Breakdown and Corona Characteristics of Rod-to-Plane Gap in Atmospheric Air under AC Voltage

By

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Abstract

The sequence from the corona onset to the complete breakdown accompanied with the applied voltage increase is observed where the diameter of the rod electrode is $\phi=2\sim50$ mm, and the gap length is $\delta=1$ mm$\sim$30 cm. The negative corona does not vanish until the applied voltage reaches the sparking voltage. Concerning the positive corona, there are three types of the streamer corona, and there exists a discontinuity in the streamer onset voltage characteristics. In some cases, the streamer corona disappears with an increase of voltage. Concerning the spark, two types can be observed: the continuous spark and the intermittent spark. In some cases, the latter disappears with the voltage increase. As for results, the various types of the corona and spark can be classified on the map of the ϕ-δ plane.

1. Introduction

Under the DC or impulse voltage application to a rod-to-plane gap, many investigations of discharge phenomena in atmospheric air have been carried out, and the discharge characteristics and their mechanism have been studied at length.[1),2)] Under the AC voltage, the practical researches, i.e. the corona losses, the radio interferences and their reduction techniques, etc. are investigated. So far,[3)~13)] however, the sequence of phenomena arising with the applied voltage increase has not yet been reported in detail.[14),15)] In this paper, the sequences from the corona onset to the complete breakdown accompanied with the voltage increase are observed for many different electrode sizes and gap lengths, and the corona- and breakdown-characteristics are reported.

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2. Experimental Apparatus and Measuring Method

A schematic diagram of experimental installation is shown in Fig. 1. In this experiment, the applied voltage is adjusted by an induction regulator (IR). The output voltage of the testing transformer (TT) is applied to a gap through the protection resistor R_s, and is measured by the voltage divider C_d. Simultaneously, the effective value of the applied voltage is measured by a digital voltmeter via the tertiary winding of TT. The test gap is constructed by a hemispherically capped cylindrical rod and a plane which are made of brass. The diameter of the rod electrode ϕ is varied between 2~50 mm, and the side length and the thickness of the plane electrode are 1 m and 2 mm, respectively. The current wave form caused by the discharge in the gap space is measured by an oscilloscope (CRO: Tektronics type 556) as the voltage drop across the 75 Ω shunt resistor. At the same time, the total light intensity emitted from the discharge is measured by a photomultiplier (PM) receiving light from the full sight of PM, and is displayed on the CRO. Also, a still photograph is taken by a popular type of camera. Furthermore, in this experiment, the appearance and the mode change of discharge are detected by hearing the acoustic corona noises by ear and also by observing the phenomena by naked eye.

The voltage is applied by the IR from zero to higher values gradually. As soon as the breakdown occurs, the main switch is opened manually, and this procedure is repeated. The increasing rate of the applied voltage should be as small as possible. At the first time in this measurement, the applied voltage is raised at the rate of about several kV/s and the approximate values of the onset voltages of various kinds of corona are checked. Then, for the second voltage application and thereafter, the voltage increasing rate is chosen below 1kV/s, and each critical voltage is read by the digital voltmeter as precisely as possible.

These measurements are repeated 6 times for each combination of ϕ and δ, and the experimental data for each corona mode are averaged except for the value obtained at the first time. Identification of each type of corona is decided synthetically from the results obtained by the current wave form, light pulse wave form, acoustics, and the

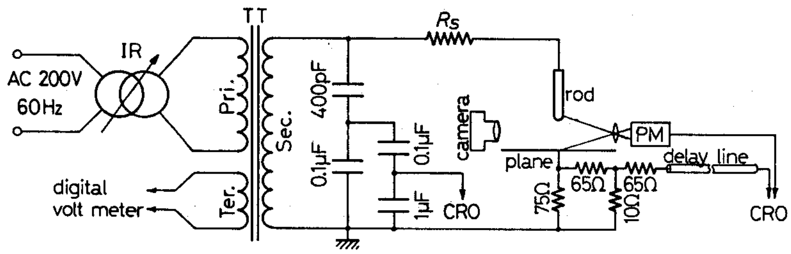


Fig. 1. Schematic diagram of experimental apparatus.

corona shape.

3. List of Terms and Symbols

In this paper, many terms and symbols are used in the following sections. Meanings and definitions of those are as follows:

Positive, negative: Polarity of the voltage applied to the rod electrode at the time of the appearance of the corona under consideration. This is decided by the observation of the corona current wave form, the instantaneous voltage at the corona appearance time, etc..

Continuous: This term is used for the case where the phenomenon takes place once or more for every cycle of the applied voltage.

Intermittent: This term is used for the case where the phenomenon does not take place for every cycle of the applied voltage.

ϕ : diameter of the rod electrode
δ : gap length
FC : positive filmy corona
SC : positive streamer corona
SC′ : positive streamer corona which is smaller than SC in the spatial magnitude
SC″ : positive streamer corona which has a conical or cylindrical shape and bridges over the whole gap
LC : positive leader-like corona
TC : negative corona (Trichel pulse corona)
V_{FC} : onset voltage of FC (peak voltage)
V_{SC} : onset voltage of SC (〃)
$V_{SC'}$: onset voltage of SC′ (〃)
$V_{SC''}$: onset voltage of SC″ (〃)
V_{TC} : onset voltage of TC (〃)
$\bar{V}_{SC}$: vanishing voltage of SC (〃)
$\bar{V}_{SC'}$: vanishing voltage of SC′ (〃)
V_a : continuous sparking voltage (〃)
$V_{a'}$: intermittent sparking voltage (〃)
$\bar{V}_{a'}$: vanishing voltage of intermittent spark (〃)

Further in this paper, the light, current, and voltage wave in oscillograms are indicated by the symbols L, i, and v, respectively.

4. Characteristics of Corona and Breakdown Voltage

In this experiment, the rod diameter ϕ and the gap length δ are changed from 2 to

50 mm and from 0.1 to 35 cm, respectively. The step of δ increment is chosen in 1～25 mm. The experimental results are shown in Figs. 2～12 and Tables 1～6. The latter indicate some gap length ranges where there appears a certain pattern of corona sequence accompanying the increase of voltage. In this section, the corona and breakdown characteristics are described where ϕ=10 mm (Fig. 6) to take a single instance among the experiments.

〈4.1〉 Characteristics of Corona Discharge Due to the Voltage Increase

Region A: No corona appears and spark occurs directly, not via corona.

Region B: TC (negative Trichel corona) appears but FC (positive filmy corona) and SC (positive streamer corona) do not appear up to the sparking voltage. The

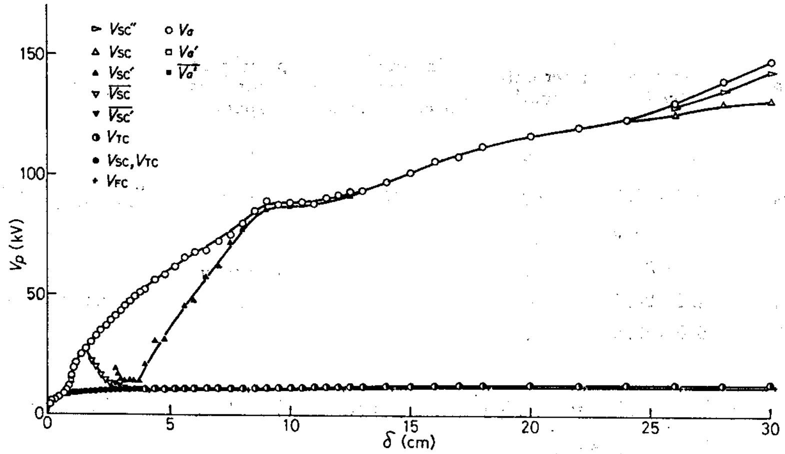


Fig. 2. Corona and breakdown characteristics for ϕ=2 mm.

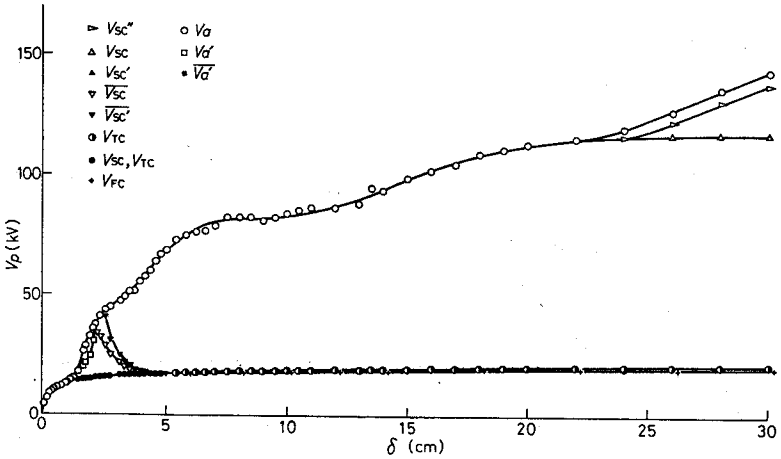


Fig. 3. Corona and breakdown characteristics for ϕ=4 mm.

