International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Electric discharges produced by artificially charged clouds: Influence of rapidly moving conductive object

Alexander Kostinskiy
National Research University Higher School of Economics
Moscow, Russia
kostinsky@gmail.com

Vladimir Syssoev, Mikhail Andreev, Dmitry Sukharevsky, Marat Bulatov
High-Voltage Research Center of the Zababakhin All-Russian Scientific Research Institute of Technical Physics
Istra, Moscow region, Russia
syssoev467@mail.ru

Evgeny Mareev, Nikolay Bogatov
Institute of Applied Physics, Russian Academy of Sciences
Nizhny Novgorod, Russia
mareev@appl.sci-nnov.ru

Vladimir Rakov
Department of Electrical and Computer Engineering
University of Florida,
Gainesville, USA
rakov@ece.ufl.edu

Abstract — **The possibility of initiation of electric discharges by a crossbow bolt (projectile) moving in the electric field of a cloud of negatively charged water droplets has been demonstrated for the first time [1]. Over one hundred of discharges have been produced. For each event, a high-speed video camera recorded the images of upward positive leaders developing from both the nearby grounded sphere and the projectile, followed by the return-stroke-like process. Corresponding currents were measured and integrated photos of the events were obtained. The results can help to improve our understanding of lightning initiation by airborne vehicles and by a vertical conductor rapidly extended below the thundercloud in order to trigger lightning with the rocket-and-wire technique.**

Charged water droplets, long-spark leaders, streamers, initiation of electric discharges by a moving conductive projectile, lightning

I. Introduction

Lightning discharges initiated by airborne vehicles in the electric field of a thundercloud may pose a serious risk to their navigation and other equipment [2, 3]. Similar discharges can be initiated from natural thunderclouds using the so-called altitude version of the rocket-and-wire lightning triggering technique (e.g., [4]). In both cases, a floating conducting object serves to enhance the electric field at its extremities, which can lead to initiation of a bidirectional leader from that object. A study of this phenomenon in nature is difficult because of the small number of events that can be recorded during the thunderstorm season and the high cost of the experiments. On the other hand, the laboratory methods can be used, with much greater efficiency, to simulate discharges initiated by isolated objects in the atmosphere.

In this study, we managed to initiate electric discharges by rapidly introducing a conducting crossbow bolt in to the electric field of a cloud of charged water droplets. We have measured the key parameters of the initiated discharges. The results may have implications for improving our understanding of both lightning discharges initiated by aircraft and altitude-triggered lightning.

II. Experimental Setup

More than one meter long sparks initiated from a grounded object in the field of artificially created cloud of charged water droplets were reported, for example, in [4,5]. In this work, we used an experimental facility for generating charged clouds (see Fig. 1), which was similar to that employed in [5, 6, 7, 8]. Clouds of either polarity were created, but the results presented here correspond only to negative polarity. The charged cloud **1** was formed by the steam generator **2** and the high-voltage source **3** coupled with the corona-producing sharp point **4**. The latter was located in the nozzle **5** through which the high-pressure steam-air jet was passing. The jet had a temperature of about 100 – 120 °C and a pressure of 0.2–0.6 MPa. It moved out at a speed of about 400–450 m/s with an aperture angle of 28°. The nozzle was located at the center of a flat metal screen **6** of 2 m in diameter with rounded edges. As a result of rapid cooling, the steam condensed into water droplets of about 0.3-0.5-μm radius. The ions charging the water droplets were formed in the corona discharge between the sharp point **4** and the nozzle **5**. A DC voltage of 10– 20 kV of negative polarity was applied to the point. The current of charge carried by the jet was in the range of 60–150 μA. As the total charge accumulated in the cloud approached 50 μC or so, spark discharges spontaneously occurred between the cloud and grounded objects nearby.

