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Space Charge Distribution of Surface Discharge in SF_6 Gas

By

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Abstract

Surface space-charge distributions produced by streamers in SF_6 are investigated using the probe method with a high speed temporal resolution. Probes which also act the role of a plane electrode, are used for measuring the space-charge field. The fields are measured oscilloscopically and converted into space-charge densities by a numerical calculation. This inverstigation has revealed the charge distribution before the disturbance caused by the well known "back-discharge" . This method is also applied for surface discharges in air, and its results are compared with that obtained in SF_6.

1. Introduction

Studies on the mechanisms of surface discharges along the surface of solid insulators have been made in order to obtain a basic knowledge for the insulation design of spacers, which suspend or hold the high voltage conductors in electric power equipments using SF_6 gas as an insulation medium. Space-charge produced by the discharge along the surface of insulators, enhances the electric fields and is considered to play an important role in further developments of the discharge. Quantitative analysis concerning the role of the space charge, however, have been very few, since the measurement of the distribution of the space-charge is difficult. This dificulty is caused by "back-discharge" phenomena which take place when applied voltages decrease and disturb the space-charge distribution. The measurement of the space-charge has been done by many researchers by the use of the dust figure method or the probe method[1),2)]. Both of these methods, however, are generally utilized after the occurrence of the back-discharge. so that the true charge can not be measured. In order to measure the true charge, it is necessary to develop a new technique which can observe the temporal behavior of the space-charge.

The purpose of this study is to develop a new technique and to make clear the space-charge and its destribution before the occurrence of the back-discharge. For this purpose, the plane electrode of a rod-plane electrode system with a dielectric plate between the electrodes, is divided into many circular parts, and each part is used as an electrostatic probe[3]. The probes are sensitive to the vertical electric field caused by the space–charge due to surface discharge on and along the dielectric plate. The electric fields are observed oscilloscopically and converted into the space charge density with the aid of a numerical calculation using a computer. The oscilloscopic measurement makes it possible to analyse the space charge before the occurrence of the back discharge.

This probe method is applied for surface discharges under a short and square voltage application with the polarity of the voltage, the material of the dielectric plate and the pressure of SF_6 gas as the parameter. The investigation is firstly caried out in air for the sake of preliminary experiment, and the results are compared with the results in SF_6. The conventional dust figure method is also employed to supplement the results.

2. Experimental apparatus and procedure.

The square voltage had a pulse width of 260 ns and a rise and a fall time of about 30 ns. The voltage generator consisted of a *DC* voltage supplier, a power cable for wave shaping, a resistance and a gas gap switch. The maximum voltage of this generator was 50 kV. The switch was equipped in a vessel, and the vessel was located at an upper part of a pressure tank as shown in Fig. 1. The power cable was charged from the *DC* voltage supplier up to twice the value of the desired voltage. Before the charging, the vessel was filled with a gas at a pressure that was adequate to withstand the charging *DC* voltage. The switch was closed when the gas was released through a valve installed in the vessel. The square voltage with a magnitude of half the charged *DC* voltage was supplied to the rod electrode.

The rod–plane electrode was housed in a pressure tank with an internal diameter of 50 cm and volume of 260 litres. The tank could withstand the absolute gas pressure of 4 atm. The rod electrode was made of brass and had a diameter of 1.0 cm with a semisphere on its head. The plane electrode was made of copper and its diameter was 20 cm. All the probes were located within a radious of 5 cm from the center of the plane, as will be explained later.

As for the materials of the solid dielectrics, polymethyl metaclylate (PMMA) was mostly used. The relative dielectric constant ε of PMMA was about 3.0. The data concerning the space charge for the PMMA are compared with the data obtained for polyethlene (PE), cross linked polyethlene (XLPE) and epoxy resin. The relative dielectric constant of PE, XLPE and epoxy was 2.3, 2.3 and 4.7 respectively. Gas gaps formed between the insulator and the plane electrode

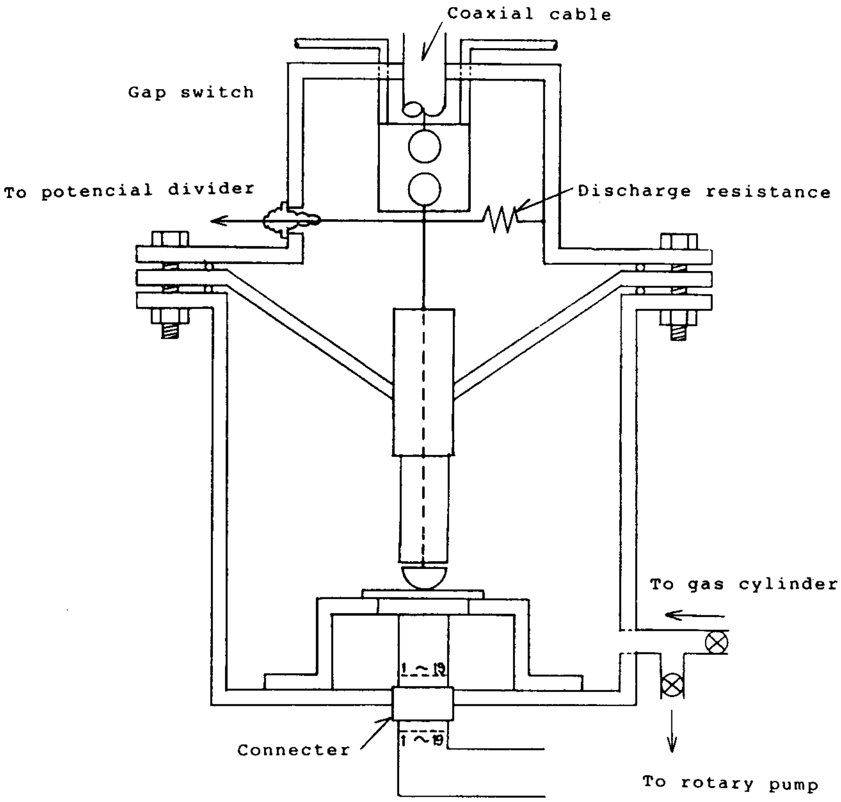


Fig.1 Experimental apparatus.

were filled up with silicon oil, otherwise a discharge would take place in the gaps and pour the conduction current into the probes. The conduction current would make the electrostatic measurement impossible.

The experiment in SF_6 gas was carried out in pressures of 0.5, 1.0 and 1.5 atm with the voltage polarity and its height as parameters. The experiment in air at atomospheric pressure was carried out only for PMMA.

The copying machine blue and brown color toners were used to observe the dust figure. Since the blue and brown toners attach respectively to the positive and negative space-charge, the charge polarity could be identified from the color.