Table 1. Special features of corona and spark regions for ϕ=2 mm.

Corona

region	δ-range (cm)	FC	TC	SC	order of corona appearance*	SC disappearance
A	0.1~ 0.6	×	×	×		
E_1	0.7~ 1.4	×	○	○	(TC, SC)	×
E_2'	1.6~ 2.6	×	○	○	(TC, SC)	○ (large SC) × (small SC)
E_3	2.8~ 3.8	×	○	○(twice)	(TC, first SC), second SC	○ (first SC) × (second SC)
F_4	4.0~13.0	○	○	○	FC, TC, SC	×
C	14.0~24.0	○	○	×	FC, TC	
D	26.0~32.5	○	○	○	FC, TC, SC	×

* ( ) means simultaneous appearance.

Spark

region	δ-range (cm)	intermittent spark	intermittent spark disappearance	polarity of continuous spark	remarks
P	0.1~ 0.7	×		+−	
S_4'''	0.8~ 1.0	○	×	+−	intermittent spark occurs at +−
P'	1.1~ 3.6	×		+−	
Q'	3.8	×		+− or +	
T_1	4.0~24.0	×		+	fluctuation in V_a
T_2	26.0~32.5	×		+	

voltage difference between V_{TC} and V_a is so small (0.25 kV) that they are observed as being almost the same.

Region E_1: SC appears at the voltage almost the same as that of the TC onset, and

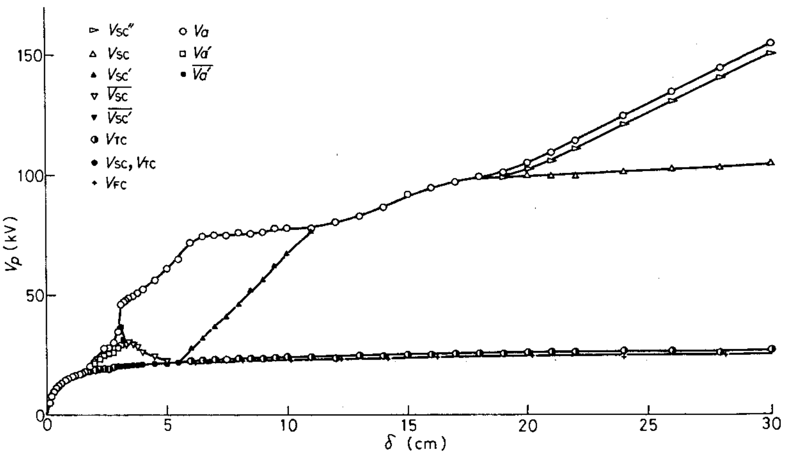


Fig. 4. Corona and breakdown characteristics for ϕ=6 mm.

Table 2. Special features of corona and spark regions for ϕ=4 mm.

Corona

region	δ-range (cm)	FC	TC	SC	order of corona appearance	SC disappearance
A	0.1～ 1.0	×	×	×		
B	1.1	×	○	×		
E_1	1.2～ 2.0	×	○	○	(TC, SC)	×
E_2'	2.1～ 2.2	×	○	○	(TC, SC)	○ (large SC) × (small SC)
E_2	2.4～ 3.8	×	○	○	(TC, SC)	○
E_2''	4.0～ 4.8	×	○	○	(TC, SC)	○
C	5.0～22.0	○	○	×	FC, TC	
D	24.0～32.5	○	○	○	FC, TC, SC	

Spark

region	δ-range (cm)	intermittent spark	intermittent spark disappearance	polarity of continuous spark	remarks
P	0.1～ 1.3	×		+−	
S_4''	1.4～ 2.1	○	×	+−	intermittent spark occurs at +−
P′	2.2～ 3.0	×		+−	
Q′	3.2～ 7.5	×		+− or +	
T_1	8.0～22.0	×		+	fluctuation in V_a
T_2	24.0～32.5	×		+	

they do not vanish up to the sparking voltage. Where δ=2.3～2.8 cm, the frequency of SC occurrence is very low, so that sometimes the applied voltage makes the sparking not via SC. In this region, the voltage difference between V_{TC} and V_a

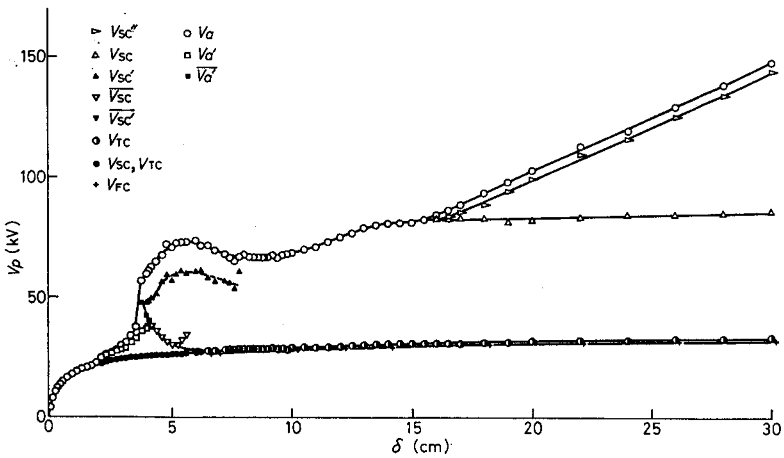


Fig. 5. Corona and breakdown characteristics for ϕ=8 mm.

Table 3. Special features of corona and spark regions for ϕ=8 mm.

Corona

region	δ-range (cm)	FC	TC	SC	order of corona appearance	SC disappearance
A	0.1∼ 1.8	×	×	×		
E_1	1.9∼ 3.8	×	○	○	(TC, SC)	×
E_3	4.0∼ 6.2	×	○	○(twice)	(TC, first SC), second SC	○ (first SC) × (second SC)
F_4	6.5∼ 7.8	○	○	○	FC, TC, SC	×
C	8.0∼15.5	○	○	×	FC, TC	
D	16.0∼35.0	○	○	○	FC, TC, SC	×

Spark

region	δ-range (cm)	intermittent spark	intermittent spark disappearance	polarity of continuous spark	remarks
P	0.1∼ 2.2	×		+−	
S_4'	2.4∼ 3.6	○	×	+−	
S_3	3.8∼ 4.1	○	○	+−	
P′	4.2∼ 6.8	×		+−	
Q′	7.0∼ 7.4	×		+− or +	
T_1'	7.6∼ 9.4	×		+	V_a decreases
T_1	9.6∼15.5	×		+	fluctuation in V_a
T_2	16.0∼35.0	×		+	

is about 2 kV. The spatial form of SC is brush-like and it bridges over the gap and arrives at the cathode.

Region E_2: Here, SC can be found at almost the same voltage at which TC appears

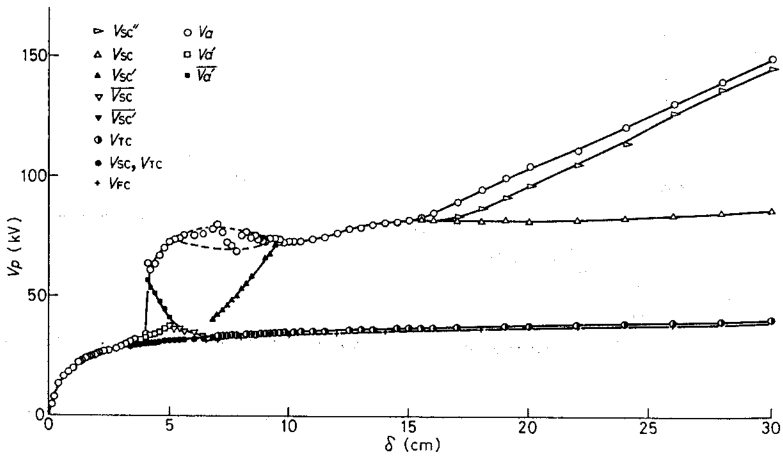


Fig. 6. Corona and breakdown characteristics for ϕ=10 mm.

Table 4. Special features of corona and spark regions for $\phi=10$ mm.

