Number and Dimensional Distribution of Stems near the Anode in a 1m Air Gap under Positive Pulse

Xiangen Zhao, Junjia He, Hengxin He,
Yishi Yue
State Key Laboratory of Advanced Electromagnetic
Engineering and Technology
Huazhong University of Science and Technology
Wuhan, China
zhaoxiangen@hust.edu.cn

Weijiang Chen
State Grid Corporation of China
Beijing, China
weijiang-chen@sgcc.com.cn

Abstract—**Characteristics of stem play an important role in the leader inception and development, and deserve comprehensive studies. In order to observe the stem experimentally, a schlieren system was established. Experiments in a 1m cone-plane gap under positive impulse voltage were carried out and the discharge current and schlieren photographs of discharge process were recorded synchronously with associated analysis. Experimental results showed that the number of stems were always more than one at the initial stage of the discharge in long gaps. Only 3% of the cases had one stem in our experiments. The number of stems followed a normal distribution with mean 4.01 and standard deviation 1.26. The first corona charge did not have a significant impact on the number of the stems. These stems were concentrated near the cone tip in the range -4 to 4 pixel. Using the method for the position of the stems described in this paper, the distribution of the stems followed a normal distribution with an average of -0.44 and standard deviation 4.31.**

Keywords-stem; number; dimensional distribution; schlieren phtotgraph;1m air gap; positive dishcarge.

I. INTRODUCTION

Stem is a short bright channel at the root of the corona streamers, where the transition from streamer to leader occurs [1]. The characteristics of stem play an important role in the leader inception and development. Much experimental and theoretical research has been carried out on the characteristics of the stem in long air gap discharge [1-5].

The observation of the stem was almost based on the streak and static photos in long gap discharge [2, 5]. It is generally accepted that filamentary branched channels (streamers) are developed from only one stem based on these experimental data. According to these results, a model was established to describe the characteristic of the stem at the initial stage of the long air discharge [1, 3]. Only one stem channel was considered along the axis of the long gap, which was used widely in the model simulating the process of discharge in the long air gap [6-10]. However, the previous approach which separated the stem and streamers through streak and static photos has been considered to be difficult. This is because the luminous of the streamers may cover that of the stem.

Furthermore, leader branching is generally observed in the laboratory discharge and in the nature lightning [11-13], which indicates that over one stem may exist simultaneously. Hence, it is meaningful to obtain more characteristics of stem by mitigating the impact of streamers.

In this paper, a schlieren system was established. Experiments in a 1m cone-plane gap under positive impulse voltage were conducted, and the current and schlieren photographs of discharge process were recorded synchronously. According to the current waveforms and schlieren photographs at the initial stage of the long air discharge, the number and distribution of stems were analyzed.

II. EXPERIMENTAL CONDITIONS

The diagram of the whole experimental system is shown in Fig.1. A 2400kV Marx generator was used as the impulse source. The impulse was applied in a rod-plane gap. The rod was hollow with a length of 2m, in which the current measurement device could be accommodated. The tip of rod was a brass cone with a radius of 2mm, which was insulated from the rod by an insulating plug so as to prevent the displacement current generated by the rod from flowing through the current sensor. The plane was an aluminum plate of radius 1m, which was well grounded. The rod was hung 1m above the plate. In all experiments, the front duration of positive high-voltage pulse was set to 58 μs, which was approximately equal to the critical value of a 1m rod-plane gap.

The discharge current was obtained by a time-resolved digital optical measurement system, which consisted of a coaxial current sensor and a digital optical fiber transmission system. The current measurement system consisted of a bandwidth ranging from DC to 70 MHz and a peak valve up to 600A [14].

