_2 and air.

3.3 Experimental Results Figure 6 shows the waveform of the voltage applied to the probing electrodes for CO_2 at 500 K. After rising gradually to about 5.0 kV with an elapse time of 0.6 msec, the applied voltage abates abruptly. This phenomenon happens repeatedly, and is considered to result from the dielectric breakdown in the gas. Therefore, this abrupt decline in the voltage shows the breakdown of CO_2 at 500 K. From the waveforms obtained in the experiments, we determined the average breakdown voltage of the CO_2 or air at a given temperature. The breakdown voltage measured in the temperature range from 300

Fig. 7. Breakdown voltage as a function of the temperature for CO_2 and air

to 700 K is plotted against temperature in Fig. 7. As seen in Fig. 7, the breakdown voltage of the CO_2 and air decreased when the temperature of the gas increased. For this electrode configuration, the breakdown voltage at 300 K was measured to be of 4.9 kV. When the CO_2 was heated to 700 K, the breakdown voltage was reduced to 2.1 kV, 43% of the breakdown voltage at 300 K.

It is also seen in Fig. 7 that when plotted on a logarithmic scale graphic, the breakdown voltage becomes a linear function of the temperature of the gas with a slope of -0.98 . This shows that the breakdown voltage decreases almost in inverse proportion to the increase in temperature in the range of 300 to 700 K.

4. Discussion on Dependence of Breakdown Voltage on Temperature

Figure 7 also presents the breakdown voltage stated in section 2. In addition Fig. 7 shows the breakdown voltage in the temperature range from 2700 to 3000 K measured in other experiment⁽⁷⁾.

As described above, the breakdown voltage of hot CO_2 decreases in inverse proportion to the temperature from almost 4.9 kV to 2.1 kV, when the temperature of the gas increases from 300 K to 700 K. However, the breakdown voltage decreases in a higher rate at higher temperatures, so that at 2700 K the breakdown voltage is reduced to 350 V, and around 4000 K it decreases to around 55 V.

In addition, in the temperatures in range of 300 to 700 K, the breakdown voltages of CO_2 and air are almost equal. However, the breakdown voltage is higher for CO_2 than that for air at the same temperature in the range from 2700 to 4000 K. For instance, at 2700 K the breakdown voltage of CO_2 is 350 V, being higher than that of 115 V for air at the same temperature.

5. Discussion on Breakdown Voltages of CO_2 and Air

5.1 Temperature Range from 300 to 700 K

5.1.1 Calculation method At a room temperature,

Fig. 8. Particle composition of high-temperature CO₂ as a function of the temperature in range from 300 to 5000 K at a pressure of 0.1 MPa

Fig. 9. Critical strength of electrical field derived from theoretical calculation as a function of the temperature in range from 300 to 2000 K for CO₂ at a pressure of 0.1 MPa

the CO₂ and the air are known to have the same breakdown voltage, as shown in a Ref. (8). As seen in Fig. 7, this relationship maintains at temperatures in the range from 400 to 700 K. To understand this maintenance of the relationship, a theoretical calculation has been performed on the breakdown voltage, as mentioned below.

The electrical breakdown phenomenon in the temperature range from 400 to 700 K is considered to result from an avalanche development, because the hot gas in this temperature range has insufficient electrical conductivity causing an ohmic heating. Therefore a theoretical calculation was made on the basis of the avalanche development to derive the dependence of the breakdown voltage on the temperature. This derived breakdown voltage corresponds to a dielectric-ignition voltage, because the present calculation is based on an avalanche development. This theoretical calculation was performed for temperatures up to 2000 K. This is because the high-temperature gas with temperatures above 2000 K has the electrical conductivity causing the leak current, as mentioned in section 5.2.

Firstly, a theoretical calculation has been carried out to obtain particle composition of high-temperature CO₂ as a function of temperature at a pressure of 0.1 MPa on the assumption of establishment of the thermal equilibrium. Figure 8 shows the determined particle composition in the temperature range from 300 to 2000 K. Whereas the high-temperature CO₂ gas principally consists of CO₂ especially at temperatures up to 1000 K, CO and O₂ produce at temperatures of 1000–2000 K due to thermal dissociation of CO₂.

