Observation of Corona Discharges in Atmospheric Air under AC Voltage

By

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Abstract

The behaviors of the filmy, Trichel and streamer coronas in atmospheric air under AC voltage are investigated by means of the current and light pulse, the synchronous optical shutter, the streak photograph, etc.. By the use of the synchronous shutter, it was made clear that the filmy corona occurs in a positive cycle of the applied voltage, and that the filmy corona occurs together with the Trichel corona at the same voltage. In the sequence of the streamer corona pulses, there can be classified three types of pulses in magnitude and nature. Also, they have inherent patterns respectively in the sequence.

1. Introduction

Discharge phenomena in atmospheric air have been investigated for a long time, and much useful information has been accumulated so far.[1)~3)] However, in regard to the corona discharges under AC voltage, it can be said that the fundamental research is not yet sufficient, except for the practical research.

A few experimental results of fundamental research about the AC corona are reported,[4),5)] but the behavior of the corona in a cycle of the applied voltage (the change of the phenomena, current and light pulse form in a cycle, etc.) is not yet clarified sufficiently. It is reported that the current and light pulse caused by the burst corona under the application of DC voltage are constructed by two types of these.[6)] Recently, it was found that there exist two types of the current and light pulses for the streamer corona under DC or AC voltage similarly to those of the burst corona.[7),8)] In this paper, the relation between the discharge phenomena of these two types of streamers is investigated;

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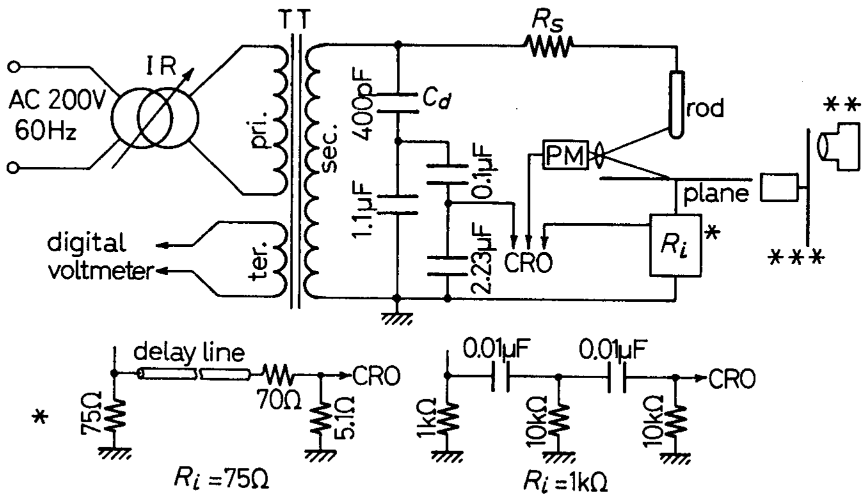
and the behavior of the filmy and Trichel corona is studied by means of the streak photograph, the synchronous optical shutter, etc..

2. Experimental Apparatus and Method

Fig. 1 shows the diagram of the experimental apparatus. The output voltage of the testing transformer (TT) is applied to a rod electrode through a protecting registor R_s (20 kΩ), and is measured by the dividing capacitor C_d and the oscilloscope. The applied voltage is controlled by adjusting an induction regulator IR connected to a primary winding of the TT, and the effective value of the applied voltage is measured by a digital voltmeter connected to a tertiary winding of the TT.

The test gap is constructed by a hemispherically-capped cylindrical rod and a plane which are made of brass. The diameter (ϕ) of the rod electrode and the gap length δ are fixed on 15 mm and 20 cm, respectively. The sizes of the plane electrode are 1 m × 1 m × 2 mm, and the plane is grounded through a current detection registor R_i (1 kΩ or 75 Ω). The voltage drop across R_i is connected to the oscilloscope (Tektronics type 556, abbreviated as CRO in the following) through a 2-stage CR type high-pass filter to eliminate a commercial frequency component in the current wave.

The light pulse emitted from the corona discharge is measured by a photomultiplier (PM) and is displayed together with a current wave. The discharge phenomena is photographed by a still camera or a rotating camera to get a still photograph or a streak photograph. Both cameras are optical ones of the usual and popular type, and the



** Still camera, or streak camera equipped with a synchronous switch
*** Rotating-plate type synchronous optical shutter

Fig. 1. Schematic diagram of experimental apparatus.

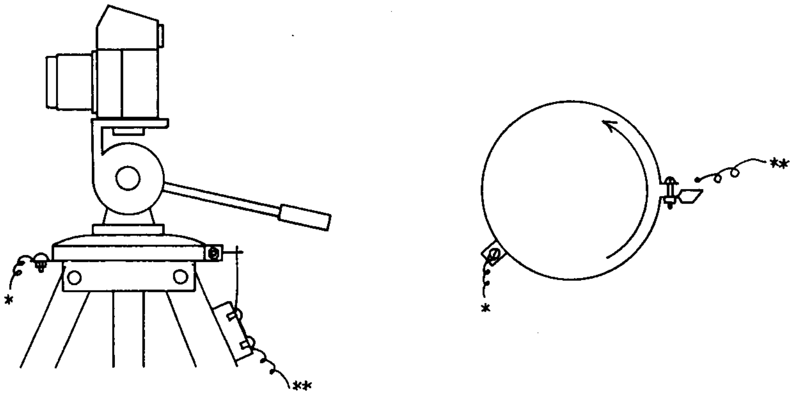


Fig. 2. Synchronous switch for taking a streak photograph.

latter is mounted loosely on the tripod and can be rotated manually to about 180° in counter-clockwise direction with the speed of about 4 rps. Fig. 2 shows the synchronous switch, which is constructed by a fixed electrode set on a tripod body and a moving electrode set on a tripod mount which triggers the CRO at a fixed position on the streak photograph. Fig. 3 shows the position at which the synchronous switch contacts. Thus, the applied voltage, the current and the light pulse wave form corresponding to a streak photograph, are obtained.

In order to determine the voltage phase θ where the corona appears, a rotating circular plate (abbreviated as RP in the following), which is driven by a synchronous motor, is used. Whose two slits have an opening angle 5° which corresponds to 10° in an electrical angle because the synchronous motor has two pairs of poles. Behind the RP, two fixed brades were set up, and the lapping and opening angle of these brades were adjusted as shown in Fig. 4. These fixed brades are used to restrict the view sight through the RP

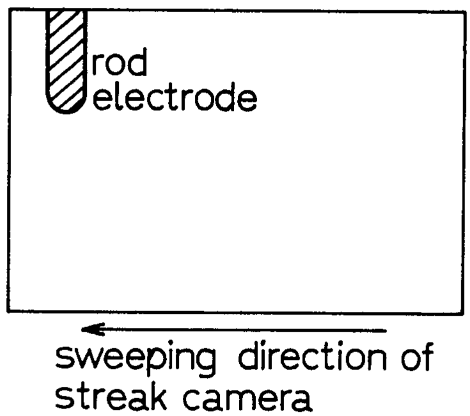


Fig. 3. View sight of streak camera when the synchronous switch contacts.