The stem was observed using a schlieren system. The system mainly included a LED light source, a collimating lens, a focus lens, a knife edge, and an imaging system. All components except the imaging system were placed coaxially in two hollow cylindrical steel pipes with a length of 2.5m. The
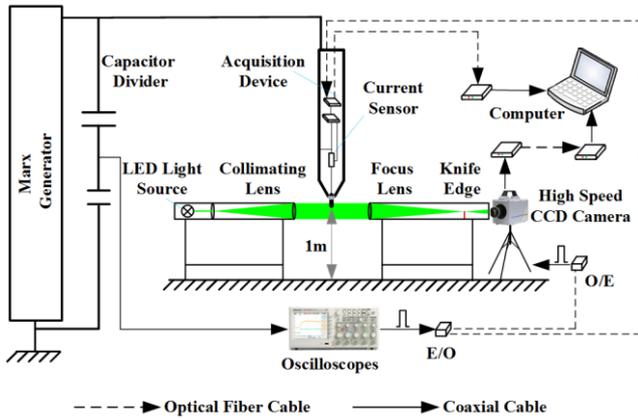
Figure 1. Schematic diagram of the whole experimental setup.

LED light source was located at the focus of the collimating lens to obtain parallel beams. The parallel beams passed through the measured area and were then focused by a focus lens to get a source image. The source image was cut by the knife edge and was then captured by the imaging system. The imaging system consisted of a camera lens (Sigma APO AF, 150-500mm, F5-6.3) and a high speed camera (FASTCAM SA5). When the temperature of the measured area varied, the deflection angle of light would be influenced, which would lead to the change of the image gray level values [15]. Hence, the area where the temperature changed from the schlieren photographs could be distinguished. In the experiments, it is 1.5m from the gap axis to the focus lens and 2.5m to the collimating lens. In order to balance the requirement of time resolution and space resolution, 200 thousand fps was used. The space resolution was 0.1mm/pixel, which was equal to the radius of the initial stem [1].

The impulse voltage was measured by a capacitor divider (ratio: 1:2052) with uncertainty of ±0.5%. The voltage waveforms were recorded by a Tektronix DPO-4104B digital oscilloscope with a 1GHz bandwidth. Both the current measurement system and high speed camera were triggered and synchronized by the oscilloscope. The delay time resulting from the triggering signal, converting circuit, and signal transmitting in optical fiber was taken into account in the experimental data process.

All the experiments were carried out at the UHV DC test base of State Grid Corporation of China. The photograph of the experimental setup was shown in Fig. 2.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A total of 92 experiments were carried out shown in Table I.

TABLE I.   TIMES OF EXPERIMENT FOR DIFFERENT CREST VALUES OF THE APPLIED VOLTAGE

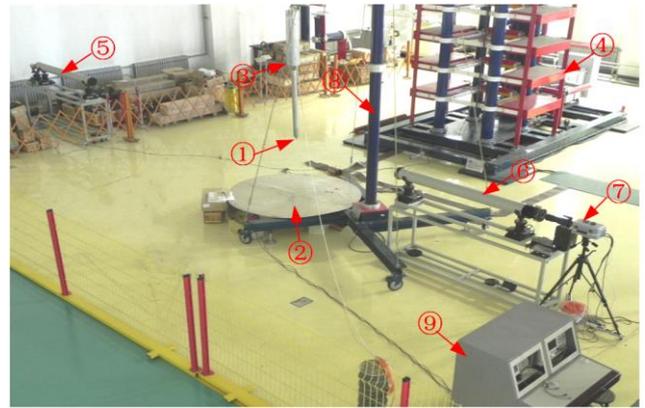| Times	Crest values of the applied voltage/kV					
	312	*390*	*435*	*480*	*524*	*569*
All	20	18	15	16	13	10
Valid	20	18	9	9	6	4

Figure 2.   Photograph of the experimental setup. 1- Cone electrode. 2- Plane electrode. 3-Current measurement device. 4-Marx generator 5- LED Light Emitting terminal. 6- LED Light receiving terminal. 7-High speed camera. 8- Capacitor divider. 9- Console of measurement system

However, with the increasing of the crest values of the applied voltage, the discharge would occur somewhere rather than around cone electrode tip which could be captured by the schlieren system. The analysis below is based on the valid ones.