3. Theory and techninque of space charge measurement.

The distribution of the space-charge on the insulator was estimated from the electric field at the plane electrode. As shown in Feg. 2, the plane electrode was divided into 19 concentric circular parts at intervals of 0.2 mm. Each circular part

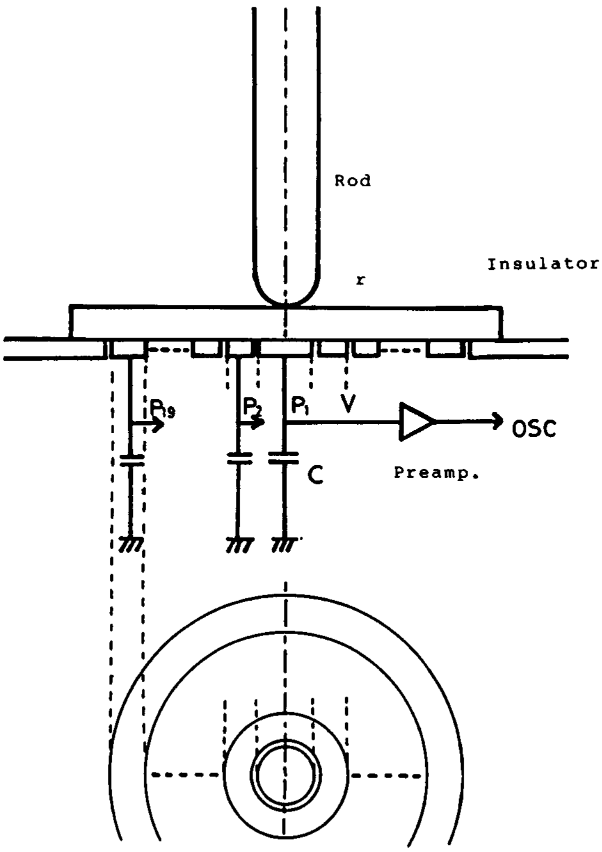


Fig.2 Electrode system and probes.

was used as the probe for the field measurement. The width of the probes was 1.8 mm for probe numbers $i=1$ to 10 and 2.8 mm for $i=11$ to 19, number $i=1$ being the center most probe. The diameter of the 19 th probe was 100 mm and each of these probes was grounded through the capacitor (C).

Concerning the discharges under pulsive voltage application in non-uniform gas gaps, it is identified that the discharges are initiated by "electron avalanche", which in turn develops to "leader" stage via "streamer" stage. The leader is a stage that leads the gap to the final flashover. In this study, space charge distribution for the streamer stage is of major concern.

Providing that the positive square voltage is applied to the rod electrode, and that the streamer propagates along the insulator surface, the electrons produced along the streamer path are drawn toward the rod. Then, the positive space-charge with an amaunt equalling that of the number of electrons absorbed by the rod, is generated along the streamer path. The electric line of force starting from the space-charge arrives at the probes through the insulation plate and induces the charge on the probes.

The induced charges were measured from voltages across the capacitors by using oscilloscopes. The signals were transmitted to the oscilloscopes through preamplifiers and coaxial cables. The preamplifiers were utilized for impedance conversion, and had an input impedance of 30 MΩ and an output impedance of 75 Ω. The step response of the preamplifiers was 10 ns. However, the response was reduced to about 40 ns to cope with the electric noise when the measurement was done for negative voltage in air, and for both polarities of voltages in SF_6 gas. Since four sets of preamplifiers were provided for this investigation, the signals of four probes were measured simultaneously with the aid of two sets of two-beam oscilloscopes (Tektronix 7844).

The electric fields E_s due to the space-charge perpendicular to the probes are expressed by *Eq.* (1), provided the space-charge produced by the streamer is distributed uniformly along the insulator surface,

$$E_s = CV / \varepsilon S, \tag{1}$$

where V denotes the voltage across the capacitor C, and S the surface area of the probe. Since the thickness of the insulator (2 mm) is small, all of the electric line of force from the space charge goes almost straight and perpendicular to the probe. Thus, the density of the space charge σ_s can simply be expressed by *Eq.* 2.

$$\sigma_s = \varepsilon E_s \tag{2}$$

In the case of the space-charge which distributes within approximately 1 cm from the rod electrode, however, it was found by numercal field calculation that part of the electric line of force was directed toward the rod electrode. Therefore, *Eq.* (2) should be modified to *Eq.* (3) in order to take into account the above effect.

$$\sigma_s = k\varepsilon E_s \quad (k > 1) \tag{3}$$

In *Eq.* (3), k is the coefficient obtained by the numerical electric field calculation assuming the uniformly distributed space-charge on the insulator surface. In the calculation, the area of the assumed space-charge was varied,

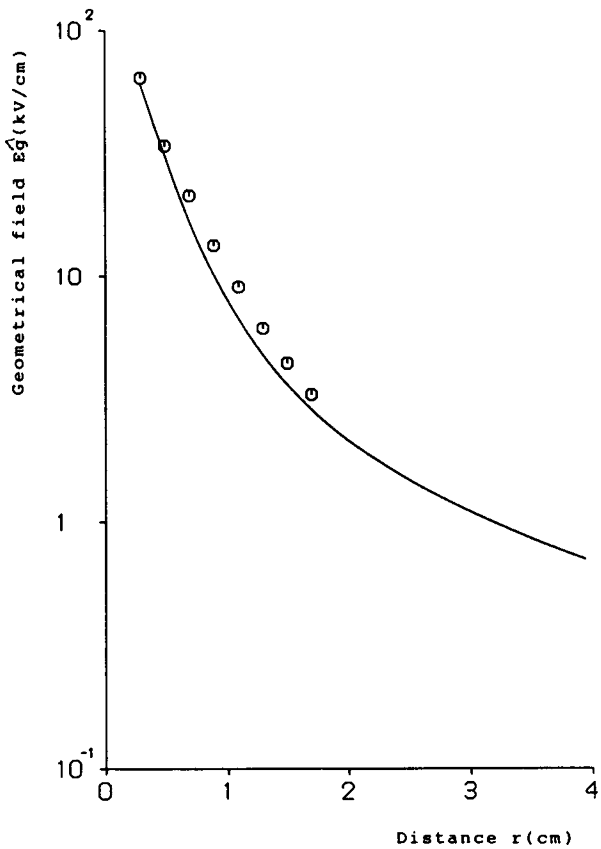


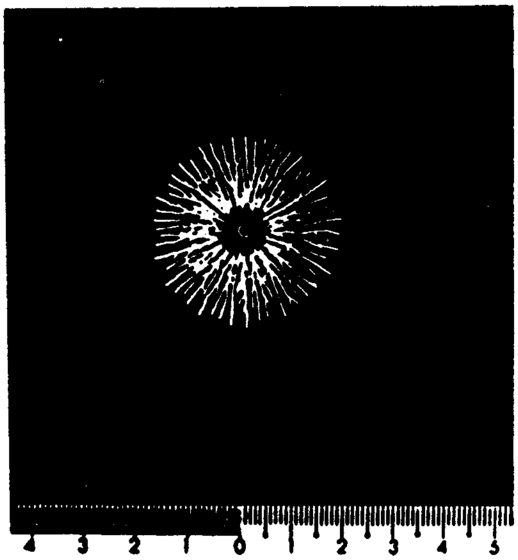
Fig.3 Geometrical field. (Insulator; PMMA, O; Experimental, —; calculated.)

depending on experimentally observed dust figures. The charge simulation method, combined with the surface charge method, were employed for the calculation.