Corona

region	δ-range (cm)	FC	TC	SC	order of corona appearance	SC disappearance
A	0.1∼ 2.0	×	×	×		
B	2.1	×	○	×		
E_1	2.3∼ 4.0	×	○	○	(TC, SC)	×
E_2	4.1∼ 6.0	×	○	○	(TC, SC)	○
F_2	6.2∼ 6.4	○	○	○	FC, (TC, SC)	○
F_3	6.8	○	○	○(twice)	FC, (TC, first SC), second SC	○ (first SC) × (second SC)
F_4	7.0∼ 9.6	○	○	○	FC, TC, SC	×
C	9.8∼15.5	○	○	×	FC, TC	
D	16.0∼35.0	○	○	○	FC, TC, SC	×

Spark

region	δ-range (cm)	intermittent spark	intermittent spark disappearnace	polarity of continuous spark	remarks
P	0.1∼ 2.5	×		+−	
Q	2.6∼ 2.7	×		+− or +	
R	2.8∼ 3.0	×		+	
S_4	3.2∼ 4.0	○	×	+	
S_3	4.1∼ 5.0	○	○	+−	
P′	5.2∼ 5.9	×		+−	
Q′	6.0∼ 6.6	×		+− or +	
T_1	6.8∼15.5	×		+	fluctuation in V_a
T_2	16.0∼35.0	×		+	

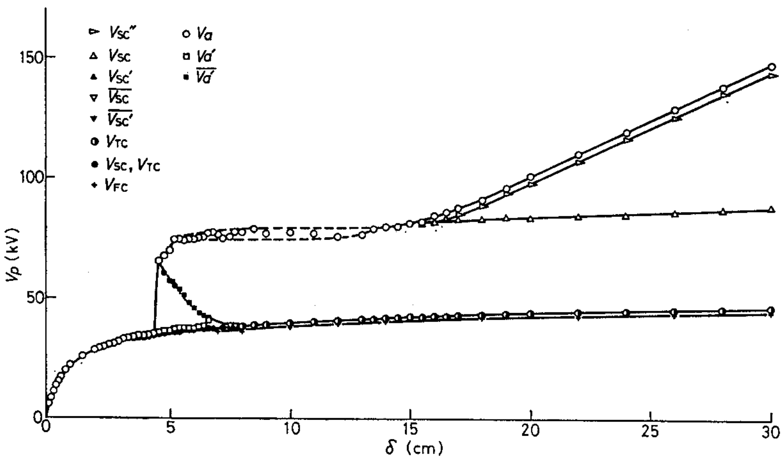


Fig. 7. Corona and breakdown characteristics for $\phi=12.5$ mm.

Table 5. Special features of corona and spark regions for ϕ=20 mm.

Corona

region	δ-range (cm)	FC	TC	SC	order of corona appearance	SC disappearance
A	0.1～ 3.0	×	×	×		
B	3.2～ 8.5	×	○	×		
E	9.0	×	○	○	(TC, SC)	×
F_1	9.5	○	○	○	FC, (TC, SC)	×
F_2	9.6～ 9.8	○	○	○	FC, (TC, SC)	○
F_3	10.0～10.2	○	○	○(twice)	FC, (TC, first SC), second SC	○ (first SC) × (second SC)
F_2	10.4～10.6	○	○	○	FC, (TC, SC)	○
C	10.8～14.0	○	○	×	FC, TC	
D	15.0～32.5	○	○	○	FC, TC, SC	×

Spark

region	δ-range (cm)	intermittent spark	intermittent spark disappearance	polarity of continuous spark	remarks
P	0.1～ 4.2	×		+−	
Q	4.4～ 5.0	×		+− or +	
R	5.2～ 9.5	×		+	
S_1	9.6～10.0	○ (twice)	○ (the first) × (the second)	+	
S_2	10.2～17.0	○ (once)	×	+	
T_2	18.0～32.5	×		+	

in the case of region E_1. However, SC disappears with the applied voltage increase, and only the TC occurs continuously up to the sparking voltage. The SC magnitude decreases and the interval of SC occurrence increases for the voltage

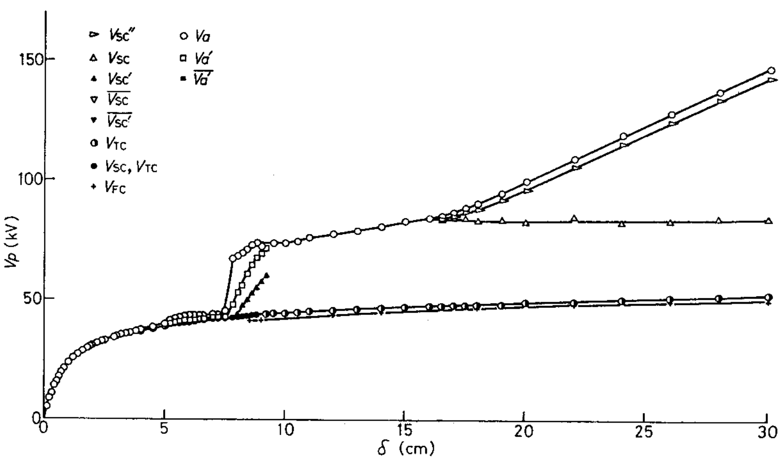


Fig. 8. Corona and breakdown characteristics for ϕ=15 mm.

Table 6. Special features of corona and spark regions for ϕ=40 mm.

Corona

region	δ-range (cm)	FC	TC	SC	order of corona appearance	SC disappearance
A	0.1~ 3.0	×	×	×		
B	3.2~12.5	×	○	×		
C	13.0~18.0	○	○	×	FC, TC	
D	19.0~32.5	○	○	○	FC, TC, SC	×

Spark

region	δ-range (cm)	intermittent spark	intermittent spark disappearance	polarity of continuous spark	remarks
P	0.1~ 7.0	×		+−	
Q	7.5~ 9.0	×		+− or +	
R	10.0~12.0	×		+	
S_1	13.0~14.5	○ (twice)	○ (the first) × (the second)	+	
S_2	15.0~21.0	○ (once)	×	+	
T_2	22.0~32.5	×		+	

increase, and SC vanishes at last. In the range corresponding to S_3 region (which is concerned with the breakdown characteristics as will be described later), the vanishing voltage of SC coincides with that of the intermittent spark.

Region F_2: Both TC and SC appear simultaneously slightly over the FC onset. The frequency of SC occurrence decreases with the voltage increase, and then SC vanishes until sparking for the voltage increase.

Region F_3: Both TC and SC occur simultaneously at a higher voltage by 1.5 kV more

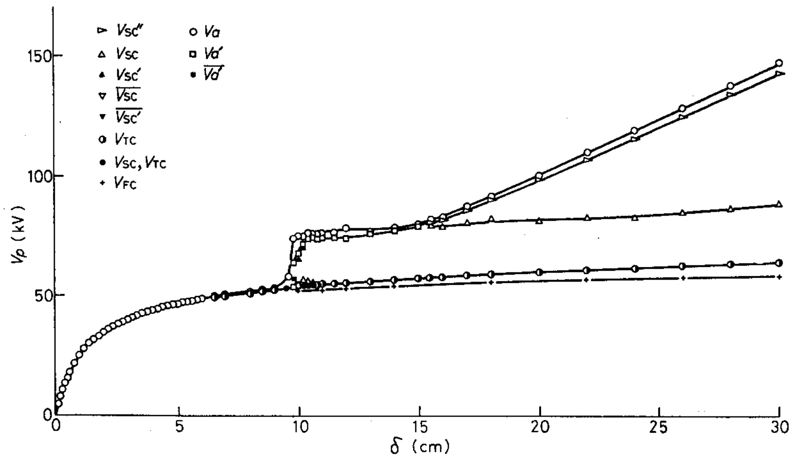


Fig. 9. Corona and breakdown characteristics for ϕ=20 mm.

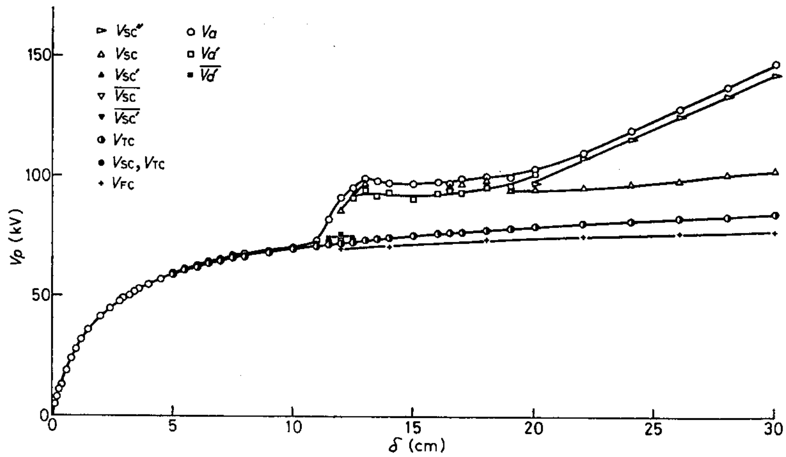


Fig. 10. Corona and breakdown characteristics foe ϕ=30 mm.

than that of the FC onset, and SC vanishes at the higher voltage of 0.3 kV. However, at a higher voltage than that by 7 kV, SC′ appears again until the sparking voltage. The SC′ magnitude in the second appearance is smaller than that in the first, but it appears continuously.