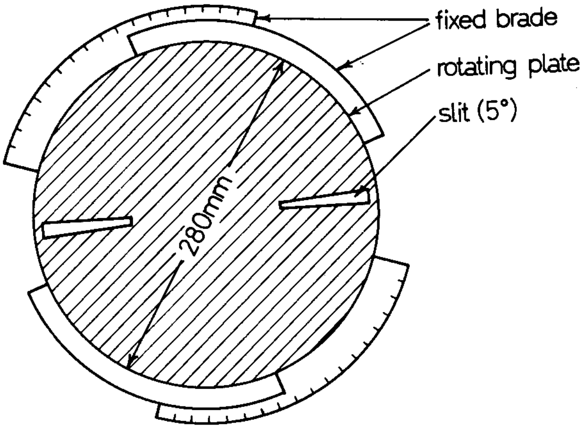


Fig. 4. Structure of rotating-plate type synchronous optical shutter.

and cut the emission from the discharge phenomena occurring at an undesirable voltage phase.

The applied voltage is indicated by the peak value V_p in the following, except for some special cases. The phase origin of the applied voltage is indicated in the usual way, i.e., the point where the polarity of the applied voltage changes from negative to positive is regarded as 0°.

Experiments were carried out in atmospheric air conditions and in a dark room.

3. Corona and Breakdown Characteristics

The corona and breakdown characteristics for the electrode used here are shown in Fig. 5. Roughly speaking, there can be found three types of coronas under the application of AC voltage. They are the filmy corona (abbreviated as FC in the following), the Trichel corona (TC), and the streamer corona (SC). A more detailed classification of the corona is reported in another paper.[9]

For ϕ=15 mm and δ=20 cm, the sequence of the corona appearance by the increase of applied voltage is as follows:

0~48.0 kV: No corona can be detected by either CRO or the naked eye.

48.0~49.3 kV: The FC is distinguishable, but the measured value of applied voltage includes error to some extent because of its weakness.

49.3~86.7 kV: The TC occurs. The magnitude of brightness is small at the beginning, and increases gradually by the increase of applied voltage. However, the spatial magnitude of the individual corona does not change very much. Acoustic noises occur with the TC.

86.7~103.2 kV: The SC appears accompanied with acoustic noises sounding someth-

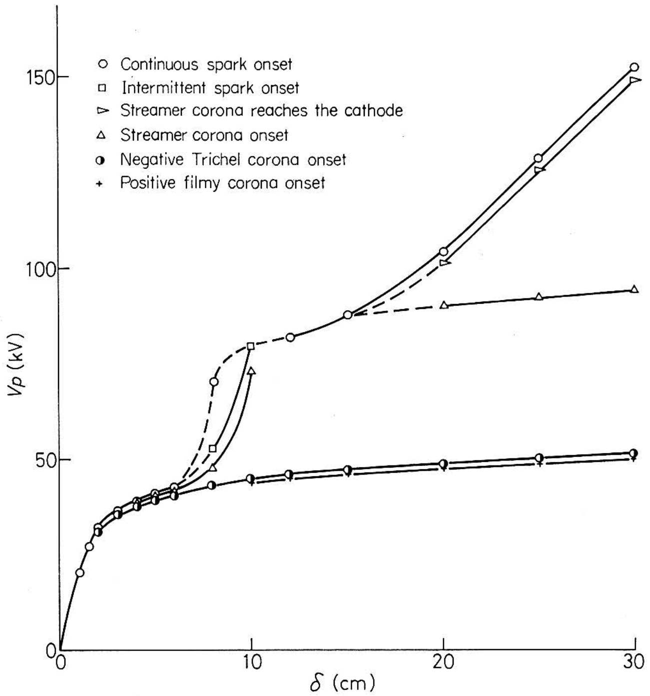


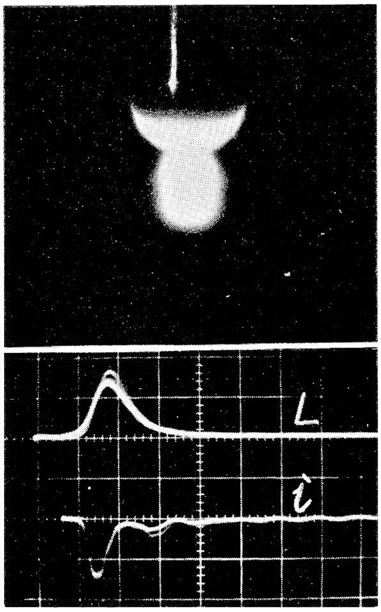
Fig. 5. Corona and breakdown characteristics for the electrode used.

ing like 'puff'. The repetition rate of the SC occurrence is low for the onset voltage (once per few seconds) and becomes continuous by a further increase of voltage. Just under the sparking voltage, SC'', the so called 'bridged streamer' having a conical or cylindrical profile, is observed reaching the cathode.

103.2 kV: Spark occurs.

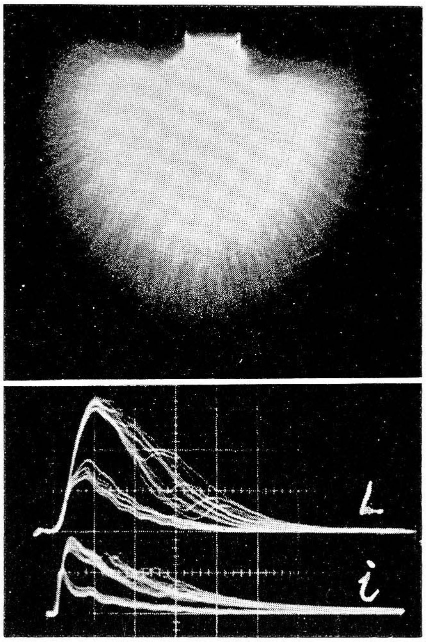
Fig. 6 shows a still photograph of the FC obtained by long time exposure (2 min.) without RP. Fig. 7 shows a still photograph of the TC and the corresponding oscillogram of the light and current pulse (indicated by symbols L and i, respectively) obtained without RP. By comparison between Figs. 6 and 7, it is observed that the apparent brightness of the TC is much greater than that of the FC. The duration of

V_p=48 kV, exposure: F 1.4, 2 min.
Fig. 6. Still photograph of FC without RP.



V_p=70.7 kV, R_i=75 Ω, exposure: F 1.8, 2 s,
sweep: 0.05 μs/div., current: 8 mA/div.

Fig. 7. Still photograph of TC without RP, and corresponding light and current oscillogram.



V_p=102 kV, R_i=75 Ω, exposure: F 1.8, 2 s,
sweep: 0.1 μs/div., current: 80 mA/div.

Fig. 8. Still photograph of SC and corresponding light and current oscillogram.

the light and current pulse of the TC is about 0.1 μs. Fig. 8 shows a still photograph of the SC and the corresponding oscillogram of the light and current pulse obtained in the same manner as the TC. From this oscillogram, it is noticed that the duration of the light and current pulse of the SC is about 0.5 μs. They can be classified into two groups of light and current pulses, different from each other in the magnitude. In the following sections, the behavior of these three types of coronas (FC, TC, and SC) are described in detail.

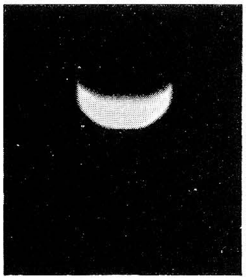
4. Filmy Corona

The light emission of the FC is very weak and is not accompanied with audible noises, so that the observation of the FC is very difficult. The light and current pulse caused by the FC occurrence could not be observed by CRO in this experiment, only by the naked eye.

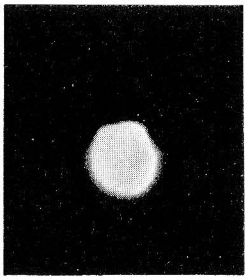
A still photograph of the FC is shown in Fig. 6 which was obtained without RP. From the observation with RP, it was made clear that the polarity of applied voltage in which the FC occurs is positive, and that the phase at the instance of the FC appearance is about 90°.

