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Formation and Characteristics of Negative Stepped Leaders in 4-10m Long Air Gap Discharges

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***Abstract*—Natural lightning flashes are stochastic and uncontrollable, and thus it is difficult to observe the formation process of a downward negative stepped leader (NSL) directly and in detail. In this paper, the formation processes of NSLs in controllable laboratorial long-air-gap discharge experiments were studies. First, a series of negative long-air-gap discharge experiments with scales of 4~10 m were designed and carried out. According to the observation results of these experiments, two kinds of formation processes for NSLs with different scales were presented, and several of the characteristic parameters, including the scale, the propagation velocity and the dark period, were obtained. By comparing these characteristics with that in natural flashes, the similarity between the NSLs in the simulation experiments and those in natural flashes was proved, and the actual formation of NSLs in natural flashes was deduced.**

Keywords-stepped leader; negative flash; formation; characteristics; simulation experiment; long air gap discharge

I. INTRODUCTION

The negative cloud-ground flash (CG) cause large amounts of equipment damage and large numbers of casualties every year. Determination of the development of negative CG flashes would be conducive to improvement of the lightning shielding analysis model, and would enable high-efficiency lightning shielding schemes to be proposed.

The formation of negative stepped leader(NSL) is the basic process in the development of negative CG flashes. Until now, its formation mechanisms remain controversial. The most widely accepted of these mechanisms is the bidirectional leader theory[1-4]. In this theory, the NSL develops from a space leader, which consists of two leader segments with opposite polarities and development directions. The upper segment is positive, and develops upward towards the tip of the last NSL, while the lower segment is negative, which develops downward. The new NSL then forms when the positive leader segment connects with the tip of the last NSL. Alternatively, various other viewpoints have been proposed. One of these viewpoints considers the NSL to be developed from downward negative streamers with radii of several meters and electron temperatures of 2×10^4 K, but with the heavy particles remaining at ambient temperature[5].

Since natural flashes are stochastic and uncontrollable, it is difficult to reveal the formation process of NSLs by direct and detailed observations. However, as the development of high-voltage test techniques, simulation experiments offer a indirect but high-efficiency way to research the natural flash under controllable laboratory conditions. Originally, most of experiments were designed to estimate the lightning strike probabilities of air-terminal systems directly[6-9]. But the equivalence of these probability experiments has always been controversial. Considering that laboratorial negative long-air-gap discharges and negative CG flashes are both gas discharges, it seems to be more accepted and reasonable using simulation experiments to study the physical mechanisms of negative CG flashes[10,11]. However, after all, the discharge scales in simulation experiments and natural flashes are much different. Therefore, the influence of discharge scale on the formation of NSLs must be discussed.

In this paper, a series of negative long-air-gap discharge with gap scales of 4~10m are carried out, and the discharge processes are recorded by a group of cameras. According to observation results, the formation processes of NSLs with different scales are revealed, and a series of characteristics of NSLs are obtained and analyzed. By comparing these characteristics with that in natural flashes, the similarity between the NSLs in the simulation experiments and those in natural flashes is proved, and the actual formation of NSLs in natural flashes is deduced.

II. OVERVIEW OF THE EXPERIMENTS

A. Experimental Circuit

In [12], a series of negative long-air-gap discharges with a symmetrical rod-rod gap arrangement were performed to study the attachment processes in competition tests. In these discharges, the scales for development of negative downward leaders were limited because of positive upward leaders that were incepted from grounded rods. To obtain more obvious and fully developed NSLs, a rod-plane gap arrangement is chosen and is used in all experiments in this paper. The overhead rod is a 10-m-long cylindrical electrode with a 4-cm-diameter spherical tip. The plane is well grounded, and the air

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gap scales (H_{gap}) used in these experiments are 4.0, 5.0, 6.0, 8.0 and 10.0 m.

Negative double exponential voltage impulses are applied to the overhead rod by an impulse generator with a capacity of 7.5 MV. The time-to-crest of the impulse voltage is ~80 μs, and the time-to-half value is ~2500 μs. The crest values of the applied voltage are the 50% flashover voltages ($U_{50\%}$) for each gap configuration. The up-and-down method is initially used to obtain the 50% flashover voltage, and then around 30 observation tests are carried out under application of the 50% flashover voltage for each gap scale. The tests were performed during the summer, when the air pressure, temperature, and humidity were ~101 kPa, 28 °C, and 13 g/m^3, respectively. The 50% flashover voltages for all gap scales are shown in Table I.