Region F_4: TC occurs at the higher voltage by about 1.5 kV more than that of FC, but SC does not appear at this voltage. By increasing the applied voltage, SC′ (small positive streamer), which is similar to the SC′ observed in region F_3, appears and does not vanish until the spark occurs. In this region, the frequency of the SC appearance is low at the beginning and at the end of this region, but high in the middle. When δ=9.2~9.4 cm, the difference between $V_{SC'}$ and V_a is small (3~6 kV) and SC′ appears intermittently. Especially, when δ=9.6 cm, SC′ occurs

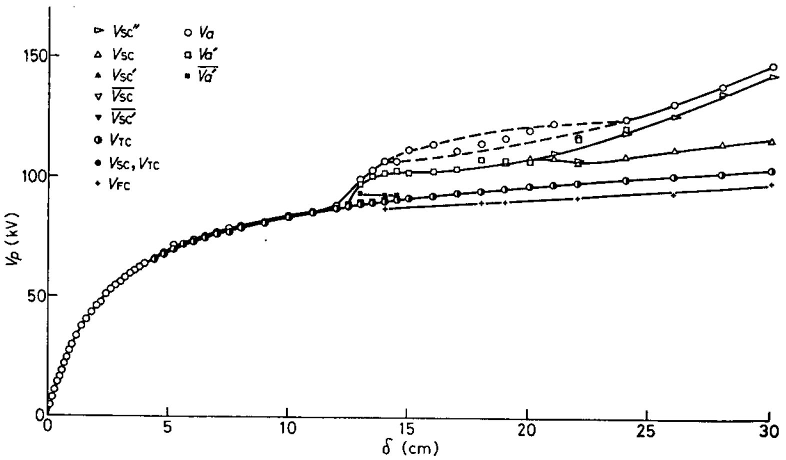


Fig. 11. Corona and breakdown characteristics for ϕ=40 mm.

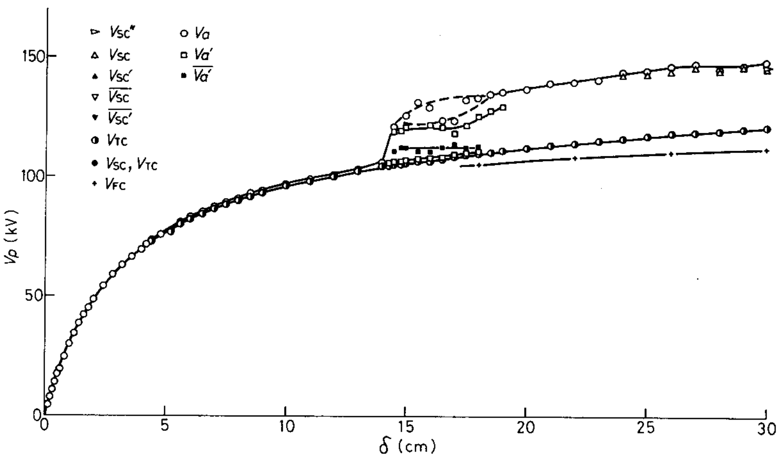


Fig. 12. Corona and breakdown characteristics for $\phi=50$ mm.

only a few times just before the spark. In this region, $V_{SC'}$ increases almost linearly with δ, so the difference between V_{TC} and $V_{SC'}$ increases from 9 to 39 kV when δ changes from 7.0 to 9.6 cm. In addition, the difference between V_{TC} and V_a in regions F_2, F_3, F_4 is about 35∼45 kV.

Region C: In region C, TC appears at a higher voltage by about 1.5 kV more than that of FC, but SC does not appear until the spark occurs. In this region, the difference between V_{TC} and V_a is 40∼45 kV.

Region D: TC appears at a higher voltage by about 1.5 kV more than that of the FC appearance, and SC appears at the voltage where the spark occurs in region C. Thus, the voltage difference between V_{TC} and V_{SC} is about 40∼45 kV. For δ in the range of 15.5∼16 cm, SC occurs intermittently. SC starts from the tip of the leader-like luminous channel LC, and forms the shape of the bridged streamer SC″. The higher the applied voltage is, the longer the LC channel becomes, and when the channel reaches the cathode, the spark occurs. When $\delta \geqq 18$ cm, SC occurs intermittently at the onset voltage and it takes a hemispherical shape around the rod tip. By increasing the applied voltage, the SC occurrence becomes continuous gradually. By increasing the applied voltage more and more, SC″ (which has a conical or cylindrical shape) appears intermittently together with SC above mentioned, and reaches the plane electrode. By increasing the applied voltage, the occurrence of SC″ becomes continuous. Also, the LC channel develops in the space occupied by both types of SC and SC″, bridges over the gap and leads to a spark.

⟨4.2⟩ Characteristics of Sparking Voltage

Region P: Sparkover occurs at each cycle for the positive and negative polarity of the applied voltage.

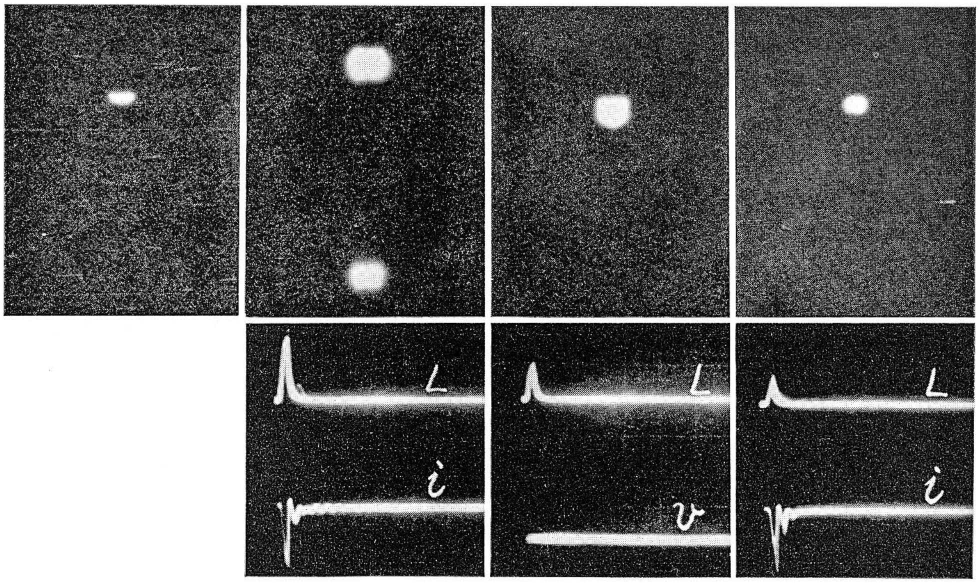
Region Q: Sparkover occurs for each cycle in which the polarity is only positive, or both positive and negative.

Region R: Sparkover occurs continuously only at the positive polarity, and V_a almost coincides with V_{TC} similarly as in the regions P and Q.

Region S_4: Intermittent spark occurs at the voltage which is equivalent to V_a in the regions P, Q and R. The spark frequency increases and reaches a continuous state by increasing the applied voltage. The spark occurs only at the positive cycle of the applied voltage.

Region S_3: Intermittent spark occurs at the voltage equivalent to V_a in the regions P, Q and R, but it vanishes by increasing the applied voltage. By further increasing the voltage, the continuous spark occurs at both the positive and negative polarity. The frequency of the intermittent spark is low at the beginning and at the end, but high in the middle range. When $\delta=4.8\sim5$ cm, the spark frequency is very low.

Region P′: Continuous spark occurs for both the positive and negative polarity, and the intermittent spark does not occur in this region. This region is different from



(a) (b) (c) (d)

Fig. 13. Still photograph, light, current and voltage wave for FC and TC.
(a) FC in region D. $\delta=30$ cm. exposure: F 1.4, 90 s.
(b) TC in region E_2. $\delta=4.6$ cm, $V_p=25.6$ kV. exposure: F 1.4, 1/4 s. sweep: 0.2 μs/div., current: 20 mA/div.
(c) TC in region C. $\delta=11$ cm, $V_p=62.0$ kV. exposure: F 1.4, 1/4 s. sweep: 0.2 μs/div., voltage: 66.3 kV/div.
(d) TC in region D. $\delta=30$ cm, $V_p=43.2$ kV. exposure: F 1.4, 1 s. sweep: 0.2 μs/div., current: 8 mA/div.

region P for the reason that the difference between V_a and V_{TC} is about 40 kV and larger than that of region P.