A. Typical Experimental Results

According to the theory of a long spark [1], the schematic representation of the initial stage is shown in Fig. 3. The temperature of stem, which is also called transition region in some other literature, is in the range 300-1500K. While temperature of the streamers zone ahead of stem is about 300K, which is almost equal to the atmospheric temperature. Therefore, only stem can be detected using the schlieren system at the initial stage of a long spark. With the temperature in the stem increasing, the leader begins to form, which can also be detected. Certainly, LED light cannot pass through the grass cone electrode, which will lead to a shadow on the schlieren photographs. A typical schlieren photograph is also shown in Fig. 3.

It should be noted that the total number of stems recorded by 2-D schlieren photograph are not as many as they actually are. Two main reasons are included. 1）Sensitivity of the schlieren system is limited. Some stems cannot be detected if the air density along the channel is with little change. 2) Some stems may be situated at the back of the anode, which cannot be detected as long as the channels are occluded by the anode all the while during their propagation.
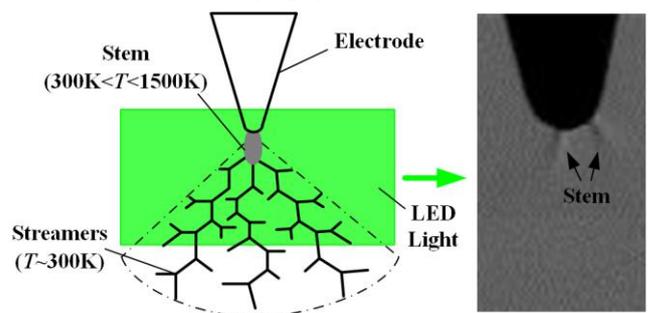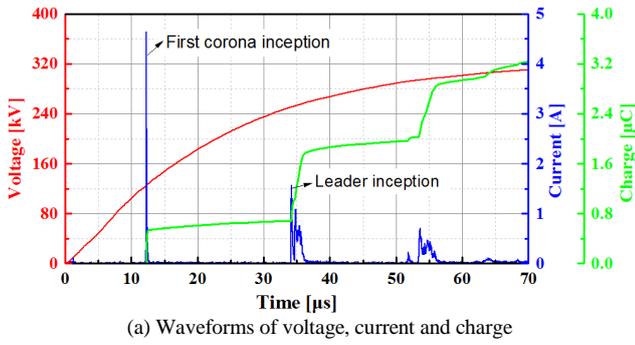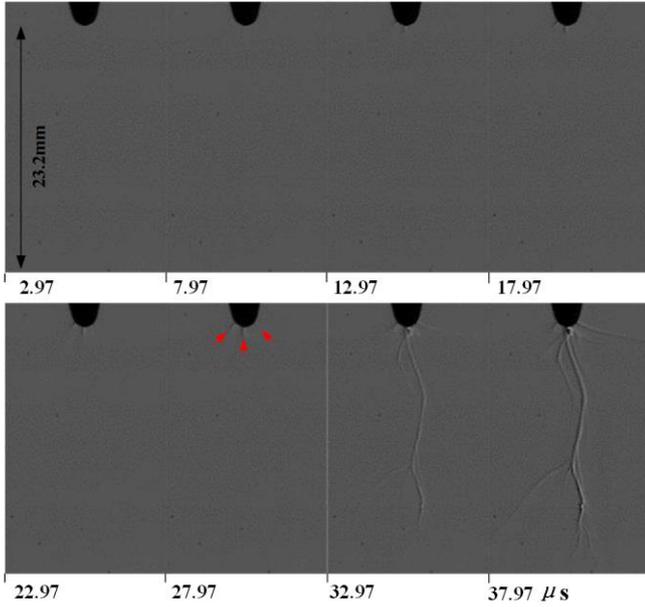