Secondly, we have performed a theoretical calculation to derive dependence of breakdown voltage of CO₂ on temperature in the range from 300 to 2000 K at a pressure of 0.1 MPa⁽⁹⁾. Since being reported in detail in a Ref. (9), the calculation method is described briefly in the present paper. In this calculation, ionization and attachment reactions arising from application of electric field to the high-temperature CO₂ were taken into account for above three molecules: CO₂, CO and O₂. In consideration of these reactions, the rate of production of electrons, P_i , due to the ionization reactions and the rate of disappearance of electrons, P_{da} , due to the attachment reactions were calculated for different strengths of the electric field at the same temperature. The strength of the electric field causing P_i to be equal to P_{da} was regarded as a critical strength E_{cr} of an electric field leading to the

breakdown of the high-temperature CO₂ at a certain temperature under a uniform electric field.

5.1.2 Calculation result Figure 9 depicts the critical strength E_{cr} derived from theoretical calculation as a function of the temperature in range from 300 to 2000 K for CO₂ at a pressure of 0.1 MPa. The critical strength E_{cr} declines inversely with augment in the temperature. This suggests that E_{cr} lessens proportionally with a reduction in a total number density of the high-temperature CO₂, further indicating that a critical strength of a reduced electric field defined as the ratio of the critical electric field to the total number density remains constant in the range of 300–2000 K.

Concerning a high-temperature air, Tanaka et al. have also shown the critical strength E_{cr} of an electric field as a function of the temperature for a high-temperature air at a pressure of 0.1 MPa⁽¹⁰⁾. This result also revealed that E_{cr} of the high-temperature air abated in inverse proportion to a temperature in the range from 300 to 2000 K.

In summary, both CO₂ and air show the inverse diminution in dielectric ignition voltage with a growth in the temperature up to 2000 K. As a result, CO₂ and air have the same breakdown voltage at temperatures of 400–700 K.

5.2 Temperature around 4000 K

5.2.1 Calculation method As seen in Fig. 3, the CO₂ shows a higher breakdown voltage than the air in the temperature range from 2500 to 4000 K. The explanations to interpret this relationship are given below.

The high-temperature gas around 2500–4000 K is considered to have sufficient electrical-conductivity, compared with the gas at temperatures below 700 K. The application of the voltage to the high-temperature gas causes a leak current to pass through the gas. Actually, the leak current is seen in Fig. 2(a)(iii) and (b)(iii). Similar leak-current due to the voltage application to the high-temperature gas was also confirmed for the hot gas ejected from a molded-case circuit breaker during current interruption⁽¹⁾. This passage of the leak-current is considered to produce ohmic heating in the gas. Accordingly, the breakdown phenomenon around several thousands Kelvin is considered to result from the ohmic heating, thus being regarded as a thermal-ignition breakdown phenomenon.

The thermal-ignition breakdown phenomenon is affected

Fig. 10. Time variation in temperature resulting from ohmic heating for initial temperature of 4000 K (Pressure: 0.1 MPa)

by a power inputted into the high-temperature gas and a power dissipated from the gas. However, the dissipated power depends on a thermal conduction and a convection losses and these losses are influenced by various factors: not only the temperature but also a shape and a dimension of the high-temperature gas. Thus, at the present stage, it is difficult to determine the dissipated power with a high accuracy. Hence, as a first approach, we derived a rise process of the temperature T of the CO_2 and the air due to the inputted power and discussed the dependence of the rise rate of the temperature T on the gas kind. An equation expressing a variation in the temperature T is written as ⁽¹¹⁾

$$\rho C_P \frac{\partial T}{\partial t} = \sigma E^2, \dots \dots \dots (3)$$

on the assumption of an establishment of thermal equilibrium. In above expression, ρ is a mass density of the gas, σ is an electrical conductivity, C_P is a specific heat at a constant pressure and E is a strength of the electric field. The quantities σ , ρ and C_P under the thermal equilibrium have been found from another calculations for high-temperature CO_2 and air. Numerical analysis of the Eq. (3) for different strengths of E enabled us to obtain the time variation in the temperature for the CO_2 and air.