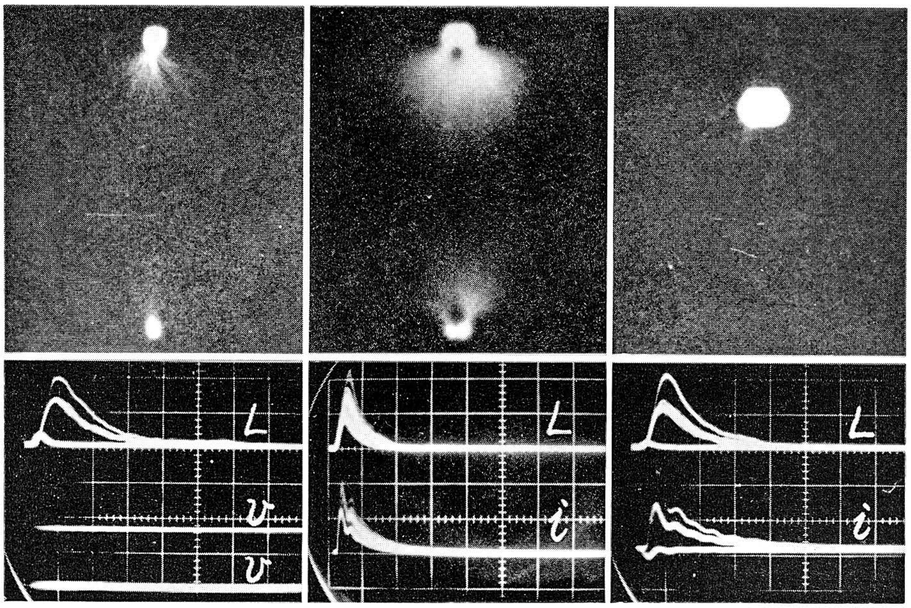
Region Q′: Intermittent spark does not occur. The polarity of the continuous spark is positive, or both positive and negative. This region is different from region Q for the reason that the difference between V_a and V_{TC} is about 40 kV and larger than that of region Q.

Region T_1: The spark occurs continuously. In this region, there are some fluctuations (about 6 kV) in V_a for fixed δ. In addition, there exists a region where V_a decreases partly by increasing δ.

Region T_2: There is no intermittent spark, and the continuous spark occurs in the positive cycles of the applied voltage. The value of V_a is very stable, quite different from region T_1. This region coincides with region D for the corona characteristics, and the difference between V_a and the voltage in which SC″ reaches the cathode is 4 kV. Furthermore, those values mentioned above increase by increasing δ.

⟨4.3⟩ Still Photograph, Current and Light Pulse

Fig. 13(a) shows a photograph of FC in region D. In this figure, the electrode tip

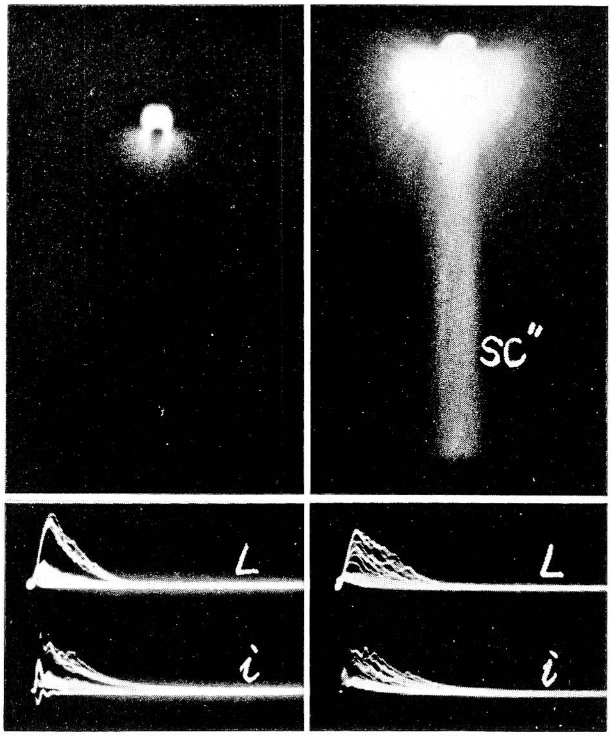


(a) (b) (c)

Fig. 14. Still photograph, light, current and voltage wave for TC and SC.
(a) SC and TC in region E_2. $\delta=6$ cm, $V_p=34.5$ kV. exposure: F 1.4, 1 s. sweep: 0.1 μs/div.
(b) SC and TC in region E_2. $\delta=6$ cm, $V_p=34.5$ kV. exposure: F 1.4, 6 s. sweep: 0.2 μs/div., current: 80 mA/div.
(c) SC′ and TC in region F_4. $\delta=8$ cm, $V_p=63.8$ kV. exposure: F 1.4, 1 s. sweep: 0.1 μs/div., current: 80 mA/div.

gleams weakly in the hemispherical shape. Fig. 13(b) shows the TC at the voltage above the vanishing voltage of the intermittent spark $\bar{V}_a$ in region E_2. In this figure, the reflection by the plane electrode is also shown. Fig. 13(c) shows the TC in region C at the higher voltage by about 30 kV more than V_{TC}. Fig. 13(d) shows the TC in region D at the higher voltage by 3 kV more than V_{TC}. From these figures, it is deduced that TC occurs in the vicinity of the electrode surface and has no tendency to develop into the gap space.

Fig. 14(a) and (b) show the photographs of SC and TC at the onset voltage in region E_2, and were taken with a short and a long time exposure, respectively. The current wave form of TC can not be observed in figure (b) because it is too small to trigger the CRO. SC has a hemispherical shape and gleams weakly. In both figures, the image of reflection by the plane electrode is also observed. Fig. 14(c) shows the SC′ in region F_4 together with TC, which corresponds to the smaller type of SC, and is hardly distinguishable. Further, the light pulse is small and the onset voltage of SC′ is low in



(a) (b)

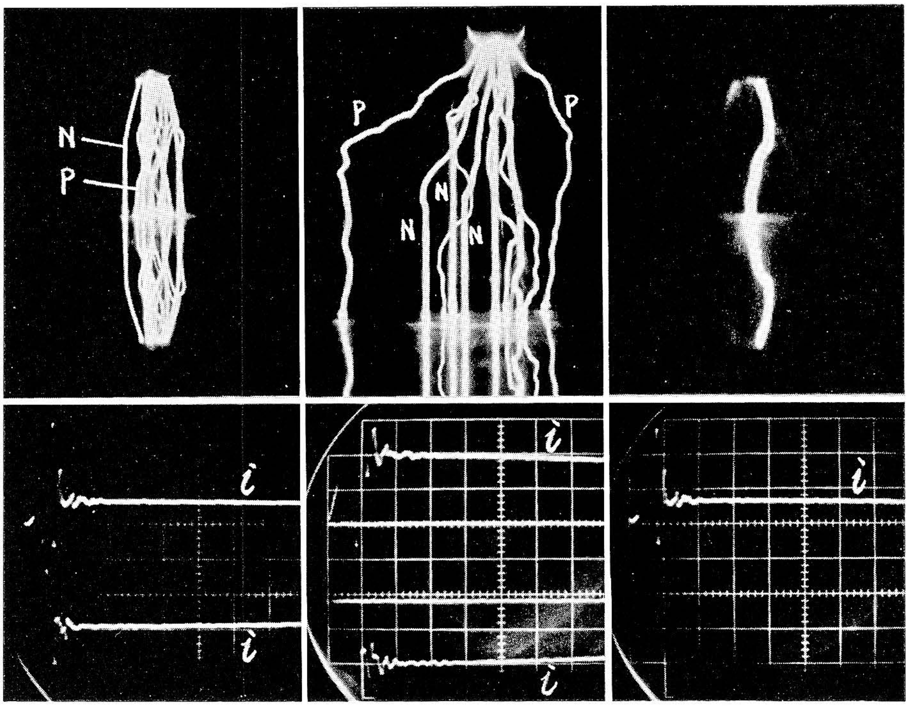
Fig. 15. Still photograph, light and current wave for SC and SC″ in region D.
(a) SC in region D. $\delta=30$ cm, $V_p=83.7$ kV. exposure: F 2.0, 1/2 s. sweep: 0.2 μs/div., current: 40 mA/div.
(b) SC and SC″ in region D. $\delta=30$ cm, $V_p=141$ kV. exposure: F 1.4, 1/4 s. sweep: 0.2 μs/div., current: 80 mA/div.

this case.

Fig. 15 shows the SC in region D. Fig.(a) and (b) are hemispherically shaped, weakly gleaming SC at the onset voltage, and the strongly luminating SC together with SC″ at slightly under the sparking voltage, respectively. Light and a current wave of large TC are included in (a) but can not be observed in (b).

Fig. 16(a) and (b) show a continuous spark occuring in both the positive and negative polarity in region P and region S_3, respectively. In figure (b), there are two types of the spark channels. One has some bendings and has leader-like filaments in places, but the other has a straight path and has no branches. They are considered to correspond to the spark of the positive and the negative polarity, respectively. Fig. 16(c) shows only a single spark in region P. In this case, a weak and fine leader-like light emission can be observed.