TABLE I. 50% FLASHOVER VOLTAGE FOR ALL GAP SCALES.

H_{gap} (m)	$U_{50\%}$ (MV)
4.0	−2.07
5.0	−2.38
6.0	−2.59
8.0	−2.94
10.0	−3.32

B. Measurement Setup

To observe the NSL development processes, two high-speed charge-coupled-device (CCD) video cameras (HSCs) and two static cameras (SCs) are set orthogonally, as shown in Fig. 1. The HSCs work in a framing mode with a frame rate of 300,000 frames per second, and the resolution of the image in each frame is 256×64 pixels. The fairly high shutter speed results in a very short exposure time. To record the faint light that is emitted by the streamers and the leader channel, primary lenses with aperture values of 0.8 are used. The two SCs have higher resolutions, and are set in long exposure mode to record the last flashover channel. These high-resolution photographs are then used to reconstruct the three-dimensional discharge channels, and we then obtain the three-dimensional scales of the NSLs ($L_{sl\text{-}3D}$) by combining these photographs with the images from the HSCs. For large discharge gaps, the imaging errors of cameras make it difficult to reconstruct the three-dimensional discharge channels accurately. The three-dimensional reconstruction technology is therefore only used for the observed results with discharge gaps of 4 or 5 m. For the other experiments, which have larger discharge scales, only the two-dimensional scales of the NSLs ($L_{sl\text{-}2D}$) can be obtained.

A capacitive divider with a divider ratio of 5358 is used to measure the impulse voltage. To analyze the spatial electric fields when the NSLs incept, the optical high-speed photographs are synchronized with the applied voltage waves by recording the shoot signals (II, III) of the HSCs simultaneously with the impulse voltage (I) by using an oscilloscope with a sampling rate of 1 GS/s, as shown in Fig. 1, and allowances are made for the transmission delays of each of the signals.

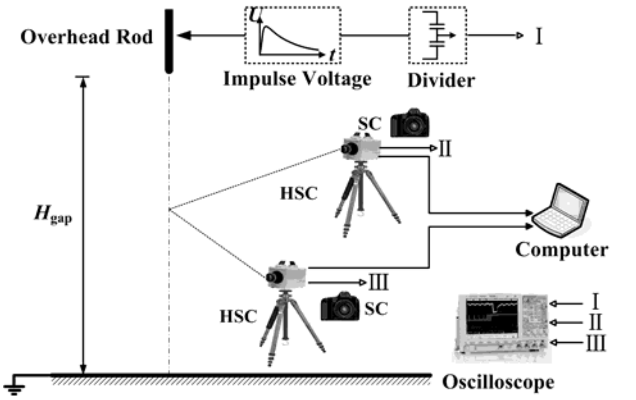


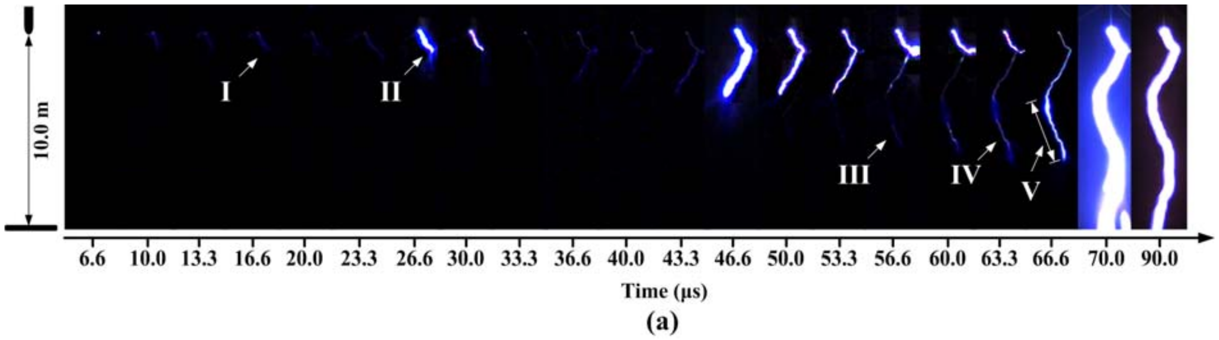
Figure 1. Experimental system. I: applied voltage, II, III: shoot signals of the HSCs