Under the AC voltage application in the range of applied voltage where some types of coronas appear simultaneously, it is very difficult to observe an individual corona separately by a still photograph or by naked eyes. However, the use of RP makes it very easy, and one can obtain precise knowledge for the behavior of the FC under the circumstances where the TC or the SC occur.

Fig. 9 shows a still photograph obtained through RP under the same gap conditions as in Fig. 7. Fig. (a) and (b) are obtained by opening the fixed brades between 0°～180° and 180°～360°, respectively. Thus, those figures correspond to the FC and the TC respectively, and it can be observed that these two types of coronas can exist together at

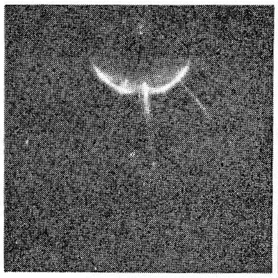


(a) Shutter is opened between 0～180°.

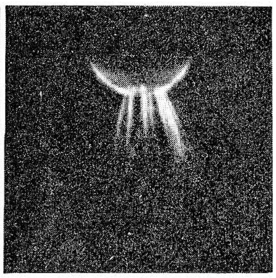


(b) Shutter is opened between 180～360°.

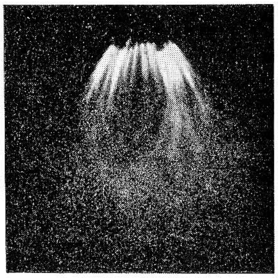
Fig. 9. Still photograph through RP. Gap conditions are same as in Fig. 7.



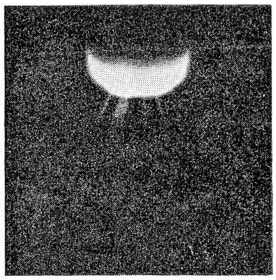
(a)
V_p=86.7 kV, F 1.4, 3 s.
θ=90°.



(b)
V_p=92.2 kV, F 1.4, 3 s.
θ=90°.



(c)
V_p=100.5 kV, F 1.4, 1 s.
θ=90°.



(d)
V_p=100.5 kV, F 1.4, 30 s.
θ=60°.

Fig. 10. Still photograph through RP under different voltage or θ.

the same voltage. Comparing Figs. 7 and 9, it is clear that the former can be made from the superimposition of the latter's figures. When the TC occurs together with the FC at a certain voltage, the brightness of the FC becomes strong, and the expansion of the range of the voltage phase where the FC appears is observed. Thus, the negative space charge produced by the TC occurrence in a certain negative cycle remains until the next positive cycle, and affects the behavior of the FC.

Fig. 10(a)~(c) show still photographs obtained with RP under some different voltages where the electrical angle θ is about 90°. In Fig. (a), the applied voltage is not so high, and while the SC scarcely appears, the FC is clearly distinguishable. In Fig. (b), the applied voltage is higher than that in Fig. (a), so the SC appears more frequently but the FC is yet visible. In Fig. (c), however, the SC occurrence is so frequent that the FC is hardly distinguishable. Thus, from these figures, it is considered that the SC and the FC could not exist at same time. Fig. 10 (d) shows a still photograph under the same conditions as that of Fig. (c) except for θ (which is 60° in this figure). In this case, the SC does not occur for all cycles at this value of θ, so that both the SC and the FC are observed in this figure.

5. Trichel Corona

The TC occurs in negative cycles (see Fig. 7). By the increase of applied voltage, an extreme change of appearance can not be observed except for the growth of the spatial magnitude, the acoustic and light emission. It is considered that the TC under AC voltage has the same character as that under DC voltage. However, under the AC voltage application, the transition from the TC to a pulseless corona can not be observed for any gap conditions.

⟨5.1⟩ Relation between Current Pulse and Voltage

Fig. 11 shows an example of current pulse caused by the TC occurrence under the low sweeping speed of CRO. The voltage wave is indicated by the symbol v in the figure. From many observations of oscillograms similar to Fig. 11, the relation between the current pulse and the applied voltage is shown in Fig. 12. The first pulse occurred

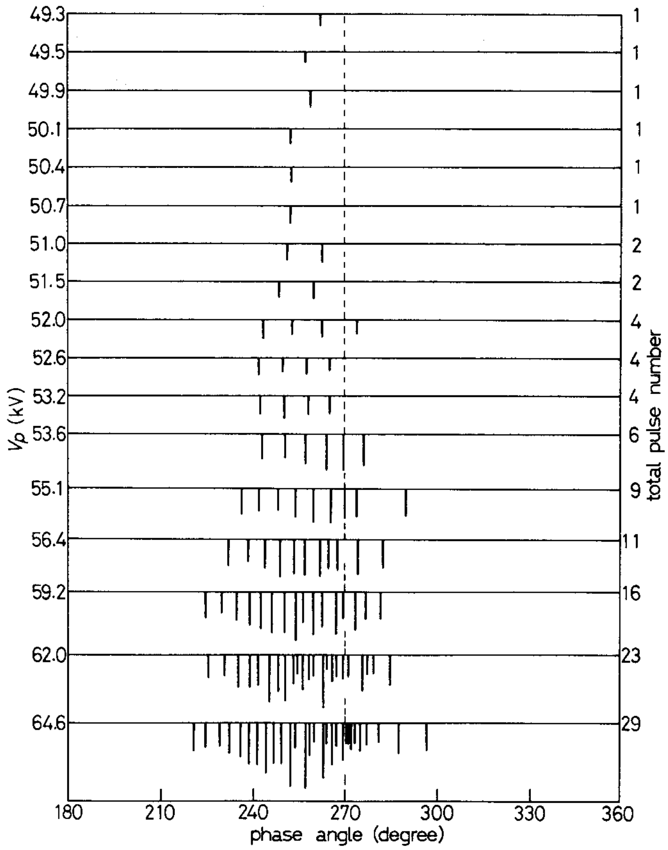
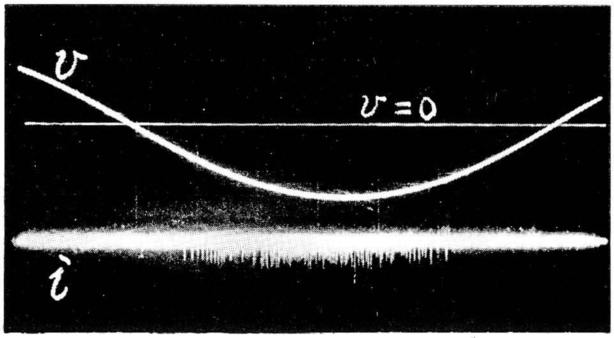
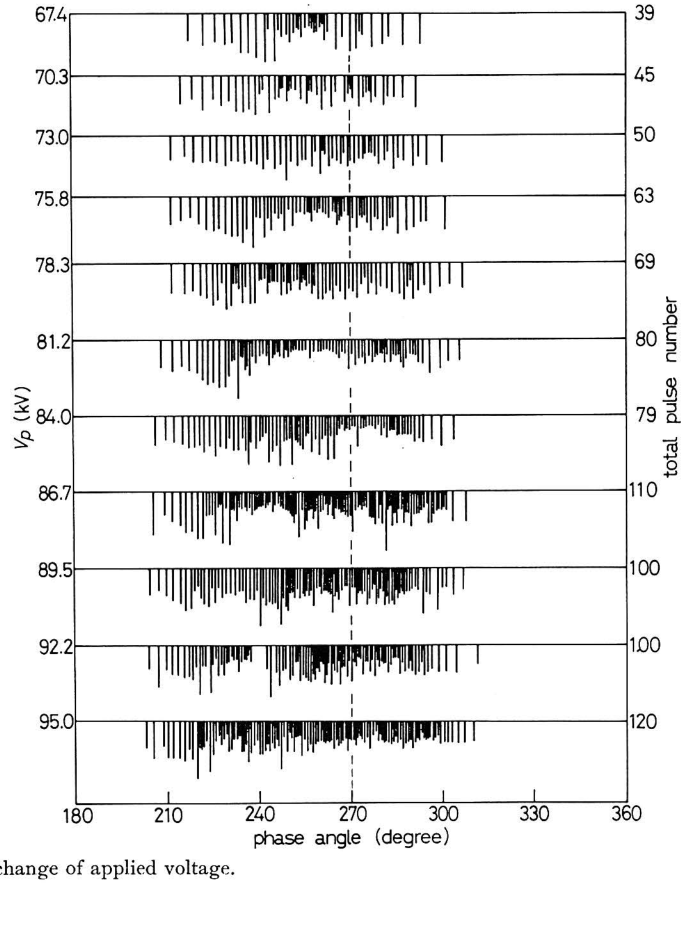