Fig. 17(a) and (b) are sparks in region Q, occuring at both the positive and negative



(a) (b) (c)

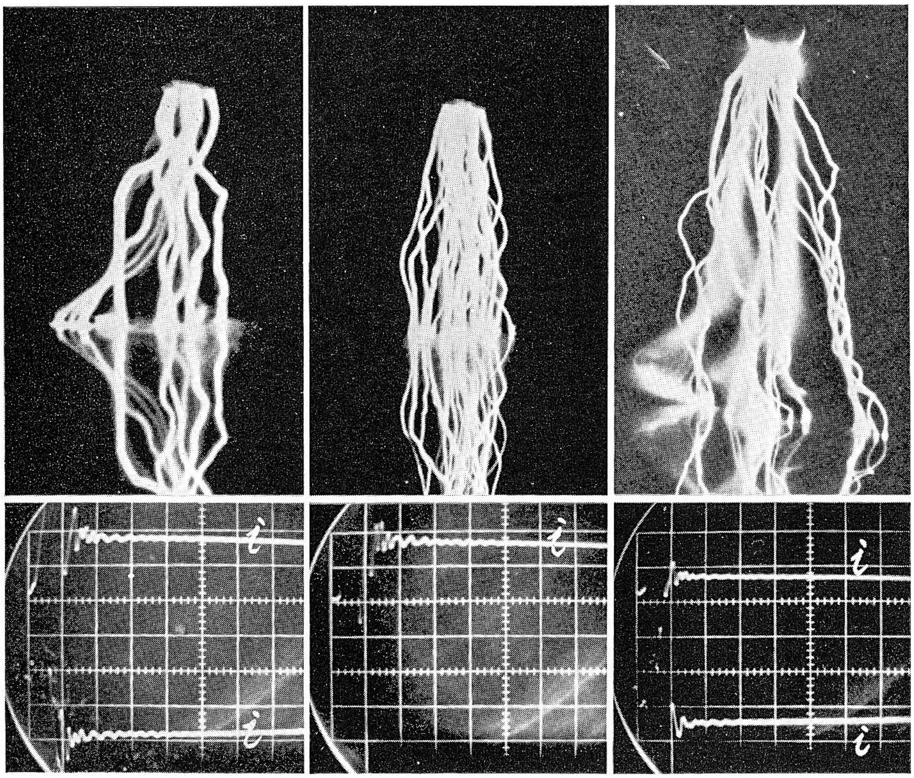
Fig. 16. Still photograph and current wave for continuous spark in region P and S_3.
(a) Continuous sparks in region P. $\delta=1.8$ cm, $V_p=24.9$ kV. exposure: F4. sweep: 0.2 μs/div., gain: 2 A/div. P and N in figure indicate positive and negative spark, respectively.
(b) Continuous sparks in region S_3. $\delta=4.6$ cm, $V_p=67.0$ kV. exposure: F8. sweep 0.2 μs/div., gain: 2 A/div.
(c) Single spark in region P. $\delta=1.8$ cm, $V_p=24.9$ kV. exposure: F4. sweep: 0.2 μs/div., gain: 2 A/div.

polarity, and at the positive polarity, respectively. Thus, the frequency of the negative spark is very low. Fig. 17(c) shows the sparks in region Q′. Furthermore, in this case, flare-like arc channels can be observed.

Fig. 18(a) shows the intermittent sparks in region S_3. In this figure, leader-like luminous channels can be observed, but only a few steps in the current increase are distinguishable. Fig. 18(b) shows the continuous sparks in region T_2 together with SC″, SC, and leader-like channels. In this case, the increasing currents, including some ten steps, are observed.

⟨4.4⟩ Some Features in Corona and Breakdown Characteristics

Characteristics of V_{FC}, V_{TC}, and V_{SC} have the tendency of saturation against the δ increase. In region T_2, the V_a curve lies parallel to the voltage curve in which SC″,



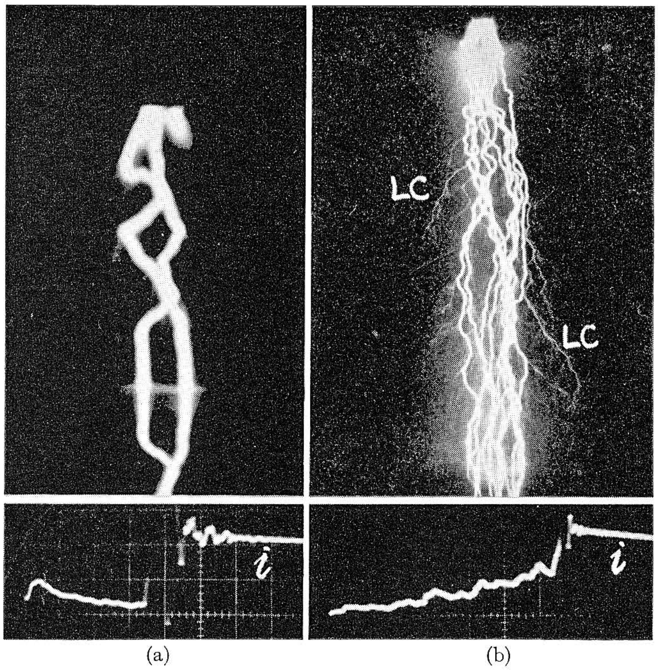
(a) (b) (c)

Fig. 17. Still photograph and current wave for spark in region Q and Q′.
(a) Continuous sparks in region Q. δ=2.5 cm, V_p=27.3 kV. exposure: F 5.6. sweep: 0.2 μs/div., gain: 0.8 A/div.
(b) Continuous sparks in region Q. δ=2.5 cm, V_p=27.3 kV. exposure: F 11. sweep: 0.2 μs/div., gain: 0.8 A/div.
(c) Continuous sparks in region Q′. δ=6.0 cm, V_p=70.3 kV. exposure: F 11. sweep: 0.2 μs/div., gain: 4 A/div.

the large conical or cylindrical type of streamer corona, reaches the plane electrode. The difference between those voltages is about 4 kV. The extrapolation of the V_a curve in region T_1 coincides with the V_{SC} curve in region T_2. The V_a curve coincides with the V_{TC} curve in regions P, Q and R, but in regions S_3, S_4, P′, Q′ and T_1, some fluctuations in the value of V_a appear. In region T_2, the V_a curve becomes linear, given as follows:

$$V_a = 6.6 + 4.7\,\delta \qquad (\delta \geqq 16\text{ cm})$$

Comparing the corona discharge in the case of the small electrode diameter with the one in the larger diameter, the occurrence and disappearance of each phenomena can be decided clearly in the former case. When $\delta=4.0$ cm, the increase of only 1 mm in δ makes a difference of 30 kV in the voltage necessary for the continuous spark. The extrapolation of V_a in the range of $\delta \leqq 4.0$ cm coincides with $V_{a'}$, necessary for the intermittent spark. The vanishing voltage of the intermittent spark decreases with the increase of δ and crosses the V_a curve for the intermittent spark. It does not appear for a greater δ than that of the crossing point. The extrapolation of the vanishing voltage curve of the intermittent spark coincides with the vanishing voltage of the first kind of



(a) (b)

Fig. 18. Still photograph and current wave for spark in region S_3 and T_2.
(a) Intermittent sparks in region S_3. $\delta=4.6$ cm, $V_p=36.2$ kV. exposure: F 2.8. sweep: 0.2 μs/div., gain: 0.8 A/div.
(b) Intermittent sparks in region T_2. $\delta=20$ cm, $V_p=99.2$ kV. exposure: F 8. sweep: 0.5 μs/div., gain: 2 A/div.

SC. This curve crosses the voltage of the SC occurrence, and the first kind of SC does not appear for a greater δ than that of the crossing point mentioned above.

5. Discussion

In the previous sections, the experimental results obtained for $\phi=10$ mm are described in detail. In this section, discussion is done about all the kinds of ϕ, including 10 mm.

⟨5.1⟩ Gap Geometry and Region of Corona Discharge

The relation between the dimentions of gap geometry and the regions of various corona types are shown in Fig. 19. Concerning the corona discharge, the ϕ-δ plane is divided roughly into 6 regions, i.e., regions A, B, C, D, E and F. The special features of these regions are shown in Table 7. Now we introduce the geometric index G as follows:

$$G=\frac{\delta}{\phi}$$

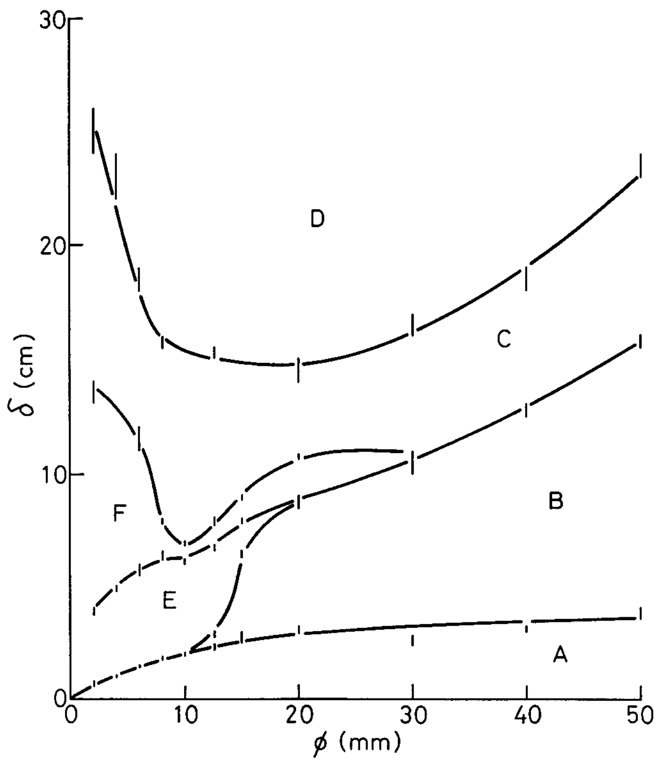


Fig. 19. Relation between the gap geometry and the corona region.