Figure 3.   Schematic representation of the initial stage of a long spark
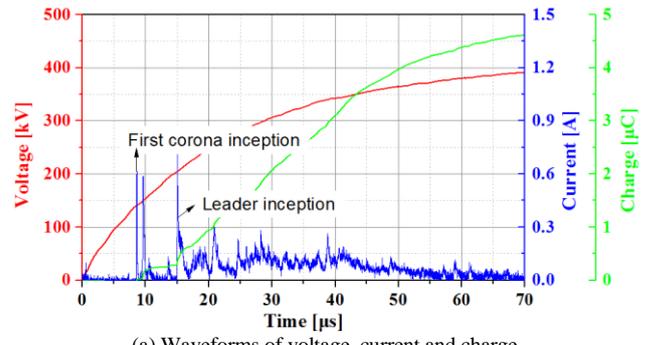
(a) Waveforms of voltage, current and charge

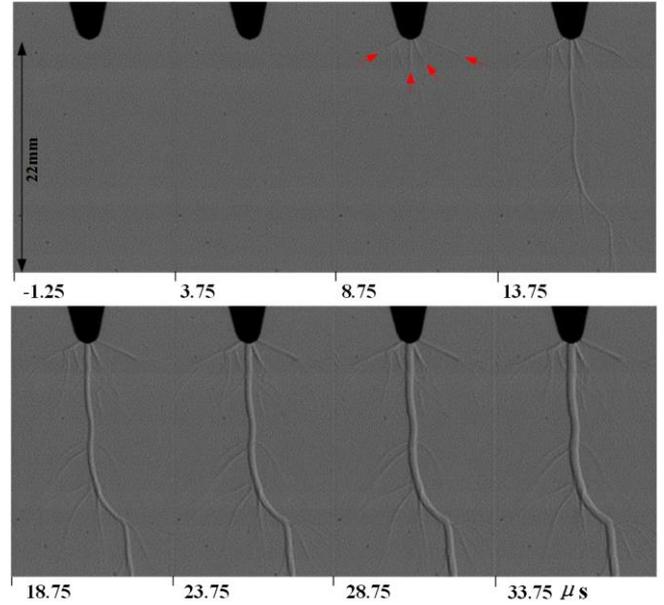(b) Schlieren photographs. Stems are marked with red arrow.

Figure 4.   Typical experimental results with a relatively long dark period.

(a) Waveforms of voltage, current and charge

(b) Schlieren photographs. Stems are marked with red arrow.

Figure 5. Typical experimental results with a relatively short dark period.

Two typical experimental results, including voltage waveforms, current waveforms, charge waveforms, and schlieren photographs, are shown in Fig.4 and Fig.5 respectively.

In Fig.4, the impulse voltage with an amplitude of +312kV is applied to the electrode. At t=12.2 µs, the first corona incepts. As a result of the corona growth, a net positive charge is rapidly injected into the gap, which is about 0.5 µC. The injected space charge is sufficient to significantly reduce the electric field around the electrode tip. As the rising rate of the applied voltage is relatively low in this case, the leader or second corona initiates at t=34.0 µs. During the time between first corona and leader inception, which is also called dark period, there is nearly no ionization processes judging from the current waveform. Hence, nothing will be observed in the dark period using an optical camera, such as streak camera and high speed camera [2, 16]. However, the schlieren system established in this paper will help us observe the stem even in the dark period, which is shown in Fig. 4(b). After the first corona inception, two stems can be observed in the schlieren photograph taken at t=12.97 µs, and then three at t=27.97. It should be noted here when counting the number and

distribution of stems as shown in this case, three will be selected. After the leader inception, one of these stems will be translated to leader channel shown in the schlieren photograph at t=32.97 µs. The expansion of leader channel can be observed using the schlieren system, while the focus of this paper is mainly put on the characteristics of stem. In the dark period, it can be observed that the stems develop slowly with a speed nearly 40m/s in this case. The result provides a direct evidence to the model considering the development of the stem during the dark period in literature [17].