5.2.2 Calculation result Figure 10 represents time variation in the derived temperature for different strengths of the electric field. This time variation was obtained for an initial temperature of 4000 K. As seen in the case of air, the temperature for E of 50 and 90 V/mm slowly rises with a passage of time, then augmenting abruptly to 10000 K around a time of 6 and 20 μs , respectively. We considered this abrupt enlargement in the temperature to correspond to the thermal ignition breakdown. However, no sudden growth in the temperature, namely no thermal ignition, is seen for E of 10 V/mm during the time period shown in the figure. On the other hand, as shown in Fig. 10(a), although the application of E of 90 V/mm to the CO_2 also causes the thermal ignition, the occurrence time of the thermal ignition for the CO_2 is slower than for the air. Furthermore, the application of E

Fig. 11. Quantity γ as a function of temperature for CO_2 and air (Pressure: 0.1 MPa)

of 50 V/mm to the CO_2 results in no thermal ignition in the time range. Above calculation results suggests that the higher strengths of the electric field results in the thermal ignition of the CO_2 than of the air. This suggestion was also confirmed for an initial temperature of 3000 K. Although being are simplified, the calculation conditions adopted in the present section explain higher breakdown voltage of CO_2 than of air.

Introduction of a coefficient γ defined as $\sigma/(\rho C_P)$ permits to transform Eq. (3) to another form:

$$\frac{\partial T}{\partial t} = \gamma E^2. \dots \dots \dots (4)$$

In this expression, only γ depends on the gas kind. Furthermore, the rate of the rise of the temperature is found to decline with reduction in γ at the same E .

Figure 11 presents γ as a function of temperature for CO_2 and air at a pressure of 0.1 MPa. The CO_2 is found from Fig. 11 to have less γ than air. This lower γ results in slower rise in the temperature, thus causing the higher thermal ignition voltage.

5.3 No Contamination of PTFE Vapor The arc chamber was adjusted to be 10 mm in thickness. Since this thickness is fat enough, no considerable amount of the PTFE-vapor is considered to be contaminated to the arc established in the arc chamber, on the basis of the facts mentioned below.

Ohno et al. have adopted a similar flat-type arc quenching chamber with various thicknesses and have performed experiment on an ac air arc with currents around interrupting capability ⁽¹²⁾. They found that the peak value of the current of the interrupting capability declined with augment in the thickness from 2 to 8 mm. They have also made the same experiments for the flat-type air arc quenching chamber sandwiched by ceramic plates, because the ceramic plates was hardly ablated even by high-current arc and thus the arc in this chamber burned in almost pure air. As a result, this chamber proved to have an interrupting capability almost same to the PTFE-plate chamber with the thickness of 8 mm. They also suggested from another experiment that contamination of the ablated PTFE vapor into the air arc results in rise in the interrupting capability of the arc chamber ⁽¹³⁾.

Above facts indicate that reduction in the interrupting capability due to augment in the thickness results from diminution in the concentration of the PTFE vapor, thereby suggesting that fatter thickness of the chamber causes smaller

concentration of the PTFE vapor in the arc.

From the viewpoint of the interrupting capability, the PTFE-plate chamber of the thickness of 8 mm is considered to allow the arc to burn in almost pure air. Since the arc chamber used in the present research had the thickness of 10 mm fatter than 8 mm, the arc chamber enabled the arc to be established in CO₂ or air almost free from ablation gas, thus generating pure high-temperature CO₂ and air.

6. Conclusion

We measured the breakdown voltage of CO₂ and air at temperatures around 4000 K and in the temperature from 300 to 700 K. The breakdown voltage of hot CO₂ decreases from 4.9 to 2.1 kV when the temperature of the gas increases from 300 to 700 K. Also, at around 4000 K, the breakdown voltage of CO₂ decreases to 55 V.