Table 7. Special features of corona regions.

region	FC	TC	SC	remarks
A	×	×	×	
B	×	○	×	
C	○	○	×	
D	○	○	○	
E	×	○	○	TC and SC appear simultaneously, or
F	○	○	○	SC magnitude is small.

The boundaries between regions A and E, and regions A and B give the minimum δ for the TC occurrence, i.e., at these values of δ, V_{TC} separates from V_a. This line saturates and passes the origin. It has a smooth shape. Thus, the G-value for the beginning of the TC occurrence is larger for smaller the ϕ. For example, the changing of ϕ from 0.2 to 5.0 reduces G from 3.0 to 0.7.

The boundary between regions E and B and regions F and C gives the minimum δ for the SC occurrence, i.e., at this value of δ, V_{TC} separates from V_{FC}. This curve has the same tendency as that obtained above, and the changing of ϕ from 0.2 to 5.0 reduces G from 20 to 3.

The boundaries between regions F and C, and between regions C and D give the value of δ in which the unstable positive streamer corona disappears and the stable SC begins to appear, respectively. In both cases, such gap lengths δ's increase when ϕ increases or decreases, thus, when ϕ tends to 0, G becomes infinitive. For the latter boundary, the ϕ-increase makes the constant $G(G=4.3)$. Furthermore, both δ's take the minimum value, i.e., 15 cm and 8 cm for $\phi=1\sim2$ cm, respectively.

Concerning the corona discharge, the larger ϕ is, the simpler the corona shape becomes. For $\phi\geqq2$ cm, the pattern of region change for the δ-increase is uniform. However, for a smaller ϕ, the sequence of region change with the δ-increase becomes

Table 8. Special features of spark regions.

region	intermittent spark	polarity of continuous spark	remarks
P	×	+ −	difference between corona onset and V_a is small
P′	×	+ −	〃 〃 〃 large
Q	×	+ − or +	〃 〃 〃 small
Q′	×	+ − or +	〃 〃 〃 large
R	×	+	〃 〃 〃 large
S	○	+ (rarely + −)	
T_1	×	+	fluctuation in V_a
T_2	×	+	

very complicated.

⟨5.2⟩ Gap Geometry and Spark Region

The relation between the dimensions of the gap geometry and the region of sparks is shown in Fig. 20. The special features of each region are shown in Table 8. The upper and lower boundaries of region S indicate the δ value for which the intermittent spark disappears and δ for onset, respectively. These values also give the boundaries where the difference between the intermittent spark onset and the continuous spark appears. For $\delta \geqq 1$ cm, these curves are almost linear and lie parallel. For $\delta < 0.6$ cm, they become linear and pass the origin, and show that the intermittent spark occurs when $G=3\sim5$.

⟨5.3⟩ Characteristics of Filmy and Negative Corona

Fig. 21 shows the onset voltage characteristics of FC and TC for each value of ϕ. From this figure, it is observed that the difference between V_{FC} and V_{TC} increases if ϕ and δ are large, and the ϕ-change is more effective than that of δ. Both the V_{FC}- and V_{TC}- characteristics have the same saturating tendency for the δ-increase.

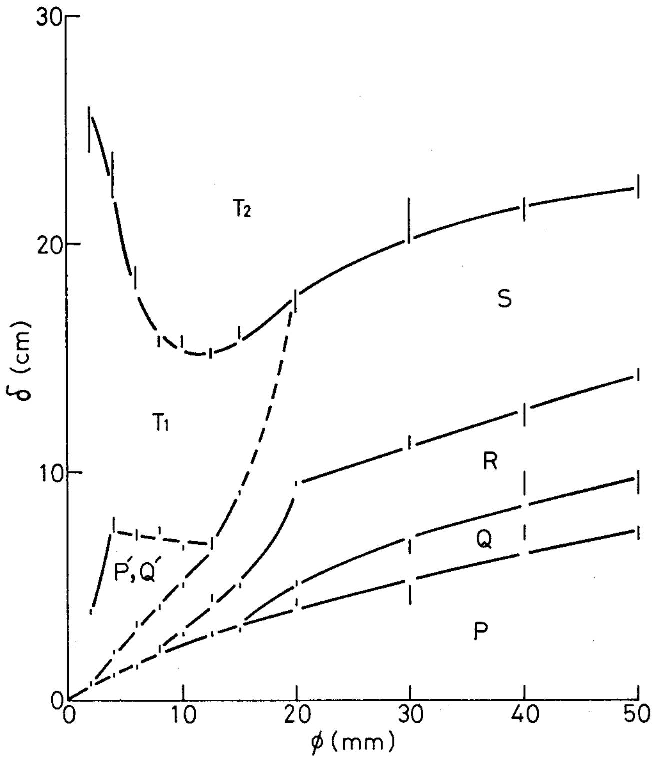


Fig. 20. Relation between the gap geometry and the spark region.

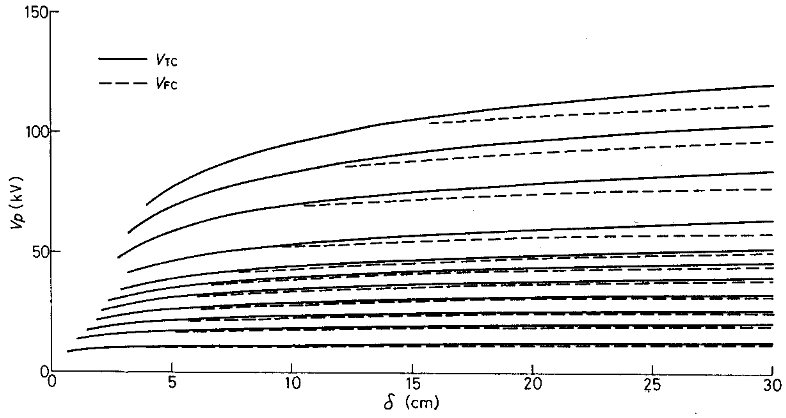


Fig. 21. Onset voltage characteristics of FC and TC with ϕ as a parameter.

Fig. 22 shows the V_{TC}-characteristics against ϕ with δ as the parameter, and they are smooth and saturating curves. From Figs. 21 and 22, it is deduced that, for the same value of G, the smaller the ϕ, the greater becomes the TC onset voltage. In other words, the smaller ϕ and δ are, the greater the electric field at the surface of the rod tip

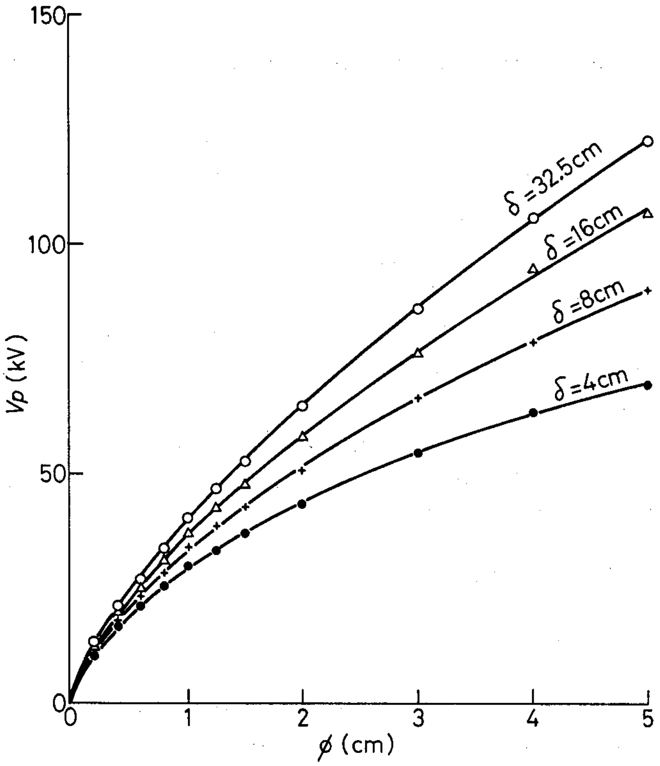


Fig. 22. Characteristics between V_{TC} and ϕ with δ as a parameter.