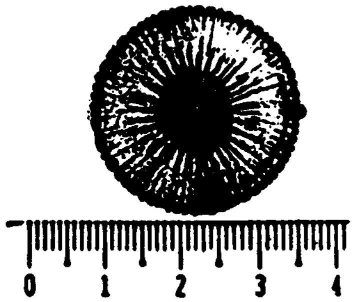
The measured electric field, using the above mentioned probes, includes a geometrical filed due to the applied voltage, as is shown later in Feg. 6. The geometrical component is denoted by E_g. The experimental and calculated geometrical fields are presented in Fig. 3 for comparison. With reference to Fig. 3, both results show a fairly good agreement with each other. The error in the results is deduced to be within 10%.

4. Experimental results in air.

4.1. Dust figure and characteristics of streamer.



(a) Positive streamer (+10kV).



(b) Negative streamer (−20kV).

Fig.4 Dust figures in air. (Insulator; PMMA.)

Figures 4 (a) and (b) demonstrate the examples of the dust figure of the streamer in air. It has been reported by many authors that the figures of streamers by applying positive voltage and negative voltage differ from each other in terms of their shape. The shape of a positive streamer; a streamer under the positive voltage application, looks like a dendrite. On the other hand, a negative streamer; a streamer under the negative voltage application, looks like a disk with a flower pattern in it. The central parts in both of the dust figures are disturbed, however, because of the occurrence of the back-discharge. The back-discharges take place and consume the space charge when the applied voltage decreases to a certain value. This is caused by the reversing of the electric field along the insulator that takes place because of the space-charge effect. This reverse field initiates a discharge from the space-charge toward the rod electrode. From Fig. 4, the disturbance is found to be more severe for the negative streamer than for the positive streamer. As mentioned earlier, the aim of this study is to measure and make clear the space-charge distribution before the disturbance.

The length of the positive and negative streamers are presented in Fig. 5. The length of the streamers in SF_6 gas are also presented for comparison. The propagation velocity of the streamers in air was found to be so fast, as will be

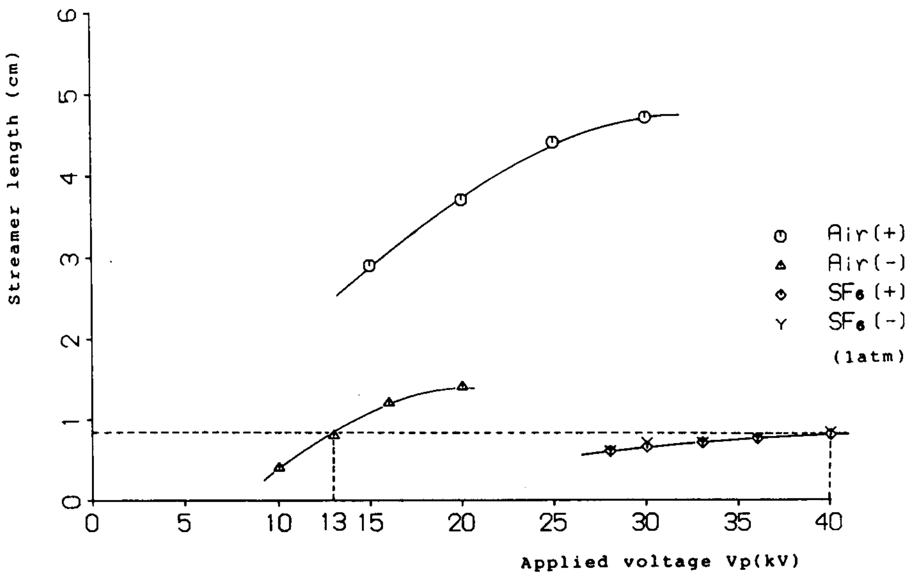


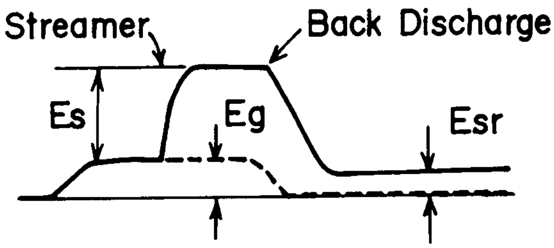
Fig.5 Relations of streamer length vs. applied voltage. (Insulator; PMMA.)

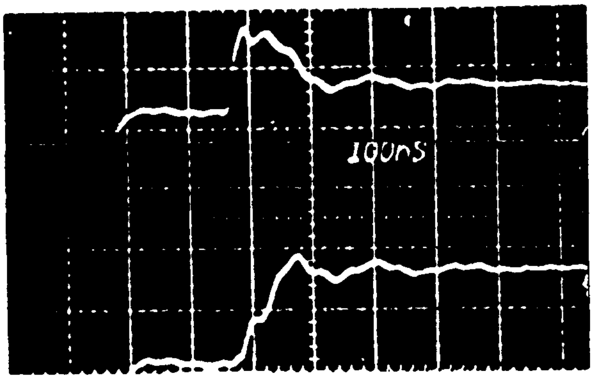
mentioned later, as to finish the propagation within the duration of the applied square voltage.

4.2 Space charge density of streamers in air.

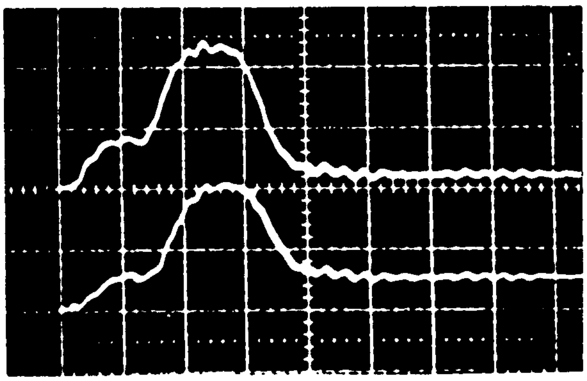
The probe signal associated with the streamer by applying the positive voltage is shown in Fig. 6 (a). In this example, the streamer occurs at 160 ns after the voltage application. The space-charge due to the positive streamer induces the electric field E_s. The field E_s is added to the geometrical field E_g. The signal shows a sudden decrease at 260 ns accompanied by the reduction of the applied voltage and also by the occurrence of the back discharge. After that, the probe signal has a remnant field E_{sr}. This field E_{sr} is the value indicating that a space-charge remained after the back discharge. The probe signal for the negative streamer is almost the same as for the positive streamer, as shown in Fig. 6 (b), where the polarity of the signals are reversed.

In order to analyse the space charge distribution, the field E_s measured as mentioned above, was converted into space charge density σ_s for each of the





(a) Positive streamer.
(V_p=+13kV. Upper trace: r=0.7cm, +36kV/cm/div.,
lower trace: r=1.5cm, +15kV/cm/div.)