(Manuscript received Oct. 28, 2004,

revised May 11, 2005)

References

- (1) Y. Yokomizu and T. Matsumura: "Arcing Phenomena through Hot Gas Ejected from Moulded-Case Circuit Breakers during The High-Current Interruption Process", *J. Phys. D: Appl. Phys.*, Vol.34, pp.116–123 (2001)
- (2) P.C. Almiron, Y. Yokomizu, and T. Matsumura: "Thermal Breakdown in High Temperature CO₂ and Air Impressed with DC Voltage at Atmospheric Pressure", The Papers of Joint Technical Meeting on Electrical Discharges, Switching and Protecting Engineering and High Voltage, IEE Japan, ED-03-230/SP-03-152/HV-03-145 (2003)
- (3) P.C. Almiron, K. Yamamoto, Y. Yokomizu, D. Ohta, and T. Matsumura: "Measurements of Thermal-Breakdown Voltage for High Temperature CO₂ and Its Electrical Conductance", Proc. of XV International Conference on Gas Discharges and Their Applications, pp.69–72 (2004)
- (4) Y. Yokomizu, K. Ito, T. Kojima, and T. Matsumura: "Decaying Processes of Conductance around Current Zero for Wall-Stabilized Arc in Various Gases", *T. IEE Japan*, Vol.121-B, No.6, pp.767–774 (2001-6) (in Japanese)
- (5) T. Uchii, H. Kawano, T. Nakamoto, and H. Mizoguchi: "Fundamental Properties of CO₂ Gas as an Arc Quenching Medium and Thermal Interruption Performance of Full-Scale GCB Model", *IEEJ Trans. PE*, Vol.124, No.3, pp.469–475 (2004-3) (in Japanese)
- (6) Y. Yokomizu, S. Arisawa, and T. Matsumura: "Conductance of Hot Gas on Occurrence of Arcing Phenomenon under Different Electrode-Shape Conditions", The Papers of Joint Technical Meeting on Electrical Discharges, Switching and Protecting Engineering and High Voltage, IEE Japan, ED-03-16/SP-03-05/HV-03-05 (2003) (in Japanese)
- (7) T. Matsumura, D. Ohta, P.C. Almiron, K. Yamamoto, and Y. Yokomizu: "Measurements of Breakdown Voltage of CO₂ and Air at Temperatures between 300 K and 3000 K at a Pressure of 0.1 MPa", The Papers of Joint Technical Meeting on Electrical Discharges, Switching and Protecting Engineering and Static Apparatus, IEE Japan, ED-04-55/SP-04-12/SA-04-38 (2004) (in Japanese)
- (8) O. Farish, M.D. Judd, B.F. Hampton, and J.S. Pearson: "SF₆ Insulation Systems and Their Monitoring", in *Advances in High Voltage Engineering*, A. Haddad and D. Warene, Ed., p.39 (2004)
- (9) K. Yamamoto, Y. Yokomizu, T. Matsumura, and M. Shibuya: "A Study on Dielectric Breakdown Strength of High Temperature CO₂ in Range from 1000 to 3000 K at Pressure of 0.1 MPa", 2003 National Convention Record IEE Japan, 6-196 (2003) (in Japanese)
- (10) Y. Tanaka, T. Sakuta, and S. Shibuya: "Investigation on Effective Ionization Coefficient and Critical Electric Field in Air in Temperature Range of 300–3500 K by Solving Boltzmann Equation", *IEEJ Trans. PE*, Vol.124, No.1, pp.162–168 (2004-1) (in Japanese)
- (11) Y. Yokomizu, P.C. Almiron, S. Hirata, and T. Matsumura: "Thermal Breakdown Resulting from Temperature Rise in High Temperature gases", The Papers of Joint Technical Meeting on Electrical Discharges, Switching and Protecting Engineering and High Voltage, IEE Japan, ED-03-215/SP-03-137/HV-03-130 (2003) (in Japanese)
- (12) H. Ohno, H. Naganawa, S. Kawamami, and Y. Kito: "Arc interruption performance in a flat quenching chamber distinguished by 70 GHz microwave diagnosis", *T. IEE Japan*, Vol.105-B, No.11, pp.933–940 (1985-11) (in Japanese)
- (13) H. Ohno, H. Naganawa, N. Kato, and Y. Kito: "Particle Composition in High Temperature Air Contaminated by Ablation Gas of PTFE and its Applications to Electron Density Measurement by a Microwave Method", *T. IEE Japan*, Vol.108-B, No.4, pp.157–164 (1988-4) (in Japanese)

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