In Fig.5, The impulse voltage with an amplitude of +390kV is applied to the electrode. The difference between these two cases shown in the Fig. 4 and Fig. 5 is that the dark period of the latter one is much shorter. The first corona and leader initiate at t=8.6 µs and t=15.0 µs respectively in Fig. 5. As a result, the initiation and development of the stems cannot be recorded using the schlieren system. However, according to the schlieren photographs, the number and distribution of stems at the initial stage can be reckoned, e.g. it is reasonable to conclude that there are four stems distributed around the cone tip at the initial stage which is same to that shown in the schlieren photograph at t=8.75 µs.

B. Number of Stems

The number of stems is counted according to the method introduced in Section II.B for each experiment at the initial stage of the long air discharge. The column for the number of stems is shown in Fig. 6. It follows a normal distribution with mean 4.01 and standard deviation 1.26. Insufficient number of samples may lead to the consequence that the relation between the number of stems and crest values of the applied voltage is not obvious. In Fig. 6, two cases, only 3% of all the cases, has a single stem at the initial stage as many models considered [1, 3, 5, 10]. From the view of previous literature, the subsequent leader channel developed always from the stem when the gas temperature within the stem was raised above a critical value in the range 1500-2000K and the rising of the temperature was due to the corona current. Considering the actual number of stems, the corona current always flows into the electrode through several stems rather than one, i.e. the calculated transition time from stem to leader may be shorter when neglecting the number of stems. Hence, it is important to take the factor into consideration when simulating the inception of leader.

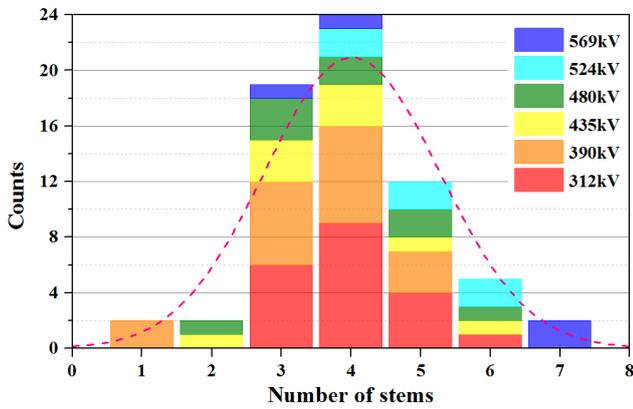As the stem is related to the first corona, the relation between the number of stems and the first corona charge is also studied [see Fig. 7]. The first corona charge is obtained by integrating its current. In Fig. 7, the relation is not obvious, i.e. the number of stems is not influenced by the first corona charge remarkably. It may be decided by the distribution of the corona streamers ahead of the cone electrode.

C. Distribution of Stems around the Electrode

Assuming Z axis vertically upwards and taking the point pixel of cone tip as grid origin, the position of the stem is defined in Fig. 8. The position of a stem is the pixel value difference along Z axis between its origin at the surface of the cone electrode and the grid origin. In order to distinguish the right side and the left side, negative values are for the former, while positive for the latter. For example, the position for the stem (a) is -8, and for (b) is 0 in Fig. 8.

According to the method mentioned above, column for number of stems distributed along the surface of the cone electrode at the initial stage is shown in Fig. 9. It follows a normal distribution with mean -0.44 and standard deviation 4.31, which is approximate to a standard one. Most of the stems are concentrated near the cone tip in the range of -4 to 4 pixel and the counts reach its maximum value at the origin grid.