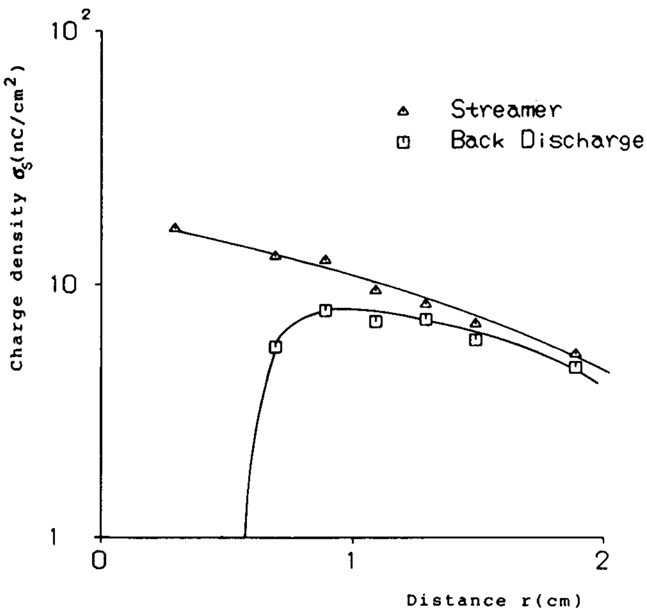


(b) Negative streamer.
(V_p =−13kV. Upper trace: r=0.5cm, −21kV/cm/div.,
lower trace: r= 0.9cm. −10kV/cm/div.)

Fig.6 Probe signals in air. (Insulator; PMMA.)

probes by using *Eq.* (2) or *Eq.* (3). The result of the relation between the density and its location for the positive streamer is shown in Fig. 7 (a), when the voltage height V_p is +13 kV. The location is denoted by r (cm) which is the distance along the surface of the insulator PMMA from the rod tip to the center of the probe in measurement. The experiment was done for various voltage heights in the range of +10 kV to +30 kV. It has been found from these measurements that the density increases with an increase in the voltage height, and decreases with the distance. All of the measured density was found to be within a range of 5 to 80 nC/cm². The density at the tip of the streamers is almost constant for the various voltages, and is within a range of 5 to 7 nC/cm².

The measurements were also carried out for various negative voltages from −13 kV up to −30 kV. An example of the results for the voltage height of −20 kV is shown in Fig. 7 (b). The space charge density for negative streamers has been found to behave, with the variation of voltage height and with the distance, in the same manner as the positive streamers. The density around the negative streamer tip was also almost constant and was within a range of −8 to −10 nC



(a) Positive streamer (V_p =+13kV).

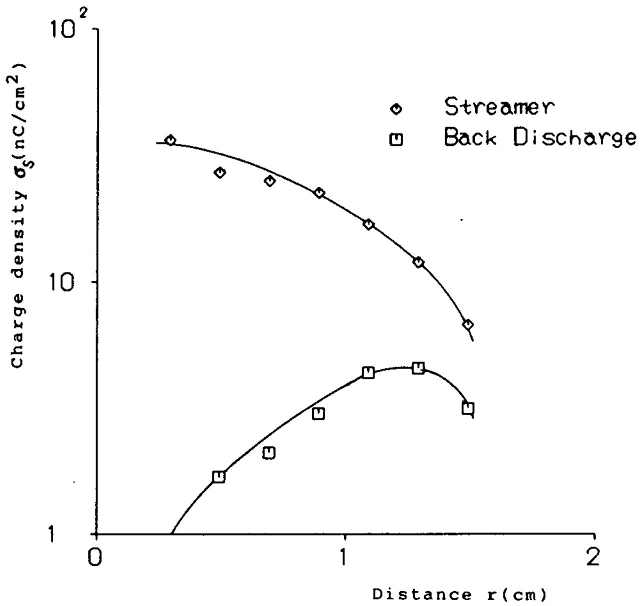
Fig.7 Distribution of space–charge for streamers in air. (Insulator; PMMA.)

/㎠. This value is a little higher than that of the positive streamers.

As explained before in Fig. 6, the back-discharges occur at the end of the square voltage. The space charge density after the back discharge was also analysed from the remnant field E_{sr}. Equations (2) and (3) were again applied to estimate the density. The results are shown and compared in Fig. 7 (a) and (b). It can be seen in Fig. 7 (a) that the density of the remnant charge for the positive streamer is extremely low around the rod electrode because the space charge due to the streamer is consumed by the back-discharge. However, the remnant density approximately keeps its previous value at a location far from the rod tip. From Fig. 7 (b), the remnant charge density for the negaiveive streamer is considerably lower as a whole in comparison with the previous value. Thus, in the case of the negative voltage application, it is found that the previous space charge densities due to the streamer and the remnant charge density are strictly different from each other.

4.3 Propagation velocity and the line charge density of positive streamer path.

It has been understood that in surface discharges the streamer starts its



(b) Negative streamer (V_p=−20kV).

Fig.7 Distribution of space-charge for streamers in air. (Insulator; PMMA.)

development in a gas gap near the tip of the rod electrode and propagates along the surface of the insulator. Then, the space-charge field E_s suddenly increases as the streamer tip reaches above the probe. Therefore, the relationship of the propagation distance r with the time t can be measured from the probe signal. The relationships for positive streamers by applying the voltages of + 12 kV, + 13 kV and + 15 kV are shown in Fig. 8. The differential of the r-t curves indicates the propagation velocity, and is found to be in a range of 2×10^7 cm/sec. to 8×10^7 cm/sec.. The velocity was found to increase with the voltage height and decrease as the streamer propagates further from the rod electrode.

As the streamer propagates, each of its paths ramifies and the number of the branches increases with the propagation distance. This appearance is shown in Fig. 9. The space-charge is generated along the path. The line charge density ρ (C/cm) along the path can be deduced from the number of the branches and the charge density σ_s (C/cm²) by Eq. (4),

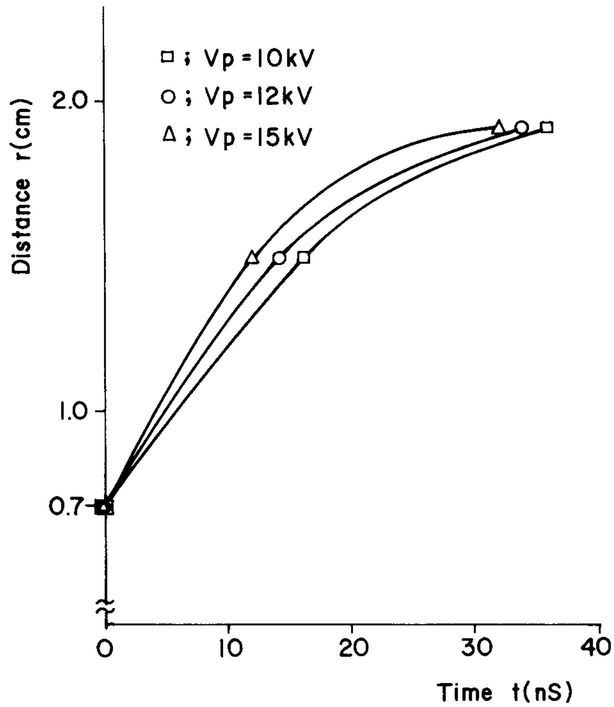


Fig.8 Relations between propagation distance r and time t of the positive streamer in air. (Insulator; PMMA.)