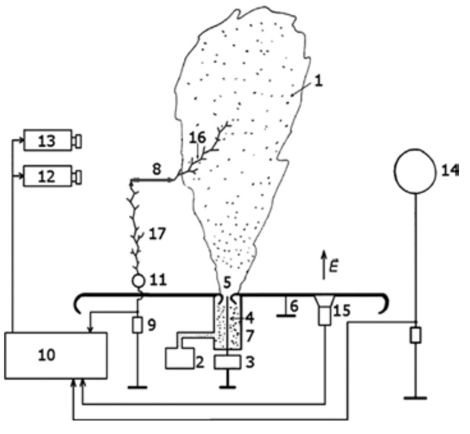

Fig. 1. Experimental setup:**1** – charged-aerosol cloud; **2** – steam generator; **3** – high-voltage source; **4** – corona producing sharp point; **5** – nozzle; **6** – grounded metal screen; **7** – steam conduit; **8** – conducting projectile; **9** – current-measuring shunt; **10** – oscilloscope; **11** – metal sphere, grounded via 1-Ω resistor 9; **12** – high-speed video camera; **13** – still camera; **14** – copper sphere for monitoring the cloud charge variation; **15** – fluxmeter; **16** – positive leader initiated from the projectile; **17** – upward positive leader initiated from the grounded sphere.

Conducting projectiles **8** (aluminum or carbon crossbow bolts; no differences in results were found) 0.58 m in length and 8.8 mm in diameter were launched horizontally using a hand-held crossbow, at a velocity of 75 m/s, toward the cloud from a distance of 10–12 m from the jet axis, at an altitude of 0.5–1.2 m above the grounded metal screen (presented in this paper are only the results for relatively low altitudes, 0.5–0.6 m). To measure the discharge current passing through the flying projectile, we used a shunt **9** with 1 Ω resistance, the signal from which was fed to a Tektronix digitalizing oscilloscope **10**. The shunt was connected to a metal sphere **11** of 5-cm diameter, the uppermost point of which was 10 cm above the screen. The sphere was 0.8 m away from the screen center and was the object from which the spark usually initiated. As the current exceeded a given value, the oscilloscope was triggered, which, in turn, generated a pulse to trigger a high-speed video camera (FASTCAM SA4) **12**, operating in the visible range. FASTCAM SA4 was operated in the loop mode at a rate of 225,000 frames per second (fps) and was stopped at the frame at which a synchronization pulse from the oscilloscope was received. Frame duration was 4.44 μs, equal to the frame exposure time (no dead time), and the resolutions was 128 x 64 pixels (128 vertical and 64 horizontal). In order to monitor the variation of the charge of the aerosol cloud, we used a copper sphere **14** of 50-cm diameter, which was essentially isolated (grounded through a 100 MΩ resistor) and the signal from which was recorded by the oscilloscope **10**. Overall picture of the discharge was recorded using a Canon still camera **13**. The speed of projectile was measured using the high-speed video camera. Electric field at the grounded plane was measured with fluxmeter **15**.

III. RESULTS

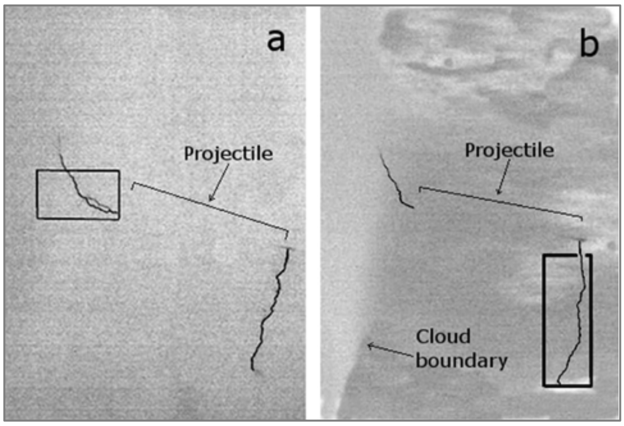

Fig. 2. Examples of integrated photos (inverted) of projectile-initiated discharges. Two separate discharges are shown in (a) and (b) with the rectangular areas showing the fields of view of the high-speed video camera imaging (pointing toward) the leaders from the projectile and from the grounded sphere, respectively. The 0.58-m long projectile is not seen on the photos, but its position is marked. The boundary of the charged cloud is visible and marked in (b).