III. EXPERIMENT RESULTS AND DISCUSSIONS

A. Typical Negative Stepped Leader Formation Process

A typical observation result of a 10 m negative discharge with a rod-plane gap is shown in Fig. 2. Three NSLs are observed prior to the breakdown, and these NSL formations appear at 26.6, 46.6 and 66.6 μs. Therefore, the two dark periods between the NSL formations are both approximately 20 μs long. The two-dimensional scales of the three NSLs are 1.02, 2.37 and 3.35 m. The development velocity of a single NSL is defined as the ratio between the length of this NSL and the duration of its last dark period. Therefore, the development velocities of the second and the third NSLs are 11.8 and 16.75 cm/μs, respectively. The applied voltages during the formation of the three NSLs are found to be −2.85, −3.23 and −3.31 MV by synchronizing the high-speed photographs and the applied voltage measurements.

In these discharge processes, after the formation of one NSL, new negative streamers start from its tip and develop continuously during dark periods. Then, the mature developed negative streamers translate into a new stepped leader or into a pilot system which is the precursor of a bidirectional space leader. Because the glimmer emitted by the streamers is fairly weak, even in the laboratory environment, the development of the streamers during dark periods is difficult to observe. The development of the discharge seems to be a discontinuous process and occurs in a stepped form, and the formation of a stepped leader is both sudden and unpredictable. However, according to the results of the observations, all NSLs develop from negative streamers. NSLs with short scales, such as the first or second NSLs shown in Fig. 2(a), develop directly from the negative streamers. In contrast, for NSLs with large scales, such as the third NSL shown in Fig. 2(a), the streamers first translate into the bidirectional space leader, and then that bidirectional space leader translates into a new NSL. The scales of the NSLs in CGs are usually much larger than the scales in the simulation experiments. The space leaders should thus be more obvious and common in CGs. Therefore, it is easy to understand why the bidirectional leader theory was widely accepted as an explanation for the formation of NSLs in CGs. However, the development processes of the negative streamers should exist during the dark period. The bidirectional leader theory and the streamer-leader theory are both realistic theories, and they describe different stages of the NSL formation.



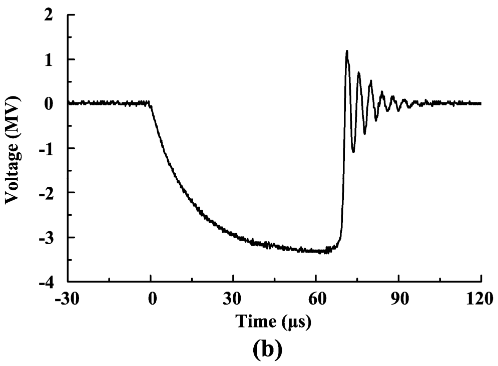


Figure 2. Typical observation results of 10 m negative discharge with rod-plane gap. (a) High-speed photographs; (b) Applied impulse voltage. I: Negative streamer, II: Negative stepped leader, III: Pilot system, IV: Space leader, V: Negative stepped leader that developed from the space leader.

B. *Characteristics of Negative Stepped Leader*

Based on the optical observation results, a series of characteristic NSL parameters were analyzed, as shown in Table II. N_{step} is the average quantity of NSL in a single discharge. L_{av} is the average length of the NSL. L_{max} is the maximum length of the NSL. L_{av} and L_{max} are both three-dimensional for 4.0 and 5.0 m discharges, while they are two-dimensional for discharges with other scales. T_d is the duration of the dark period. v_{av} is the average development velocity, which is defined as the ratio between the length of the NSL and the duration of the dark period. v_{max} is thus the maximum development velocity.