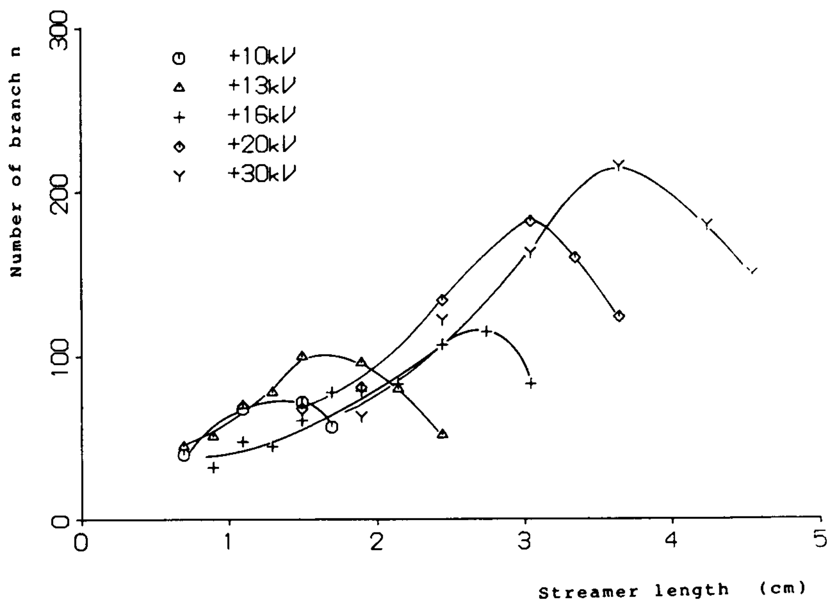


Fig.9 Relations between number of branches and streamer length for positive streamer in air. (Insulator; PMMA.)

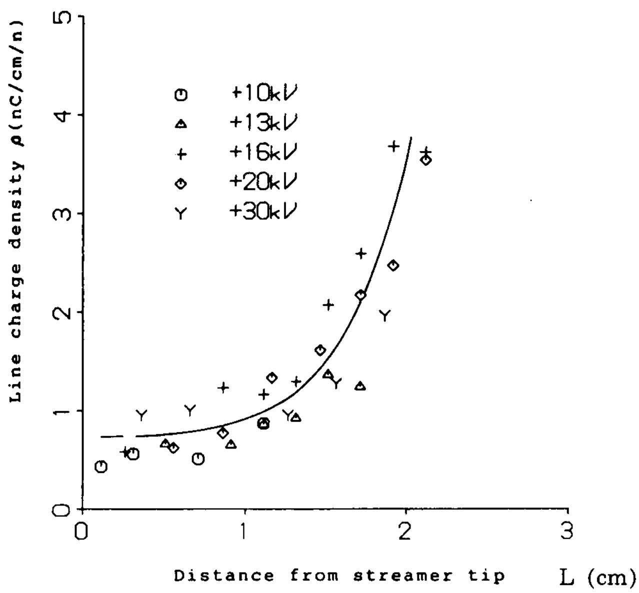
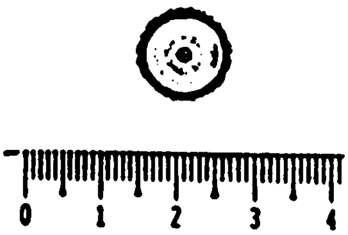
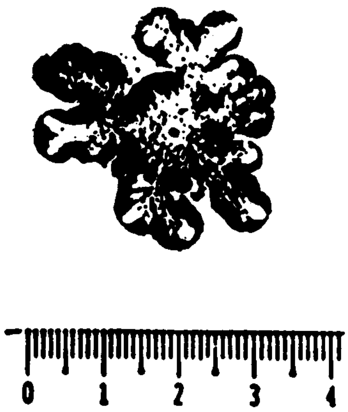


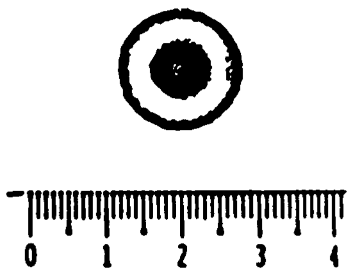
Fig.10 Line charge density of the positive streamer in air. (Insulator ;PMMA.)



(a) Positive streamer (V_p=+30kV).



(b) Positive leader (V_p =+40kV).



(c) Negative streamer (V_p =−40kV).

Fig.11 Dust figures in SF_6 of 1 atm. (Insulator ; PMMA.)

$$\rho = \pi\sigma_s \, (2R+\Delta R) \, \Delta R / n \qquad (4)$$

where n is the number of the branches above the probe in concern, R is the inner radius of the probe and ΔR is the width of the probe. ρ is the average line charge density for the streamer path at a section from R and $R+\Delta R$. Figure 10 shows the relation betwen ρ and the distance L with voltage height as the parameter, where L is the distance from the tip of the streamer; $L = l-r$, $r = R$

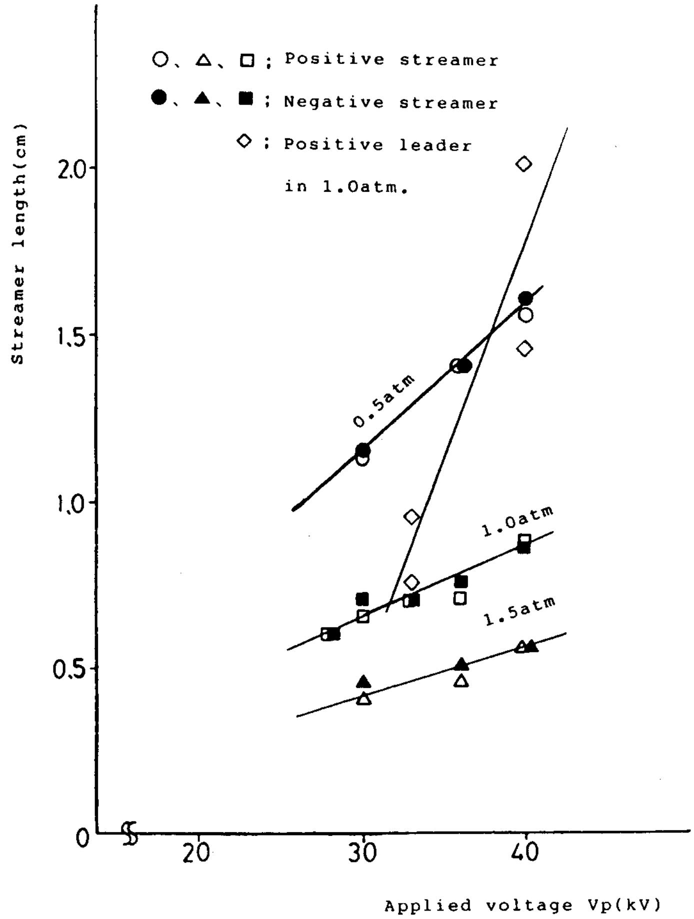


Fig.12 Relations of streamer length vs. applied voltage. (Insulator; PMMA.)