In these experiments, the cloud was charged to 50–80 mC, so that spark discharges spontaneously occurred, mostly connected to ground via the sphere **11**. As measured by fluxmeter **15**, the electric field generated by the cloud on the surface of the grounded screen at about 0.8 m from the jet axis was 400–500 kV/m (4–5 kV/cm) and slightly increased toward the cloud. It was estimated that the electric field of the cloud nowhere exceeded 1.0–1.1 MV/m (10–11 kV/cm). This was also confirmed by the absence of the negative streamer corona extending towards the grounded plane from the cloud, which requires the presence of such fields [5, 6].

As noted above, the projectile was launched toward the cloud at a velocity of 75 m/s, almost parallel to the grounded plane at a height of 0.5–0.6 m above it. In about 20% of the launches, a discharge involving the cloud, projectile, and grounded plane was initiated, and in about 10% of the cases, the discharge currents could be measured. In the remaining about 80% of the cases (out of a total of over 100), there was only a burst of luminosity (recorded with still camera) at the frontend of the projectile, when it was at a distance of less than one meter from the jet axis. The discharge current was measured only when the sphere equipped with the shunt was involved. Simultaneously, we recorded the signal from the isolated sphere **14** (which is indicative the cloud charge variation), video images of the discharge development, and a still photograph. The viewing angle of the video camera precluded simultaneous recording of the leaders at both ends of the projectile. It was only possible to image for each event the processes either between the tip of the projectile and the cloud or between the grounded sphere and the tail of the projectile (followed by the return-stroke-like process in both cases). The synchronization of the oscilloscope and the video camera, along with still photography, allowed us to reconstruct the complete sequence of events (at both ends of the projectile) with about 1.5-μs uncertainty.

Still photos of two separate discharges are shown in Fig. 2a and b. The lower channel bridges the gap between the ground and the projectile (or the ungrounded wire which was sometimes attached to the projectile). The upper channel bridges the gap between the projectile and the cloud, at an angle of 20–60° with respect to the projectile. The projectile in Fig. 2 was at a height of 0.5–0.6 m above the grounded sphere.

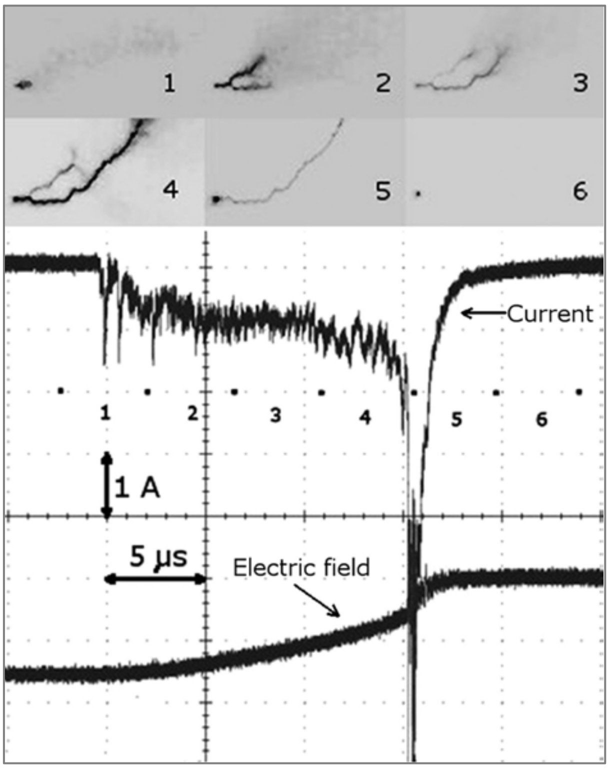

Fig. 3. Six 4.44-ms video frames (top panel) showing the development of discharge processes between the projectile and the cloud, and the corresponding current to ground (middle panel). Exposure times of the six frames are indicated by small squares and frame numbers on the current record. The first three frames correspond to a positive leader from the projectile. Discharge processes between the projectile and ground were not imaged for this event. Also shown is the electric field representing the variation of cloud charge (bottom panel). The event corresponds to the still photo in Fig. 2a showing the approximate field of view of the video camera. Still photo was taken at an angle of 150° relative to the line of sight of high-speed video camera.