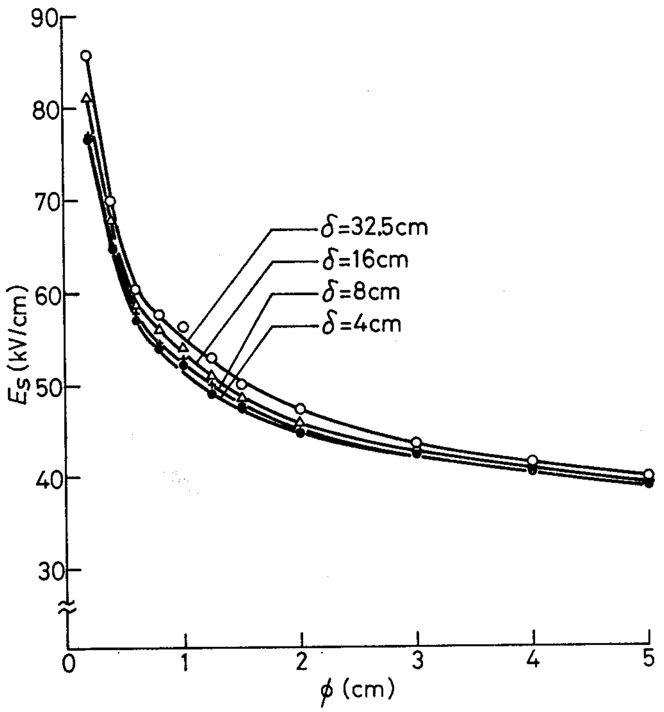


Fig. 23. Electric field at the surface of the rod tip calculated for the TC onset voltage.

must be. In order to confirm this, the electric field E_s at the surface of the rod tip for the TC onset voltage is calculated, and the results are shown in Fig. 23. From this figure, the following notations are made:

(1) For the fixed δ, the smaller the ϕ, the larger the E_s becomes, but the rate of the E_s-increase increases as δ decreases.

(2) For the fixed ϕ, the smaller the δ, the larger the E_s becomes, but the gradient of the E_s curve increases as ϕ decreases. For a large ϕ, the δ-change has scarcely any effect on E_s.

(3) If ϕ increases to a large value ($\phi \rightarrow \infty$), E_s approaches gradually to a value of about 30kV/cm regardless of δ, which is about equal to the electrical breakdown strength in the case of a uniform field in atmospheric air.

⟨5.4⟩ Spark Voltage Characteristics

Concerning the V_a curve corresponding to the continuous spark, there is a special range in δ where the V_a-value increases discontinuously by a small change of δ for any case of ϕ. Fig. 24 shows the relationship between ϕ and ΔV_a, which is the value of the discontinuous V_a-increase as mentioned above. From the comparison between Fig. 24 and Figs. 3~13, it is noticed that the larger the ΔV_a, the wider the δ-range becomes, in

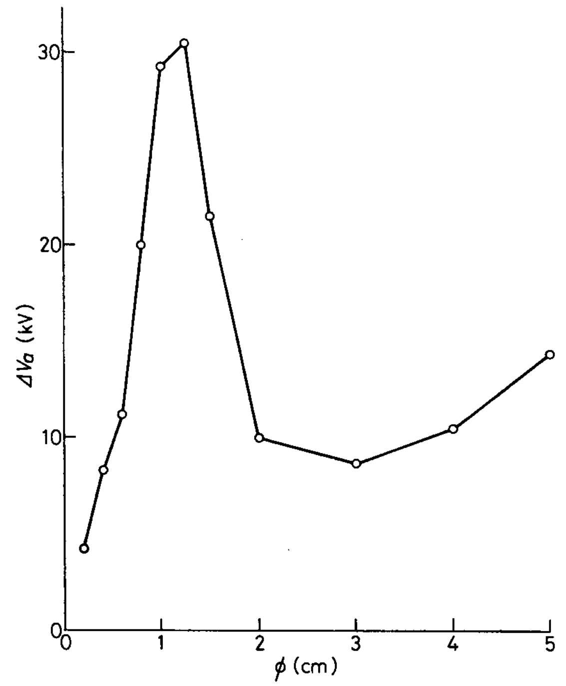


Fig. 24. Characteristics between ϕ and ΔV_a.

which the intermittent spark does not appear. Thus, the intermittent spark occurs at δ in which the V_a for the continuous spark discontinuously rises. For $\phi \leqq 20$ mm, it is deduced that the vanishing of the intermittent spark is closely related with the vanishing of SC, i.e., the large SC occurrence leads to an intermittent spark.

When the circuit impedance including the TT is sufficiently low, the first spark leads to a continuous arc discharge and the applied voltage could not be increased. Let V_{a0} be the first sparking voltage among the intermittent and continuous sparks. The relation between V_{a0} and ϕ is shown in Fig. 25 with δ as a parameter. From this figure, the following results are obtained:

(1) For $\delta=30$ cm, the V_{a0}-value is almost constant for the ϕ-change, and is about 145~150 kV.

(2) For $\delta=24$ cm, the V_{a0}-value is almost constant (about 120 kV) for $\phi \leqq 3$ cm, but it increases with the ϕ-increase for $\phi \geqq 4$ cm.

(3) For $\delta=18$ cm and 8 cm, V_{a0} has minimum values for $\phi=1.5$ cm and 1 cm, being 90 kV and 44 kV, respectively. For $\delta \fallingdotseq 12$ cm, the ϕ-value, where V_{a0} has a minimum, is not obvious.

(4) For $\delta=0.5$ cm, the V_{a0}-curve has a smooth shape passing through the origin, and coincides with the V_{TC} curve.

As the result, for a large δ, the V_{a0} becomes constant, and for a small δ, V_{a0} coincid-

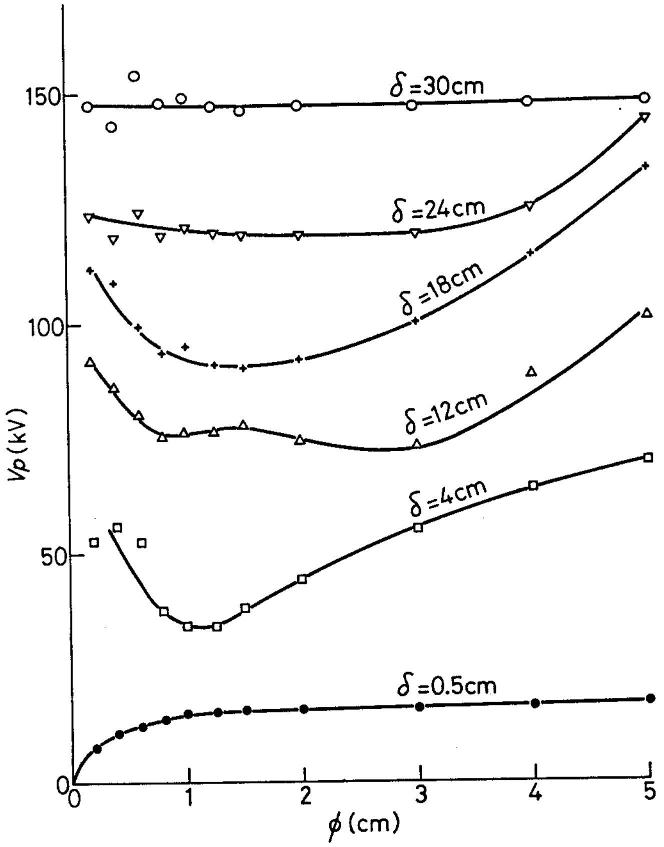


Fig. 25. Characteristics between V_{a0} and ϕ with δ as a parameter.

es with V_{TC}. For a middle range of δ, the V_{a0}-characteristics become very complicated because of the intermittent spark occurrence, but have a tendency to increase for both a large and small ϕ.

6. Conclusion

In this study, the characteristics of the corona and sparking voltage under the AC voltage applying to a rod-to-plane gap in room air are investigated. The results obtained here are summarized as follows:

(1) The onset voltages of positive filmy corona and negative Trichel corona increase and saturate by increasing δ. The larger the rod diameter, the higher becomes the onset voltage.

(2) The negative corona does not vanish until the applied voltage reaches the sparking voltage, and the smaller the rod diameter, the stronger becomes the tendency to localize coronas in the vicinity of the rod tip.

(3) The onset voltage of positive streamer corona increases with the δ-increase. There exists a discontinuity in this onset voltage, because in some cases, the streamer corona disappears with the voltage increase.

(4) Concerning the positive corona, there exist three types of streamers: (i) the first type which has a hemispherical shape around the rod tip, (ii) the second type which has a conical or cylindrical shape and arrives at the cathode, (iii) the third type whose magnitude is so small that one can hardly find it.

(5) Concerning the spark, there exist two types. The first type of spark occurs at each cycle, but the second type does not occur at each cycle. Both types occur at the positive and negative polarity, or, at only the positive polarity.

(6) Most of the intermittent sparks occur in the positive cycle. When the intermittent spark disappears with the increase of the applied voltage, the disappearing voltage coincides with the vanishing voltage of the positive streamer corona.

(7) Characteristics of the onset or the disappearing voltage of the various types of corona and spark are classified into some regions by the gap length and rod diameter.

(8) The disappearing voltage of the intermittent spark and positive streamer corona decrease with the increase of the gap length. For the gap length longer than the value where these curves cross the characteristics of their onset voltage, they do not exist any longer.

(9) For a large δ, the sparking voltage is almost constant for all rod diameters. For a small δ, the sparking voltage coincides with the onset voltage of the negative corona.

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