When the positive impulse voltage is applied on the electrode, the strength of the geometrical electric field decreases away from the cone tip. According to the streamer

Figure 6. Column for number of stems at the initial stage of the long air discharge, for different crest values of the applied voltage.
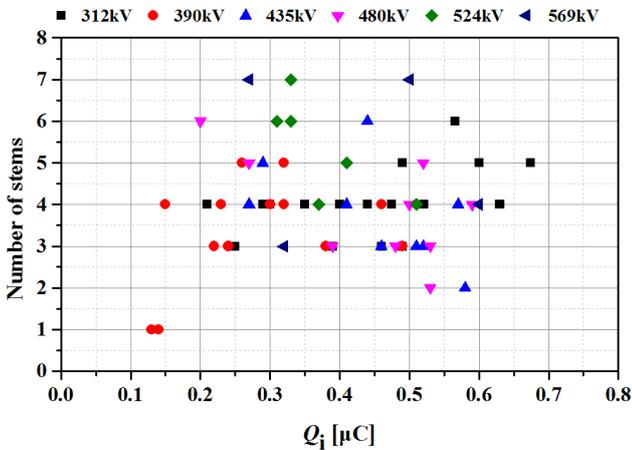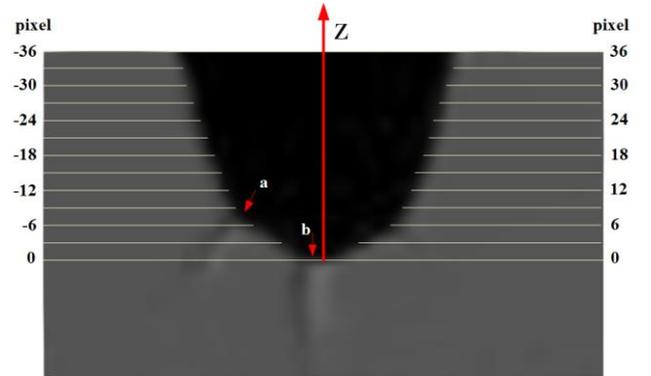

Figure 8. Measuring method for the position of the stems along the surface of the cone electrode.

Figure 7. Number of stems as a function of the first corona charge Q_i, for different crest values of the applied voltage.
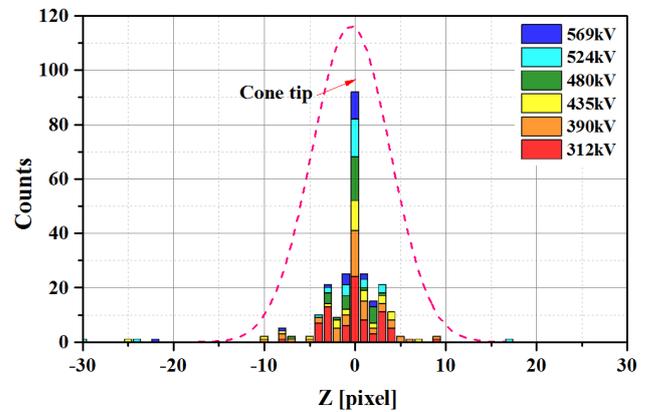

Figure 9. Histogram for number of stems distributed along the surface of the cone electrode at the initial stage of the long air discharge, for different crest values of the applied voltage.

theory, a streamer discharge will incept when the electrical field reaches its critical value. Hence, the streamer will incept most likely around the cone tip, then the stem will form following the track of the streamers. That is the reason why most stems are concentrated near the cone tip as shown in Fig. 9.

Therefore, it is reasonable for the models [1, 3, 5, 10] assuming that the stem initiated from the electrode tip when the number of the stems is neglected.

IV. CONCLUSION

In this paper, a schlieren system for observing the stems was established. Experiments were carried out in a 1m cone-plane gap under positive impulse voltage. The discharge current and schlieren photographs of discharge process were recorded synchronously with associated analysis. The experimental results showed that the number of stems were always more than one at the initial stage of the discharge in long gaps. Only 3% of the cases had one stem in our experiments. The number of stems followed a normal distribution with mean 4.01 and standard deviation 1.26. The first corona charge did not have a significant impact on the number of the stems. These stems were concentrated near the cone tip in the range -4 to 4 pixel. Using the method for the position of the stems described in this paper, the distribution of the stems also followed a normal distribution with mean -0.44 and standard deviation 4.31.