Fig. 12. Variation of current pulses by the



V_p=97.2 kV, R_i=1 kΩ. sweep: 1.16 ms/div., current: 10 mA/div.
Fig. 11. Example of voltage and current pulse for TC occurrence.

at near 262.5° and shifts to an earlier phase by an increase of voltage. Hence, it is considered that the voltage at the instance of the TC appearance is important for the corona discharge. By further increasing the applied voltage, the second pulse appears at the



change of applied voltage.

phase where the first pulse occurred against the lower voltage. In the same way, the first pulse shifts to an earlier phase and the pulse number increases by the voltage increase. At V_p=59.2 kV, the envelope of the pulse group takes on a mountain-like shape. For the voltage higher than 92.2 kV, different types of small pulses appear in the middle range of the pulse group. The total number of pulses increases, but the magnitude of pulses decreases slightly. By further increasing the applied voltage, the magnitudes of the small type pulses increase gradually, and the tendency for all pulses to be uniform becomes predominant as in the DC voltage application. (See the case of V_p=95.0 kV.)

For V_p=92.2 kV, there can be found a region where no pulse is observed. When the applied voltage is high, this pulseless state is frequently observed. However, it is not clear whether this state is the same phenomena as that of the pulseless corona under

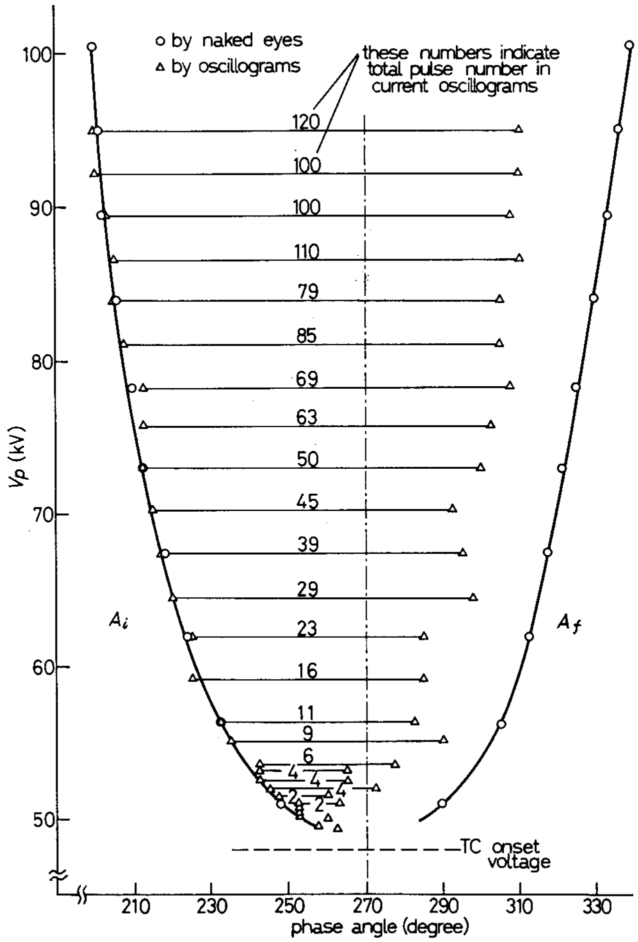
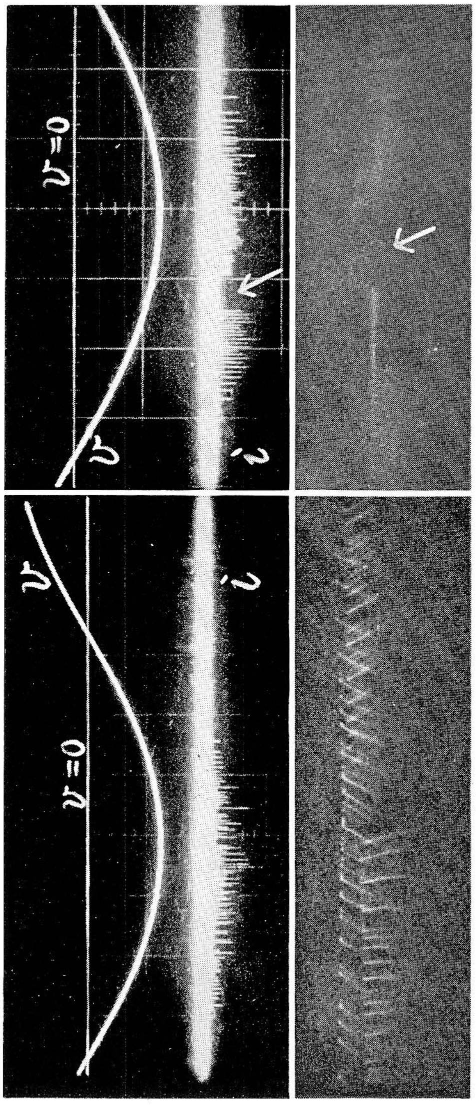


Fig. 13. Characteristics of initial and final angle for TC occurrence.

DC voltage.

At a voltage higher than 96.7 kV where the SC occurs, the number of the TC pulses increases rapidly. This phenomenon is considered as follows: The positive space charge produced by the SC occurrence in the positive cycle remains until the next negative cycle, so that the TC pulses increase in number due to the cancellation of the positive space charge.

Fig. 13 shows the characteristics of the initial and final angles for the TC occurrence, obtained from the observation of the TC through RP and by naked eye (direct observation) together with those obtained from the oscillograms as shown in Fig. 12. From the



(a) V_p=97.8 kV

(b) V_p=97.2 kV

Fig. 14. Streak photograph of TC and corresponding voltage and current oscillogram. R_i=1 kΩ, sweep: 1.16 ms/div., current: 10 mA/div.

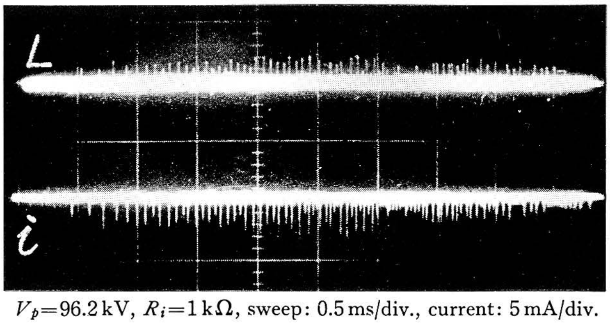
comparison of the direct and oscillographic observation, the initial angles obtained in both methods coincide well. However, the final angles obtained in both methods do not coincide with each other.