We now describe the sequence of events based on the data obtained in the experiments. Most often the cloud–projectile–earth discharge started with a streamer flash followed by a positive leader extending from the tip of the projectile in the direction of the cloud. This scenario is supported by the fact that in the case of no full-fledged cloud–projectile–earth discharge there was a 90% chance to observe a cloud-directed flash from the tip of the projectile. Figs. 3 and 4 illustrate the development of positive leaders from the projectile tip and from the ground, respectively. The leaders presented in these two Figures correspond to different events, but in each case the current oscillogram can be used to follow the entire sequence of processes involved. Specifically, it follows from Fig. 3 that the leader from the ground starts almost simultaneously (within 1.5-μs uncertainty) with the leader from the projectile. The two leaders move at similar speeds. Once the gap between the grounded sphere and the tail of the projectile is bridged by the leader plasma channel, a quasi-return-stroke (involving also the channel between the projectile and the cloud) occurs. Current in the latter rises to its peak in about 150 ns and then falls to its half-peak value in about 400–500 ns. The quasi-return-stroke process corresponds to an abrupt increase in channel brightness (see frame 4 in each Figs. 3 and 4). The quasi-return-stroke process was always observed when the cloud–projectile–earth discharge was initiated by the projectile. This is in contrast with the discharges initiated spontaneously, for which the quasi-return-stroke process was observed in no more than 5% of the cases.

It is seen from the oscillogram of current measured at the grounded sphere and the synchronized frames recorded by the camera shown in Fig. 4 that during the projectile's passing over the sphere a positive leader started from the sphere and moved almost vertically upward for about 12 μs until the gap between the sphere and the projectile was bridged. After the first maximum of current, which corresponds to the moment at which the leader from the sphere is initiated (Fig. 4, frame 1), the current slightly falls off and then rises until the gap between the sphere and the tail of the projectile is bridged by the plasma channel. This is followed by the quasi-return-stroke phase during which both the current and the channel brightness increase abruptly (Fig. 4, frame 4). In the first three frames (frames labeled 1–3) in Fig. 4, besides the growing leader channel, one can see a long streamer corona, which fills the entire gap between the grounded sphere and the projectile, at least starting with frame 2. The charge of the cloud decreases (as indicated by the electric field variation in Fig. 4). As a result, a significant portion (up to 20–30%) of the negative charge of the cloud is effective transported to ground. Recharging of the cloud takes about 0.5–1 s. Channel decay is seen in frame 5 and in the next frame (not shown in Fig. 4). We did not observe the descending negative leader from the projectile tail meeting the ascending positive leader from the grounded sphere. Most likely this process is very brief and, hence, unresolved with the framing rate employed in our experiments (4.44 μs per frame).

IV. DISCUSSION

Electric discharges between the charged cloud and earth initiated by moving elongated conductors (projectiles) were studied using a high-speed video camera. Currents to ground and corresponding electric field changes were measured. The initiated dis charges exhibited both similarities and dissimilarities relative to sparks initiated spontaneously (in the absence of projectile) in the same experimental set-up and to the rocket-and-wire triggered lightning.

Characteristics of the positive leader ascending from the grounded sphere in the presence of projectile differ from those of the leader also ascending from the sphere but initiated spontaneously. The current of the projectile-initiated positive leader from the sphere tends to increase monotonically after the initial maximum until the quasi-return-stroke process (see Figs. 3 and 4). If the sphere-projectile gap is more than one meter, then the leader current increases in the first phase and then reaches a steady value until the quasi-return-stroke process onset. In both cases, this behavior of the positive leader is different from that of the leader spontaneously initiated from the sphere, when after the first maximum the current typically decreases to 0.25–0.5 A and stays at that level with small variations until the quasi-return-stroke phase, if any. The current of projectile-initiated positive leader ascending from the sphere is typically higher than the current of spontaneously initiated leader. This difference suggests that the upward positive leader from the projectile tip facilitates the earlier initiation of positive leader from ground, possibly via the initiation of undetected negative leader from the projectile tail.