$+\Delta R/2$, and l is the length of the streamer. With reference to the figure, the line charge densities are independent of the voltage height. The density within 1 cm from the streamer tip is in a range of 0.5 nC/cm to 1.0 nC/cm, and then increases with the destance L. Sakai et. al.[1),2)]. have utilized a surface potential meter and have measured the line charge density near the tip of the positive streamer in air. Their result is approximately consistent with ours. This consistency means that the back-discharge under positive voltage application does not severely affect the charge distribution as already shown in Fig. 7 (a).

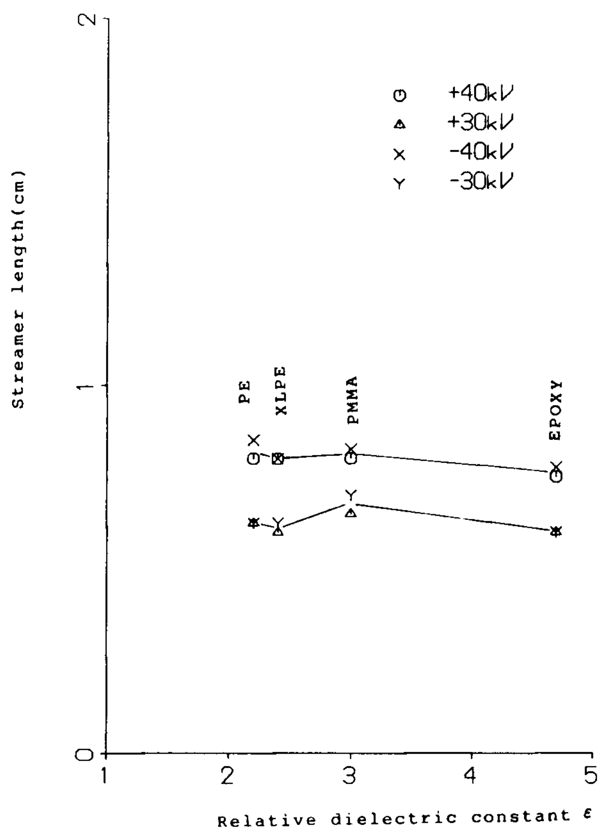


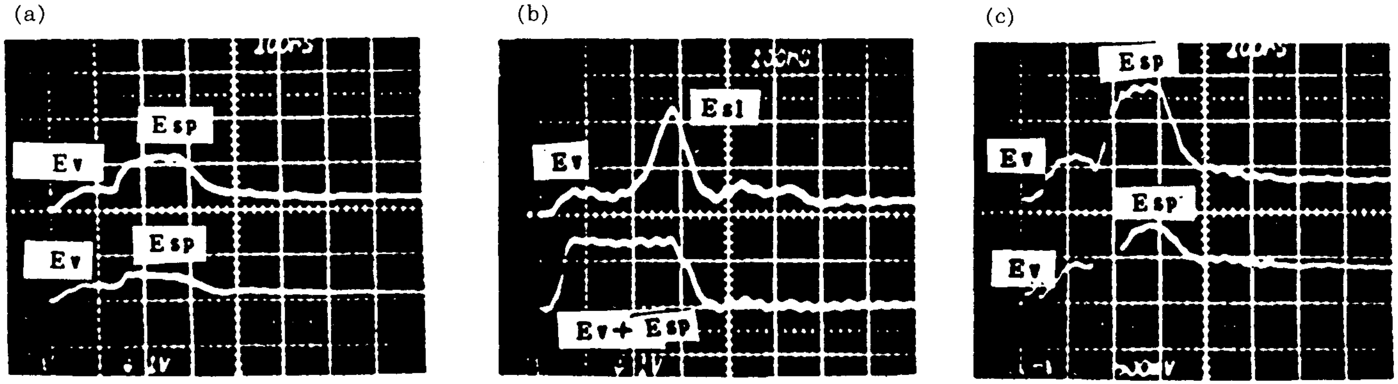
Fig.13 Relation of streamer length and relative dielectric constant in SF_6 of 1atm.

5. Experimental results in *SF_6* gas.

5.1 Dust figure and characteristics of streamer.

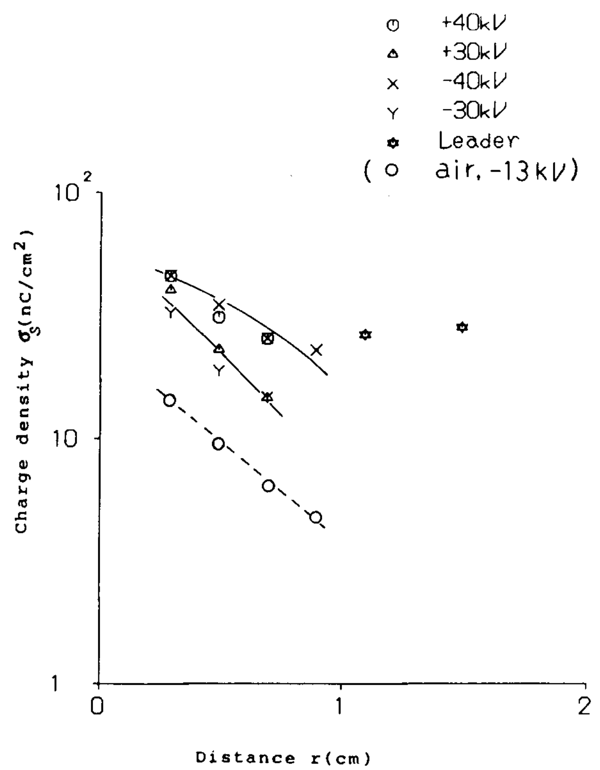
The streamer onset voltage in SF_6 gas of 1 atm was 25 kV and was independent of the polarity of the applied voltage. This value was about 2.5 times higher than that in atmosphere. The dust figures on PMMA observed in SF_6 gas are shown in Fig. 11. Figures 11 (a) and (b) are for the positive voltage and (c) is for the negative voltage. The dust figures for positive and negative streamers look like a ring. The charge within the ring is considered to be consumed by the back-discharge. The shape of the dust figures of streamers are almost independent of the polarity of the applied voltage, as seen in Fig. 11.