As the discharge gap scale increases, N_{step}, L_{av}, L_{max}, v_{av} and v_{max} all obviously increase. In the 10 m discharges, L_{max} and v_{max} can reach 3.35 m and 17.6 cm/μs, respectively. The duration of the dark period did not change much for the different discharge gap scales. This may be because the crest times of the applied voltages are unchanged, and each applied voltage is the 50% flashover voltage for the corresponding discharge configuration.

TABLE II. CHARACTERISTIC NSL PARAMETERS IN 4–10-M LONG AIR GAP DISCHARGES.

H_{gap} (m)	N_{step}	L_{av} (m)	L_{max} (m)	T_d (μs)	v_{av} (cm/μs)	v_{max} (cm/μs)
4.0	1.76	0.84	1.98	15.3±5.1	7.6±2.9	12.3
5.0	2.0	0.89	1.75	19.6±11.8	6.5±2.3	10.7
6.0	2.63	0.93	1.94	15.8±7.6	7.2±2.4	10.9
8.0	2.91	1.34	2.52	20.0±7.3	9.0±3.2	14.1
10.0	3.67	1.51	3.35	16.7±4.2	10.8±4.4	17.6

C. *Comparison with Natural CG Flashes*

According to the observation results described above, the NSLs with shorter scales are usually transformed from the negative streamers directly, while for the formation of longer stepped leaders, the negative streamer transforms into a space leader, and then that space leader transforms into the stepped leader. A comparison between the characteristic parameters of negative long air gap discharges and those of natural CG flashes is shown in Table III. The scale of the stepped leader (L_{step}) in natural lightning is in the range from meters to hundreds of meters. The normal scale is from 10 m to 100 m. The minimum scale was proposed by Berger[12], and is approximately 3 m. The stepped leader scale in natural lightning is mostly longer than that produced in the experiments described in this paper. Therefore, the stepped leader formation process in natural lightning is similar to that of the longer stepped leaders in the discharge experiments, and a space leader should usually be observed.

Also, the comparison indicated that the scales and development velocities (v_{step}) of the stepped leaders in long air gap discharges will be similar to those that occur in natural lightning when the discharge gap increases to values longer than 8 m. Therefore, the stepped leader from the experimental discharge is similar to that in natural lightning, and not only in terms of formation processes, but also with respect to their characteristic parameters. Some characteristic parameters of stepped leaders in natural lightning can be obtained by extrapolating the corresponding data obtained from the simulation experiments.

TABLE III. CHARACTERISTIC PARAMETER COMPARISON BETWEEN NEGATIVE LONG AIR GAP DISCHARGES AND NATURAL CG FLASHES

	Negative CG flashes		Simulation experiments
L_{step} (m)	Schonland[13]	10-200	≤3.35
	Berger[14]	3-50	
T_d (μs)	Schonland[13]	34–124	15.3–20.0
	Berger[14]	29–52	
v_{step} (m/s)	Schonland[13]	$0.8–26×10^5$	$0.4–1.76×10^5$
	Berger[14]	$0.9–4.4×10^5$	
	Thomson[15]	$1.3–19×10^5$	

IV. CONCLUSIONS

According the observation results of simulation experiments, the NSLs with shorter scales are usually transformed from the negative streamers directly, while for the formation of longer stepped leaders, the negative streamer transforms into a space leader, and then that space leader transforms into the stepped leader. Therefore, the bidirectional leader theory and the streamer-leader theory are both realistic theories, and they describe different stages of the NSL formation. Since the stepped leader scale in natural lightning is mostly longer than that produced in the experiments described in this paper, the stepped leader formation process in natural lightning is similar to that of the longer stepped leaders in the discharge experiments, and a space leader should usually be observed.

The characteristics of the NSLs in the simulation experiments with different discharge gap scales were then analyzed, and these characteristics were compared with those of NSLs in natural CGs. The comparison results indicate that as the discharge scale in the laboratory increases, the characteristics of the NSLs in the simulation experiments gradually approach to those of NSLs in natural CGs. When the experimental gap reaches approximately 8 m, the characteristic parameter values of the NSLs in the simulation experiments are similar to the lower limit values of NSLs in natural CGs. Also, by considering the similar physical natures of NSLs in laboratory discharges and in natural CGs, some of the characteristic parameters of NSLs in natural CGs can be estimated from those of laboratory discharges with extra-long discharge gaps when using suitable experimental conditions.

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