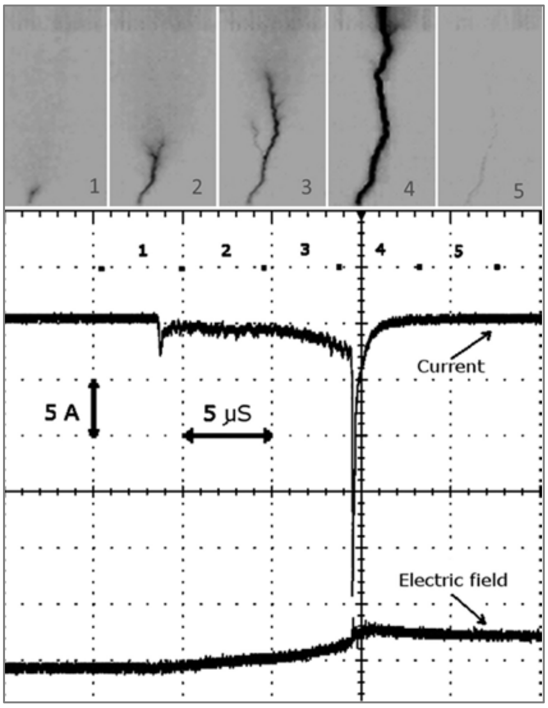

Fig. 4. Five 4.44-μs video frames (top panel) showing the development of discharge processes between the grounded sphere and the projectile and the corresponding current to ground (middle panel). Exposure times of the five video frames are indicated on the current record. Discharge processes between the projectile and the cloud were not imaged for this event. The first three frames correspond to a positive leader from the grounded sphere. No negative leader from the projectile was imaged. Also shown is the electric field representing the variation of cloud charge (bottom panel). The event corresponds to the integrated photo in Fig. 2b showing the approximate field of view of the video camera.

The negative leader propagates in the direction of the positive leader from the grounded sphere. The positive leader ascending from the sphere interacts with the negative leader from the tail of the projectile until the entire gap between the sphere and the projectile is bridged. It is possible that the streamer zone of positive leader from the grounded sphere rapidly extends, via the projectile and its leaders, to the cloud, making the following process similar to the break-through phase of the lightning attachment process. Probably, this is the reason why current of the positive leader ascending from the sphere tends to rise all the time until the quasi-return-stroke process.

As noted above, we did not observe with the high-speed camera the downward negative leader from the projectile tail that meets the positive leader ascending from the sphere. The resolution of the camera is probably not sufficient for detection of the descending negative leader. The existence of the negative descending leader is supported by the fact that all the static photos and video frames show a significant enhancement of the channel brightness at a distance of about 10 cm from the projectile tail (the possible point where the positive and negative leaders meet). However, it cannot be ruled out that, in the case of relatively low height of the projectile above the grounded plane, the negative descending leader has insufficient time to form (note that in the altitude triggered lightning the descending negative leader begins with a millisecond-scale delay after the onset of ascending positive leader [3]).

Another interesting result of this work is the initiation of positive leader from the tip of the projectile moving at a speed not exceeding 75 m/s, which is appreciably lower than the rocket speed (usually about 150–200 m/s) in triggered-lightning experiments. It is often assumed that a relatively high speed is required in order for the rocket to outrun the corona space charge accumulation near the top of the triggering wire. Indeed, [9] showed that, in the laboratory, a spark discharge could be triggered by the rapid introduction of a thin wire into an electric field, whereas the steady presence of the wire did not result in a spark. They suggested that the corona discharge from a stationary conductor acts to shield the conductor, so that the high fields necessary to initiate electrical breakdown are not obtained, whereas the field enhancement due to the rapid introduction of a conductor is not significantly reduced by corona, since there is insufficient time for its development.