In the case of the positive voltage application, a different descharge was



(a) Positive streamer. (V_p=+36kV. Upper trace: r=0.5cm, +103kV/cm/div. +103kV/cm/div., lower trace: r=0.9cm, +100kV/cm/div..)
(b) Positive streamer. (V_p=+40kV. Upper trace: r=1.1cm, +45kV/cm/div., lower trace: r=0.9cm, +100kV/cm/div..)
(c) Negative streamer. (V_p=−30kV. Upper trace: r=0.5cm, −52kV/cm/div., lower trace: r=0.9cm, −27kV/cm/div..)

Fig.14 Probe signals for streamer and leader in SF_6. (1atm., PMMA)



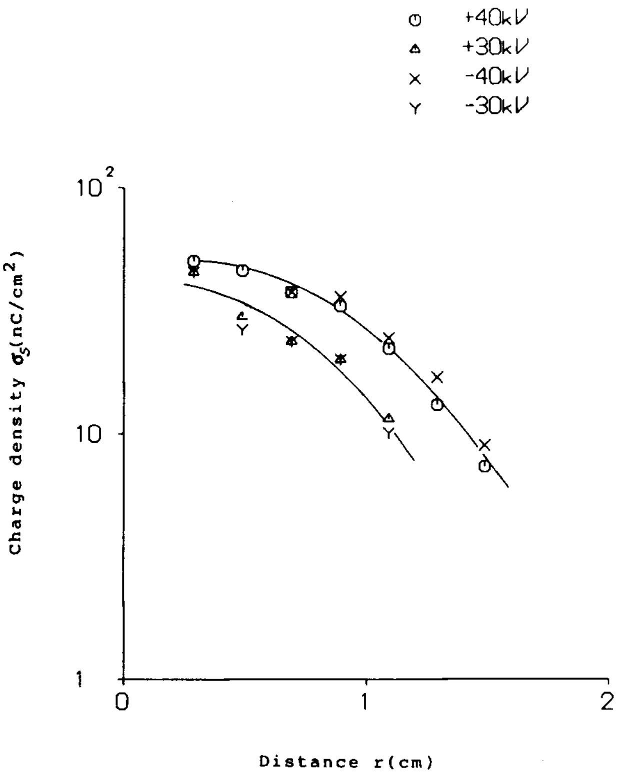
(a) 1.0 atm SF_6.

Fig.15 Distribution of space charge in SF_6. (Insulator; PMMA.)

observed to develop. The shape of this discharge is asymmetric, as seen in Fig. 11 (b), and has been identified as the leader as mentioned earlier. In this experiment, the leader propagation occurred only under the positive voltage application and in 1 atm SF_6. It propagated further than the streamers.

Figure 12 shows the relations between the streamer length on PMMA and the applied voltage V_p with SF_6 gas pressure as the parameter. The streamer lengths of both the positive and the negative streamers are proportional to V_p. Furthermore, noticeable differences cannot be seen in the streamer lengths between different polarities of streamers. The leader lenght vs. applied voltage is shown in Fig. 12. It is seen that the length increases with applied voltage much faster than streamer length.

The relationship of the streamer length with the relative dielectric constant



(b) 0.5 atm SF_6.

Fig.15 Distribution of space charge in SF_6. (Insulator; PMMA.)

of the insulators was investigated in SF_6 of 1 atm. The results are shown in Fig. 13 with the voltage height as the parameter. The streamer length is almost constant, though the relative dielectric constant varied from 2.3 to 4.7, which indicates that the dielectric constant dose not affect the streamer length siverely.

5.2 Space charge density of streamer in SF_6.

Figures 14 (a) and (c) indicate the probe signals of the electric field when the streamers propagate in 1 atm SF_6 on PMMA. As explained already, regarding Fig. 6, the space-charge field is added to the geometrical field E_g. The space-charge field in this case is called E_{sp} to be distinguished from that of the leader. For the positive voltage application, the electric field E_{sl} of the leader is also added to the probe signal as shown in Fig. 14 (b). The applied voltage

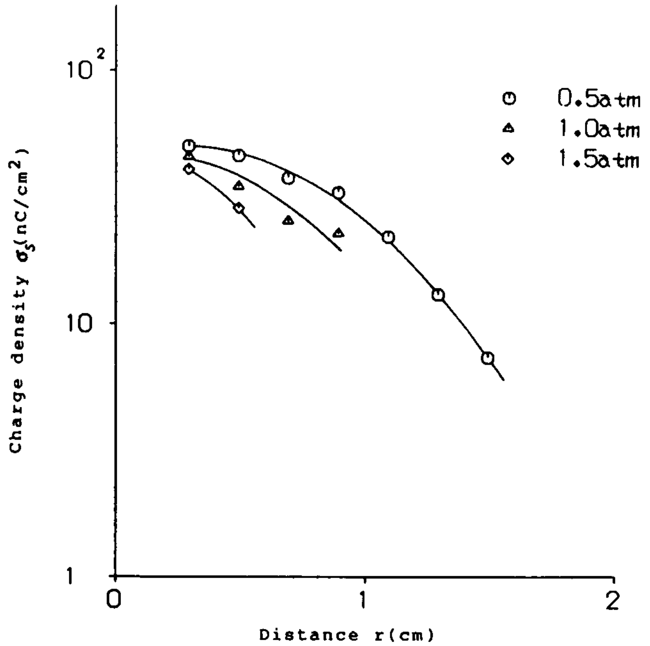


Fig.16 Variation of charge density with pressure of SF_6. (Insulator; PMMA.)

being reduced to zero, the probe signals suddenly decrease.

The space-charge density of the streamers of both polarities were estimated by substituting the measured field E_{sp} into E_s in Eq. (2) or (3). Figures 15 (a) and (b) show the results for 1 atm and 0.5 atm respectively. It can be seen that the density is in a range of 8 to 80 nC/cm². It decreases with the distance and increases with the voltage height. These charge densities are again irrespective of the polarity of the applied voltage. The shape of the charge distribution after the back-discharge was found to be similar to the results for the negative streamer in air.

The space-charge distributions for the gas pressure of 0.5, 1.0 and 1.5 atm are compared in Fig. 16, where the applied voltage height is + 40 kV. The area where the charge is distributed is extended as the pressure decreases. However, the charge density is almost the same under the different pressures.