⟨5.2⟩ Observation and Analysis by Streak Photograph of TC

The streak photograph taken by an ordinary optical camera is very useful for the observation of an AC corona which has a duration time of the order of ms. However, the photograph obtained by this method has a lower density compared with the still photograph because the light emission from the corona can not be integrated sufficiently in this method. Thus, for the low voltage application, a streak photograph of the TC could not be obtained.

As shown in Fig. 14, the TC develops pulsively corresponding to the current pulse. Especially in Fig. (b), there can be observed a region where no visible corona corresponds to the pulseless state in the current wave (indicated by arrow signs). Fig. 15 shows the total light pulses emitted from the corona discharge and the current pulses obtained by the simultaneous measurement. From this figure, it is deduced that the light pulses correspond well to the current pulses in time and magnitude.

In Fig. 14(a), images of the individual TC corresponding to the individual current pulses lie parallel. Thus, the individual TC pulse occurs in the same path of the precedings. Furthermore, from this figure, it is deduced that the TC occurs at some different points on the electrode surface simultaneously because the image of the TC takes a multiple band structure. Generally, the TC appears at the rod tip at first, then the second TC appears a little above the tip, and finally shifts down to the tip. Furthermore, there is a tendency that the first appearances of the TC disappear early. In Fig. 14(b), there can be found a short duration where no pulse is observed. The cause of this duration is considered to be an interval between the first and the second groups of the TC, or to be the occurrence of a pulseless corona similar to that under the DC voltage application. It is very difficult to clarify the true cause of this phenomena. In Fig. 14(a), the ind-



V_p=96.2 kV, R_i=1 kΩ, sweep: 0.5 ms/div., current: 5 mA/div.

Fig. 15. Example of light and current pulses for TC obtained by simultaneous measurement.

ividual TC is accompanied by a weak light emission on the cathode which does not develop into the gap space, so it is observed as a short line in a sweeping direction of the streak photograph.

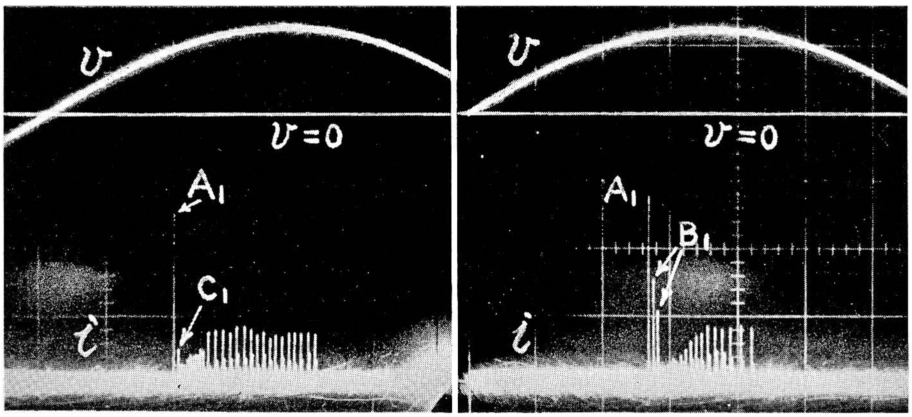
6. Streamer Corona

As shown in Fig. 8, for the SC, there can be found two groups of the light and current pulses different from each other in the magnitude. In this chapter, the difference and relationship between those two groups in the current wave are investigated by observing the current pulse and the streak photograph under a slow sweeping speed.

⟨6.1⟩ Current and Light Pulse of Streamer Corona

Fig. 16 shows some examples of the current pulse caused by the SC under a low sweeping speed (1.16 ms/div.) together with the applied voltage wave. From many such figures, a typical SC pulse form is obtained as shown in Fig. 17. As indicated in Fig. 17, the largest pulse occurs at the head of the sequence of all the SC pulses, and is called the A_1 type pulse (abbreviated as A_1 in the following). After the occurrence of A_1, another pulse, the peak value of which is about 20% of that of A_1, appears, and is called the C_1 type pulse. However, there is another pulse greater than C_1, occasionally appearing in the range between A_1 and C_1, and is called the B_1 type pulse.

After the C_1 occurrence, a group of successive small pulses (C'_1) appear, and are called PG. Successively after the PG, pulses become stable gradually in magnitude, and a transient state appears before the steady state. In this paper, the pulses included in this transient state are referred to as a transient pulse sequence. The pulses included in the steady state after the transient state as mentioned above are



(a) (b)

V_p=97.8 kV, R_i=1 kΩ, sweep: 1.16 ms/div., current: 20 mA/div.

Fig. 16. Example of voltage and current pulses for SC occurrence.

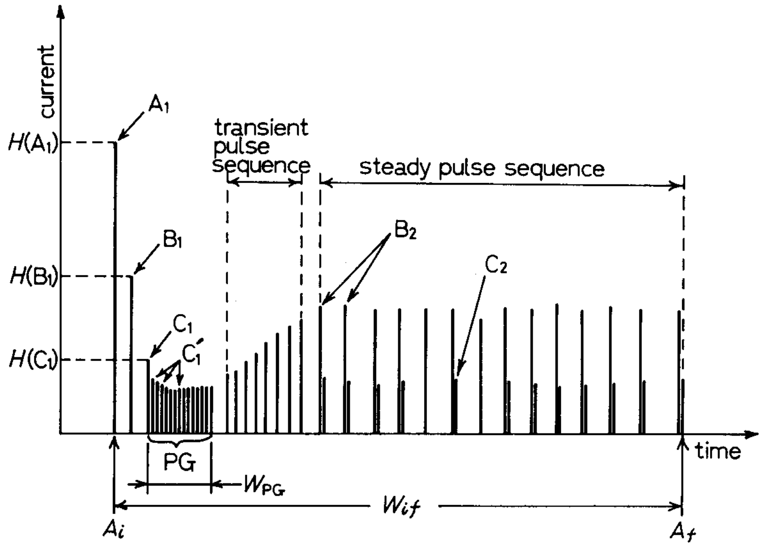


Fig. 17. Typical SC pulse form.

referred to as a steady pulse sequence. The reason for using the term 'steady' is as follows: the transition from this state to another state can be scarcely observed, and the current pulse form in this state is similar to that in the SC sequence under the DC voltage application.

In the steady pulse sequence, most of individual pulses are accompanied by small pulses. In this paper, they are called B_2 and C_2 type pulses, respectively. The steady pulse sequence has constant time intervals and pulse height, but disappears suddenly.

Fig. 18 shows an example of the simultaneous measurement of light and current pulses for the SC. From this figure, the ratio of the light to the current pulse height can be obtained as shown in Fig. 19. Thus, it can be deduced that the intensity of the light pulse is almost proportional to the current pulse.