The experimental results can help us have a deeper understanding of stem, and also help us look at the positive leader branching from other perspectives. In the future, more experiments under different experimental conditions will be conducted, and conditions for that more than one stems develop to leader simultaneously will be further studied.

REFERENCES

[1] I. Gallimberti, "The mechanism of the long spark formation," Le Journal de Physique Colloques, vol. 40, pp. C7-193-C7-250, 1979.

[2] Les Renardières Group, "Research on long air gap discharges at les Renardières–1973 results," Electra, pp. 49-156, 1974.

[3] I. Gallimberti, G. Bacchiega, A. Bondiou-Clergerie, and P. Lalande, "Fundamental processes in long air gap discharges," Comptes Rendus Physique, vol. 10, pp. 1335 - 1359, 2002.

[4] E. M. Bazelyan and Y. P. Raizer, Spark discharge, CRC press, 1997.

[5] E. M. Bazelyan, Y. P. Raizer and N. L. Aleksandrov, "The effect of reduced air density on streamer-to-leader transition and on properties of long positive leader," Journal of Physics D: Applied Physics, vol. 40, pp. 4133 - 4144, 2007.

[6] A. Bondiou and I. Gallimberti, "Theoretical modelling of the development of the positive spark in long gaps," Journal of Physics D-Applied Physics, vol. 27, p. 1252, 1994.

[7] N. Goelian, P. Lanlade and A. Bondiouclergerie, "A simplified model for the simulation of positive-spark development in long air gaps," Journal of Physics D-Applied Physics, vol. 30, pp. 2441-2452, 1997.

[8] M. Becerra and V. Cooray, "A self-consistent upward leader propagation model," Journal of Physics D-Applied Physics, vol. 39, pp. 3708-3715, 2006.

[9] N. A. Popov, "Study of the formation and propagation of a leader channel in air," Plasma physics reports, vol. 35, pp. 785-793, 2009.

[10] C. L. Da Silva and V. P. Pasko, "Dynamics of streamer‐to‐leader transition at reduced air densities and its implications for propagation of lightning leaders and gigantic jets," Journal of Geophysical Research: Atmospheres, vol. 118, pp. 13,561 - 13,590, 2013.

[11] A. G. Andreev, E. M. Bazelyan, M. U. Bulatov, I. P. Kuzhekin, L. M. Makalsky, D. I. Sukharevskij, and V. S. Syssoev, "Experimental study of the positive leader velocity as a function of the current in the initial and final-jump phases of a spark discharge," Plasma Physics Reports, vol. 34, pp. 609-615, 2008.

[12] P. Lalande and V. Mazur, "A physical model of branching in upward leaders," AerospaceLab, p. p-1, 2012.

[13] T. A. Warner, M. M. Saba and R. E. Orville, "Characteristics of upward leaders from tall towers,", pp. 2-3, 2012.

[14] Y. Yue and J. He, "Digital time-resolved optical measurement of discharge currents in long air gaps," Review of Scientific Instruments, vol. 84, p. 085107, 2013.

[15] C. Alvarez-Herrera, D. Moreno-Hernández, B. Barrientos-García, and J. A. Guerrero-Viramontes, "Temperature measurement of air convection using a Schlieren system," Optics & Laser Technology, vol. 41, pp. 233-240, 2009.

[16] C. Wu, S. Xie, F. Qi, B. Li, J. Wan, and J. He, "Effect of Corona Discharges on the Inception of Positive Upward Leader-Streamer System," International Journal of Modern Physics B, vol. 27, p. 1350165, 2013.

[17] S. Xie, J. He and W. Chen, "An improved model to determine the inception of positive upward leader–streamer system considering the leader propagation during dark period," Physics of Plasmas, vol. 20, p. 042107, 2013.