The variations of the charge density with the streamer length, at a certain position r, are demonstrated in Figs. 17 (a), (b) and (C). The position corresponding to these figures is r= 0.3, 0.5 and 0.7 cm respectively. These results indicate that the charge density at any position increases gradually as the streamer propagates, and has an ultimate value of about 60 nC/cm², which is

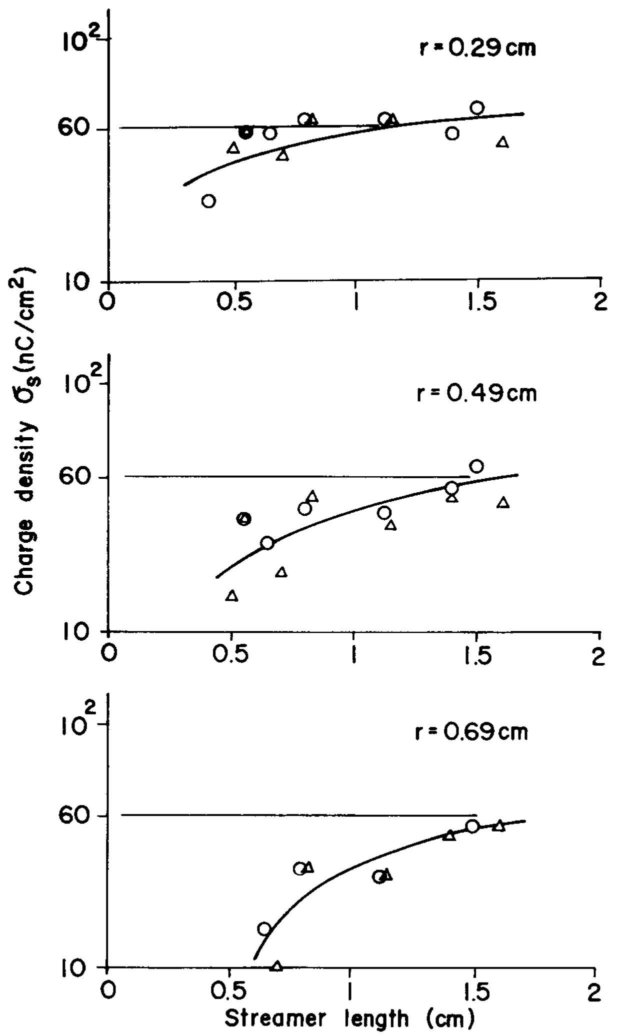


Fig.17 Variation of space charge density with streamer length at various distances. (○; Positive streamer, △; Negative streamer. Insulator; PMMA.)

attainded when the streamers have propagated more than 1.5 cm.

The streamer length in 1 atm SF_6 has already been compared with that in air. (See Fig. 5.) This comparison shows that the streamer length in SF_6 at $V_p = \pm 40$ kV corresponds to that in air at $V_p = -13$ kV, the negative streamer. The comparison between the charge densities for the above streamers can be seen in

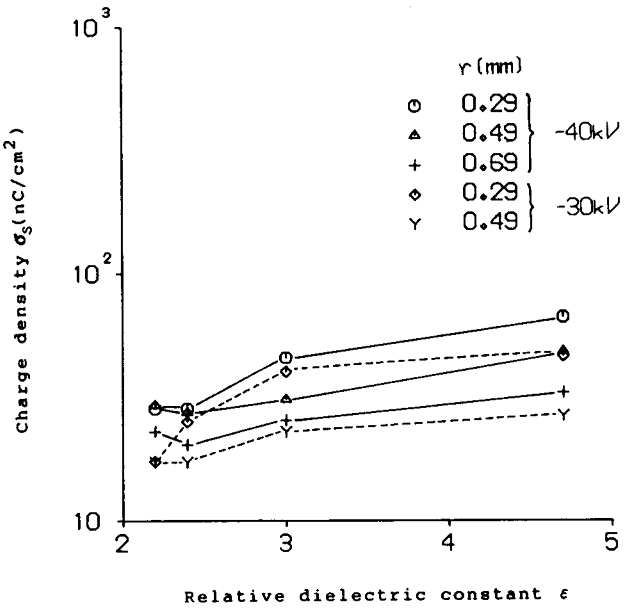


Fig.18 Relation of charge density vs. relative dielectric constant in SF_6 of 1atm.

Fig. 15. From these results, it is found out that a voltage three times higher and a charge density five times higher are necessary for the streamer to propagate in SF_6 with respect to that in air.

Figure 18 shows variations of the charge density with the relative dielectric constant at the various positions r. As previously stated regarding Fig. 13, the streamer length is independent of the dielectric constant. On the contrary, however, the charge densities shown in Fig. 18 have a tendency to increase with an increase in the dielectric constant.

6. Discussion.

The electrode system shown in Fig. 2 is the one which is used mostly for the basic study of surface discharges. The shape of the discharge in this case is expected to be radial and symmetrical over the insulator surface as seen in Fig. 4 and Fig. 11, except those parts where leader develops. Therefore, the probe with the shape of concentric circle is suitable and effective for the measurement of the space charge. However, there exists a space between the branches of the positive streamer in air (See Fig. 4 (a)), where the distribution of the space charge is not uniform as assumed before. Therefore, the charge density of the positive streamer, obtained using Eq (2) or Eq. (3), is the average. The charge distributions of other streamers treated in this study are considered also to be non-uniform in a strict sense. However, the uniformity is assumed to be high in the case of negative streamer in air and both polarities of streamers in SF_6 with reference to their dust figures (See Fig. 4 (b) and Fig. 11 (a), (c))). For this reason, the results presented in Fig. 7 (b) and Figs. 15 (a), and (b) are much closer to the actual density on the surface of the insulator.

On the other hand, since the leader in SF_6 gas develops assimmetrically as seen in Fig. 11 (b), its charge density cannot be estimated from Eq. (2) or Eq. (3). However, an approximate charge density for the leader can be estimated, assuming that electric line of force from the leader charge goes straight and perpendicular to the probe. The consequential electric field E_{sl} on the probe accompanied by the leader is expressed by Eq. (5),

$$E_{sl} = CV'/\varepsilon S', \tag{5}$$

where S' is the area of the leader above the probe evaluated from the dust figure. The charge within the area S' induces the voltage V' across the capacitor. Thus, the charge density of the leader is estimated from Eq. (6).

$$\sigma_{sl} = \varepsilon E_{sl}. \tag{6}$$

The results are obtained for the leader by applying positive voltage, and is presented in Fig.15 (a) together with the charge density of the streamers. From the figure, it can be recognized that the charge density of the leader in SF_6 is approximately the same as the density of the streamers.

7. Conclusion.

Space-charge and its density due to streamers along the surface of insulators are investigated quantitatively by the use of the dust figure method and probe method supplemented by a numerical calculation. The results of this study are summarized as follows.

1) The probe method is useful for the measurement of the space charge before the occurrence of the back-discharge. This method is also applicable for the measurement of the propagation velocity of the surface discharge.
2) The back discharge phenomena severely disturb the distribution of the space charge for positive and negative streamers in SF_6 gas and for the negative streamer in air.

3) In SF_6 gas, the polarity of the applied voltage has no effect on the streamer characteristics in terms of the charge density, the length and also the shape of the dust figure.

4) In SF_6 gas, the charge density increases slightly with the relative dielectric constant, while length of the streamer is almost constant.

5) In SF_6 gas, the length of the streamer increases with the voltage height. The charge density at a certain location, however, has the tendency to be independent of the streamer length.

6) For the streamer to propagate in 1 atm SF_6, a voltage with a magnitude three times higher and a charge with a density five times higher than that for air are needed.

7) The charge density due to the leader in SF_6 is deduced to be in the same order as that of the streamer.

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