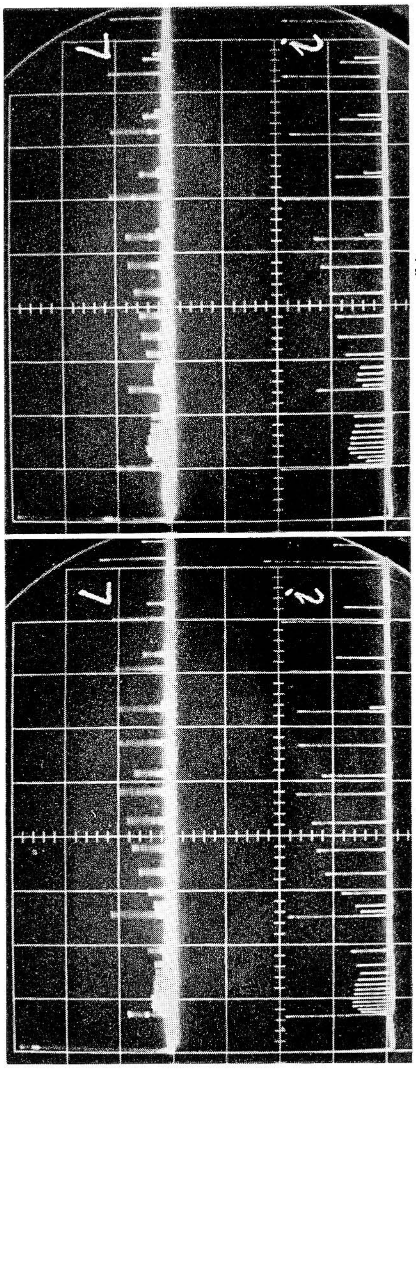
⟨6.2⟩ Characteristics of Streamer Corona

In this section, the characteristics of each variable indicated in Fig. 17 are described.

A_i, the initial phase angle of the SC occurrence, is not fixed and the condition determining A_i can not be clarified. Figs. 20 and 21 show the relation between A_i and A_f, and also between A_i and W_{if}, respectively. From these figures, it can be observed that A_f ranges between 100°~110° without regard to V_p and A_i, and W_{if} decreases linearly by the increase of A_i. Namely, the earlier the A_i, the longer the W_{if} becomes. The reason why the value of A_i does not take a constant value is considered as follows: in a certain positive cycle, the space charge produced by the FC preceding the SC suppresses the SC occurrence and an accidental condition is needed for the SC to overcome this suppression. From the fact that A_f is fixed in the range of $100°\sim110°$ regardless of A_i, it is considered that the applied electric field is an important factor for sustaining the SC.

Fig. 22 shows the characteristics of A_i and A_f for the SC occurrence, together with those for the FC. In this figure, the large difference between A_i for both the intermittent and continuous SC occurrence is explained by the reason mentioned above.

Fig. 23 shows the relation between $H(A_1)$, that is the peak current of A_1, and $V_s(A_1)$, that is the applied voltage at the instance of the A_1 pulse occurrence. From this figure, it can be observed clearly that the greater the $V_s(A_1)$, the larger the $H(A_1)$ becomes.



(a) (b)

V_p=95.0 kV, R_i=1 kΩ, sweep: 0.1 ms/div., current: 10 mA/div.

Fig. 18. Example of light and current pulses for SC obtained by simultaneous measurement.

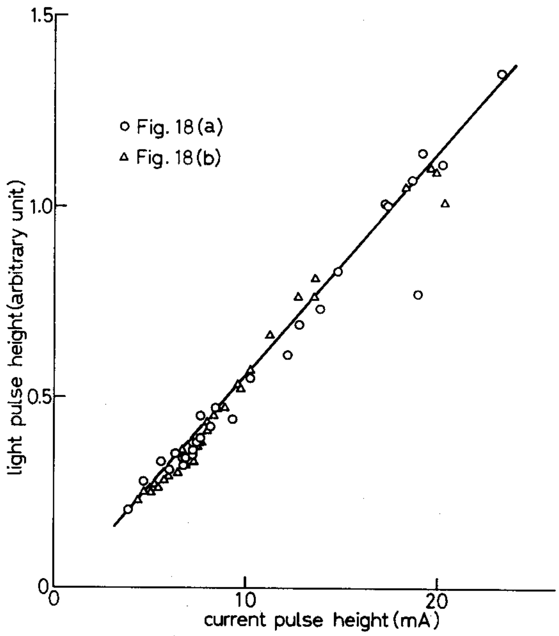


Fig. 19. Ratio of light to current pulse height obtained from Fig. 18.

The A_1 pulse corresponds to the first developing streamer into the gap space, so it is reasonable that the correlation between $H(A_1)$ and $V_s(A_1)$ as defined above exist. However, no correlation can be observed between $H(A_1)$ and $H(B_1)$, nor between $H(A_1)$ and $H(C_1)$. Between W_{PG} (the duration of PG) and $H(A_1)$, however, a small proportional correlation can be found as shown in Fig. 24.

From the current oscillograms, the pulse number increases by the increase of W_{if}

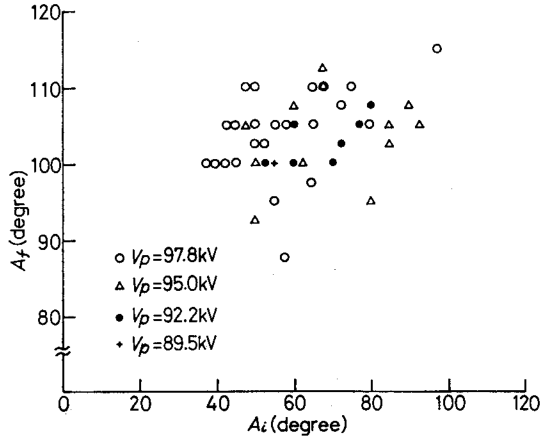


Fig. 20. Relation between A_i and A_f.

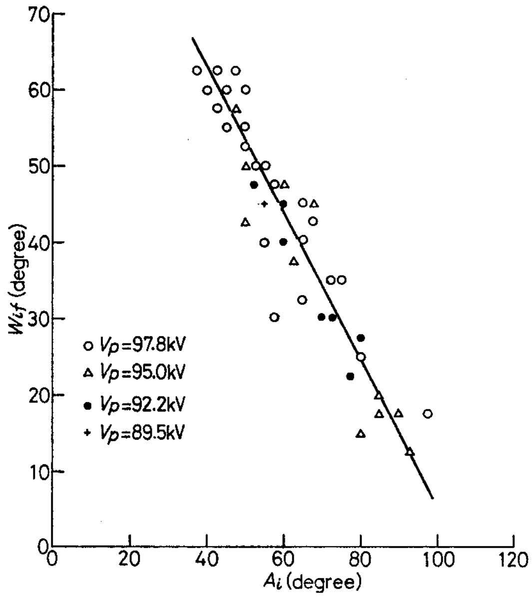


Fig. 21. Relation between A_i and W_{if}.

(the duration of the SC). The average time interval between successive B_2 pulses in the steady pulse sequence is about 150 μs, and that of C'_1 pulses in PG is about 10 μs.

⟨6.3⟩ Streak Photograph of Streamer Corona

Fig. 25 shows some examples of streak photographs of the SC together with the corresponding voltage and current oscillograms. From these figures, it can be observed clearly that the current pulses correspond to the bright channels in the streak photographs. The bright channels occur repeatedly on the same path. The magnitude of the current pulse seems to be in proportion to the channel brightness, and not to be in

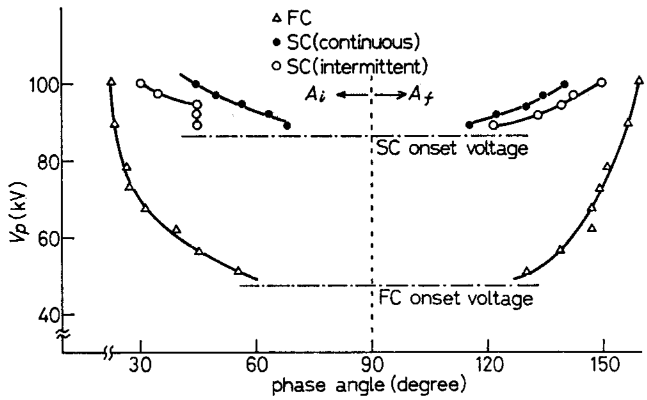


Fig. 22. Characteristics of A_i and A_f against the change of V_s for SC and FC occurrence.