V. SUMMARY

It has been demonstrated for the first time [1] that electric discharges can be initiated by a moving elongated conductor (projectile) in the electric field of a cloud of negatively charged water droplets. The discharge involves two positive leaders, one launched from the tip of the projectile and the other from the ground. The leader from the projectile apparently starts first, followed, within 1.5 μs, by the leader from the ground. The two leaders move at similar speeds. The quasi-return-stroke process is always observed when the cloud–projectile–ground discharge is initiated, in contrast with discharges not involving the projectile; that is, occurring spontaneously in the field of the cloud. In the latter case, not more than 5% of the events exhibited the return-stroke-like process.

ACKNOWLEDGMENT

The authors thank Leonid Makalsky, Vladimir Kuznetsov and Alexander Aleshchenko for their useful discussions and are grateful to the Ministry of Education and Science of the Russian Federation for the financial support (project 14.B25.31.0023). The data reported in the paper are available upon request from the corresponding author A.Yu. Kostinskiy (kostinsky@gmail.com).

REFERENCES

[1] A.Y.Kostinskiy, V.S.Syssoev, E.A.Mareev, V.A.Rakov, M.G.Andreev, N.A.Bogatov. L.M.Makal’sky, D.I.Sukharevsky, Electric discharges produced by clouds of charged water droplets in the presence of moving conducting object, Journal of Atmospheric and Solar-Terrestrial Physics 135 (2015) p.36–41, doi:10.1016/j.jastp.2015.10.00606

[2] Fisher, F.A., Plumer, J.A., Perala, R.A. Lightning Protection of Aircraft. Light ning Technologies Inc., Pittsfield, MA,USA, 1999.

[3] Rakov, V. A., and M. A. Uman, Lightning: Physics and Effects, Cambridge Univ. Press, Cambridge, 2003.

[4] Lalande, P., Bondiou-Clergerie, A., Laroche, P., Eybert-Berard, A., Berlandis, J.-P., Bador, B., Bonamy, A., Uman, M.A., Rakov, V.A., Leader properties determined with triggered lightning techniques. J.Geophys.Res. 103, 1998, 14109–14115.

[5] Vereshchagin, I.L., Koshelev,M.A. ,Makal’sky, L.M., Syssoev, V.S., 1988. Preliminary results of using a charged-aerosol generator for modeling of atmospheric discharges (inRussian).In: Proceedings of the Third USSR Symposium on Atmospheric Electricity, Tartu, Gidrometeoizdat, Leningrad, 1986, pp.119–223.

[6] Antsupov, K. V., I. P. Vereshchagin, M. A. Koshelev, L. M. Makalsky, and V. S. Syssoev, Discharges from cloud of charged aerosol, in Proc. 7th Int. Symp. on High Voltage Engineering, pp. 15–17, Tech. Univ. of Dresden, Dresden, Germany, 1991.

[7] Kostinskiy,A.Y., V. S. Syssoev, N.A. Bogatov, E.A.Mareev, M. G.Andreev, L. M.Makalsky, D. I. Sukharevsky, and V. A. Rakov, Observations of a new class of electric discharges within artificial clouds of charged water droplets and its implication for lightning initiation within thunderclouds, Geophys. Res. Lett., 42, 16 October 2015 Pages 8165–8171. doi:10.1002/2015GL065620

[8] Kostinskiy, A. Y., V. S. Syssoev, N. A. Bogatov, E. A. Mareev, M. G. Andreev, L. M. Makalsky, D. I. Sukharevsky, and V. A. Rakov, Infrared images of bidirectional leaders produced by the cloud of charged water droplets, J. Geophys. Res. Atmos., Volume 120, Issue 20, 27 October 2015, Pages 10,728–10,735, doi:10.1002/2015JD023827

[9] Brook, M., Armstrong, G., Winder, R.P.H., Vonnegut, B., Moore, C.B., Artificial initiation of lightning discharges. J.Geophys.Res. 66, 1961, 3967–3969.