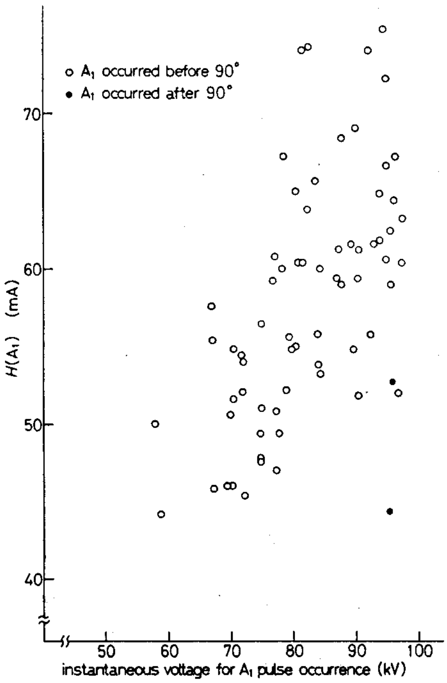


Fig. 23. Relation between $H(A_1)$ and $V_s(A_1)$.

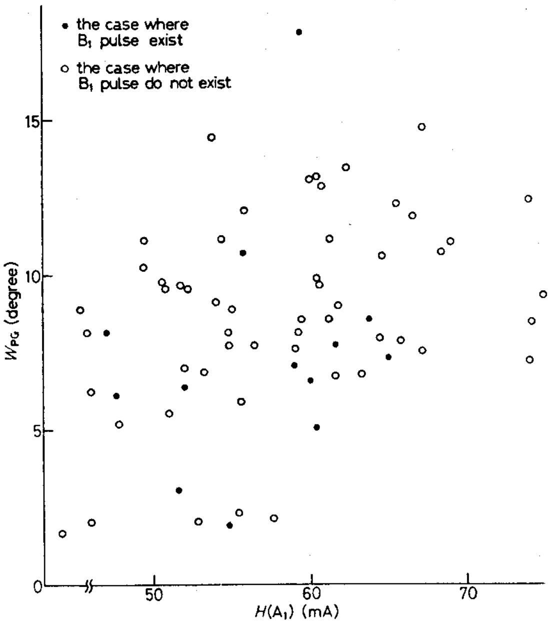
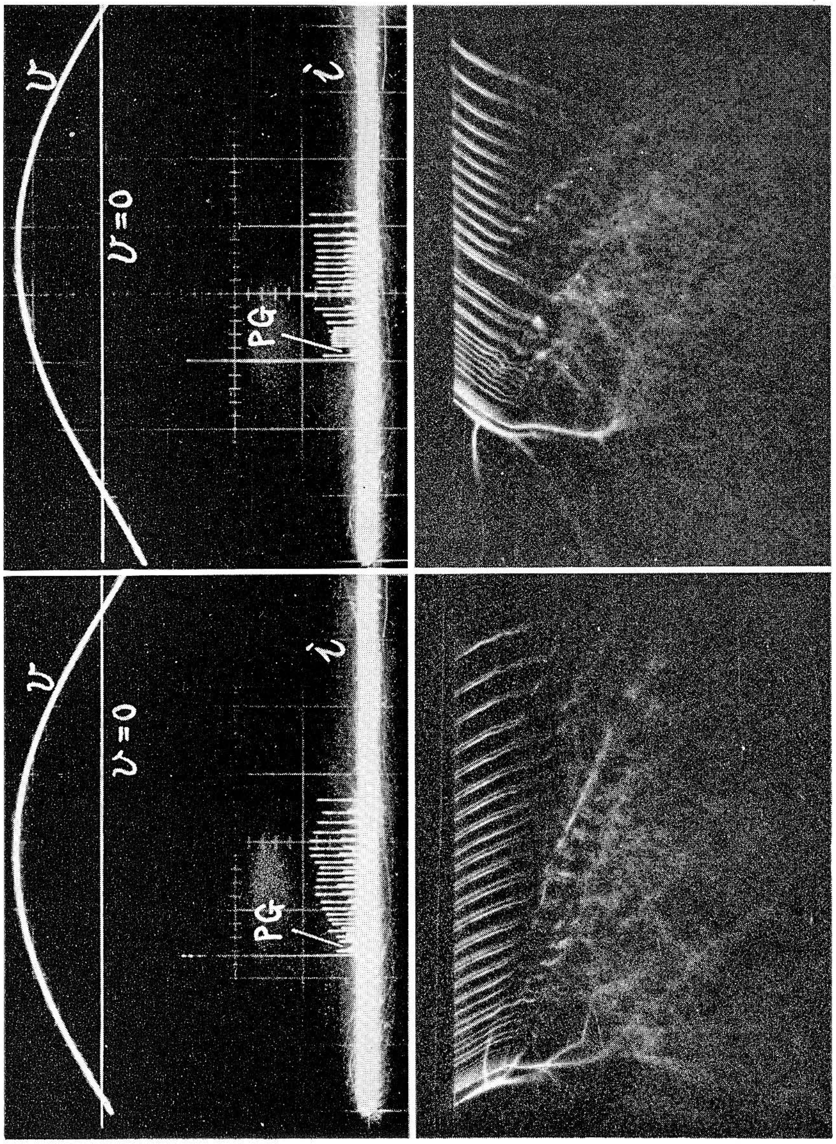


Fig. 24. Relation between $H(A_1)$ and W_{PG}.

proportion to the channel length. For example, the first current pulse is the largest of all the pulses, and the first channel in the streak photograph is the brightest of all the channels. In Fig. (a) and (b), though they are the most popular types of the SC current pulse, the second channel in the streak photograph becomes very long, and it corresponds to the PG in the current pulse. In Fig. (c), the B_1 pulse is observed in the current, and the longest channel, which corresponds to the PG, appears at the third. Furthermore, in Fig. (d), the PG can not be observed in the current, and correspondingly, the well-

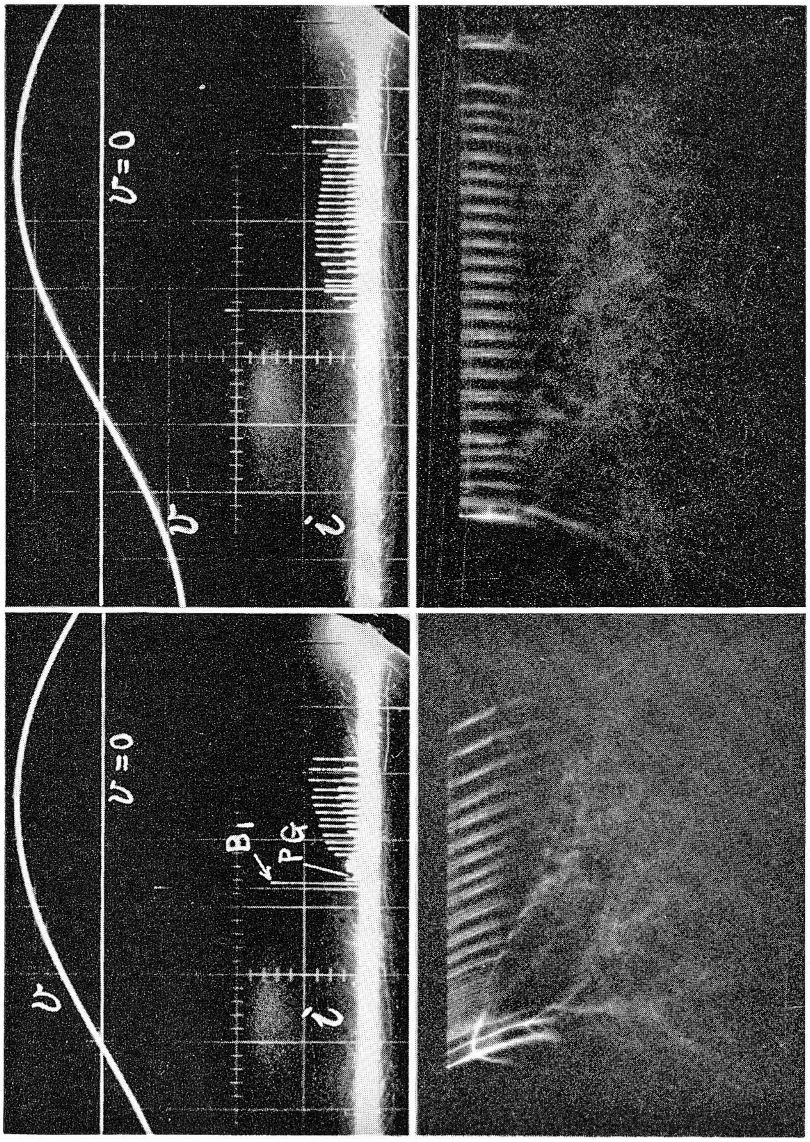


(a) (b)

V_p=97.8 kV, sweep: 1.16 ms/div., current: 20 mA/div.

Fig. 25. Some examples of streak photographs of SC and corresponding voltage and current oscillograms.

developed channel is not observed in the streak photograph. Thus, the channel corresponding to the PG is constructed by many small channels corresponding to the individual C'_1 pulses composing the PG. It is considered that each channel corresponding to the individual C'_1 pulses has branching streamers at the tip of the channels. However, since the resolving power of the streak photograph is not sufficient, the second channel is observed as one corresponding to the whole PG. Furthermore, each channel corresponding to the pulses in the SC has branching streamers, but the



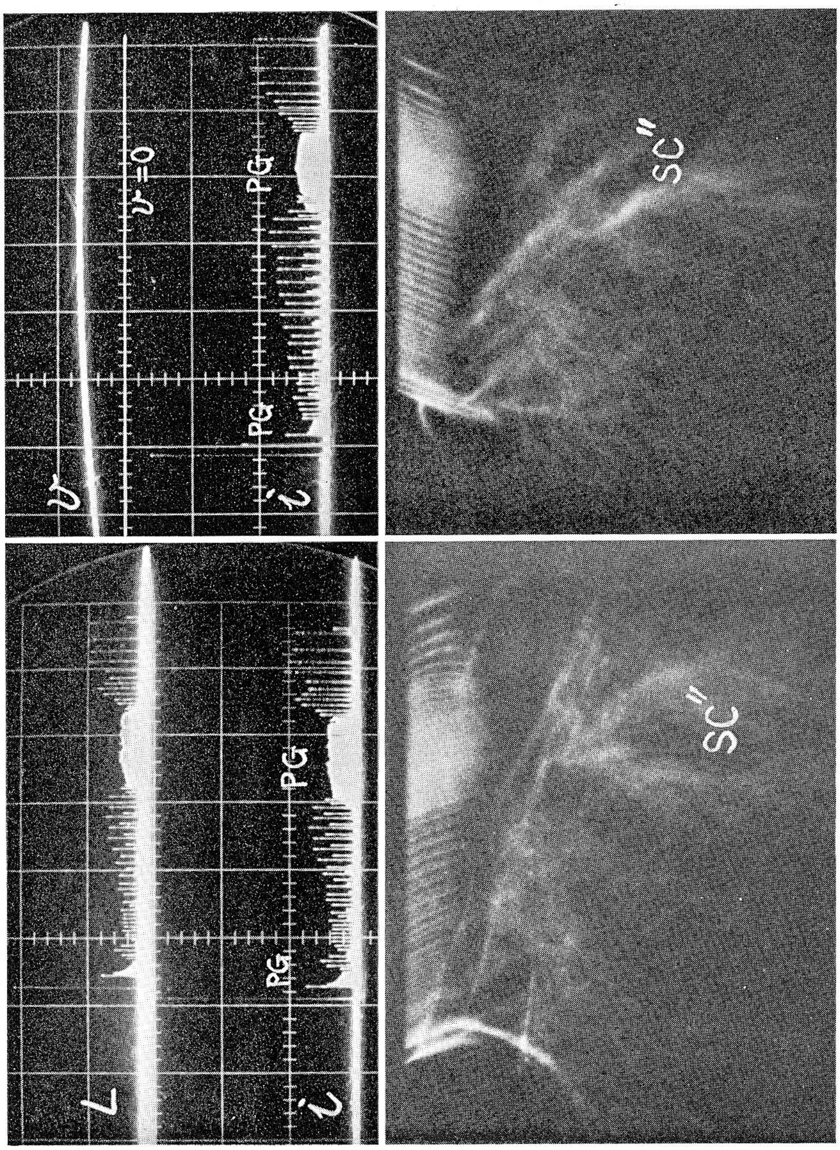
(c) (d)

V_p=97.8 kV, sweep: 1.16 ms/div., current: 20 mA/div.

Fig. 25.

brightness is so weak that clear images can not be taken by the streak camera used here.

Fig. 26 shows the streak photographs of the SC together with the light and current oscillograms at slightly under the sparking voltage. The special feature of these figures is in the occurrence of the second PG. This second PG corresponds to SC″, i.e. the streamer corona having the conical or cylindrical shape. It reaches the cathode, and appears at near 90°. Thus, the peak value of the applied voltage plays an important role for the SC″ occurrence.



(a) V_p=102.1 kV, sweep: 0.5 ms/div., current: 20 mA/div.

(b) V_p=101 kV, sweep: 0.5 ms/div., current: 20 mA/div.

Fig. 26. Some examples of streak photographs of SC and corresponding voltage or light and current oscillograms.

As a result, in the SC pulse sequence three types of pulses are classified. They are (i) the large A_1 type pulse, which is the first one in the SC pulse sequence, (ii) the B_1 or B_2 type pulse having the middle magnitude, which is observed in the steady pulse sequence, (iii) the small C_1, C'_1 or C_2 type pulse, which constructs the PG and/or occurs after the B_2 type pulse. From the oscillograms obtained by fast sweeping, it is deduced that all the pulses are observed separately by some ten μs time intervals. Thus, it is considered that the life time of the channels observed in the streak photograph is of the same order as the time interval mentioned above, because the channels occur repeatedly on the same path.

7. Conclusion

In this study, the behavior of coronas under the AC voltage application to a rod-to-plane gap in atmospheric air were investigated. The results obtained here are summarized as follows:

(1) By the use of the synchronous rotating-plate type optical shutter, it was made clear that the filmy corona occurs in the positive cycle of the applied voltage.

(2) The filmy corona and the streamer corona can not be found simultaneously. In other words, when the streamer corona occurs in a certain cycle, the filmy corona occurs at a different phase than the streamer occurring phase.

(3) The filmy corona occurs together with the Trichel corona at the same voltage.

(4) In the sequence of the streamer corona pulses, their magnitudes can be classified into three types, named as A, B and C, and they have inherent patterns in the sequence, respectively.

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