Computation of the electric fields of system of the artificial thunderstorm cells

Alexander G. Temnikov, Leonid L. Chernensky, Alexander A. Orlov, Tatiana K. Kivshar, Nikolay Y. Lysov, Olga S. Belova, Daria S. Zhuravkova

***Abstract*—**Method of the computation of the electric fields of a system of the artificial thunderstorm cells is considered in paper. It is based on the theoretical and experimentally measured parameters of a turbulent charged aerosol flows. Approaches for calculation of the electric field characteristics of the separate charged aerosol flow have been analyzed for the case of an aerosol chamber. Application of this method for computation of the electric fields of two unipolar or differently charged artificial thunderstorm cells has been considered in paper. It is shown that the maximal electric field strength will achieve in the gap between the positively and negatively charged artificial thunderstorm cells, and above upper and beneath bottom unipolar artificial thunderstorm cells. It was experimentally shown that the model hydrometeor arrays posed in these places could initiate intensive discharge phenomena (powerful streamer and leader discharges) between the charged clouds and between the artificial thunderstorm cells and the ground.

***Keywords*—**Artificial thunderstorm cells, electric field computation, method of equivalent charges, volume charge.

I. Introduction

APPLICATION of the artificial thunderstorm cells (clouds of charged water aerosol) for a physical simulation of the discharge phenomena that could form inside the thunderclouds and between a thundercloud and a ground could be perspective for understanding of the peculiarities of the spark discharge initiation and intensive development inside the thunderstorm clouds and beneath them [1]. To create the artificial thunderstorm cells of negative or positive polarity capable to induce the spark discharges the turbulent water aerosol jets are used. Method of an electric field calculation of the fully developed submerged charged aerosol turbulent flows has been proposed in [2]. A model of the formation dynamics of the artificially charged water aerosol flows created by a charged aerosol generator of a condensate type and a method of calculation of the electric field near the boundaries and inside the forming charged part of the cloud have been developed in [3, 4].

System of the artificial thunderstorm cells of a negative and/or positive polarity could be used for investigation of the possible mechanisms of the "cloud-to-ground" and intracloud lightning initiation and stimulation propagation on the arrays of the large hails to find the methods for an active influence on the processes of a lightning initiation and thundercloud discharging [5, 6]. Such task is requiring the computation of the electric fields as inside each artificial thunderstorm cell as in the gap between the unipolar or bipolar charged cells and between the bottom charged cell and the ground. Method and results of computation of the electric fields of the vertically disposed system of the artificial thunderstorm cells of different/same polarity are presented for the case of an aerosol experimental chamber.

II. Method for Electric Field Calculation of Artificial Charged Aerosol Flow

Method for electric field calculation of a turbulent charged water aerosol flow has been proposed in [2-4]. It was experimentally checked through direct measurements of the charged water aerosol volume charge and of the electric field distribution near an artificial charged aerosol formation [2]. Method suggests that an electric field strength E of artificial cell depends on the parameters of a turbulent charged aerosol flow as in

$$E = f\left(I_{out}, V_0(p_b), d_0, G, s\right). \quad (1)$$

where I_{out} – outlet current of charged aerosol generator of a condensate type, V_0 – flow outlet velocity, p_k – pressure in a boiler, d_0 – diameter of a nozzle outlet section, G – geometry and disposition of the charged flow in an aerosol chamber, s – coordinates of a calculation point.

All charge is practically concentrated on the water aerosol particles that are the additives for a gas dynamic flow. So, considering the laws of a distribution of the additives in the turbulent flows, distribution of the volume charge density $\rho_m(p)$ in the axis direction of the charged turbulent jet will be

$$\rho_m(p) = \left(5.35\, d_0 \rho_0\right)/p\,. \quad (2)$$

where p – axis coordinate beginning from the nozzle, ρ_0 – volume charge density in the outlet cross-section of the nozzle, that could be found as:

The reported research has fulfilled due to the grant of the Russian Science Foundation (project No. 16-19-00160).

A.G. Temnikov, L.L. Chernensky, A.V. Orlov, T.K. Kivshar, N.Y. Lysov, O.S. Belova, D.S. Zhuravkova are with the Department of Electrophysics and High Voltage Technique, National Research University "Moscow Power Engineering Institute", Moscow, Russia (e-mail: TemnikovAG@mpei.ru, a_g_temnikov@mail.ru).

$$\rho_0 = I_{out} / (V_0 S). \qquad (3)$$

where S – outlet cross-section of the nozzle.

Distribution of the volume charge density in a radial direction ρ_r in the given jet cross-section will be:

$$\rho_r = \rho_m(p)\left[1-\left(r/R\right)^{1.5}\right]^2. \qquad (4)$$

where r – coordinate in the radial direction of the jet cross-section, R – radius of the jet in the given cross-section.

Volume charge of the charged aerosol flow depends on the outlet current of a charged aerosol generator. Increase of the expansion angle of the charged jet occurs due to the action of the electric field of its own charge. Experimental dependencies of the expansion half-angle α of the positively and negatively charged jet from the outlet current could be approximated as following [2]:

$$\begin{aligned} tg\alpha_+ &= tg\alpha_0 + 0.62\cdot 10^{-4} I_{out} \\ tg\alpha_- &= tg\alpha_0 + 0.12\cdot 10^{-3} I_{out} \end{aligned} \qquad (5)$$

where I_{out} – outlet current of the charged aerosol generator in μA, α_0 – half-angle of the non-charged submerged turbulent jet ($tg\alpha_0 \sim 0.23$).

As a common charge of the charged aerosol flow stays constant under an expansion and has an auto-model profile [1], change of the volume charge density on the jet axis $\rho^*_m(p)$ has considered in the method as:

$$\rho^*_m(p) = \rho_m(p)\left[R(p)/R^*(p)\right]^{0.5} \qquad (6)$$

where $R(p)$ – radius of jet in the given cross-section without expansion, $R^*(p)$ – radius of jet in the given cross-section after expansion.

For electric field computation, method of equivalent charges has been applied. Volume charge of the charged aerosol flow (artificial thunderstorm cell) has been separated on the discs by the parallel planes (Fig. 1).

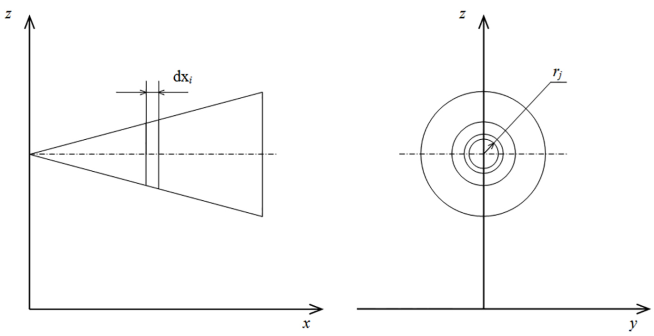

Fig. 1. Scheme of separation of volume charge of charged aerosol region

To consider the radial distribution of charge in the disc, the last has been separated on the ring charges Q_k that could be found as:

$$Q_k = \rho(p_i, r_j)\cdot 2\cdot\pi\cdot r_j\cdot dr\cdot dx \qquad (7)$$

where $\rho(p_i,r_j)$ – volume charge density in the ring j of the disc i, dx – step of the charged region separation on the discs, dr – step of separation of the discs on the rings.

Volume charge density of the circle has calculated as:

$$\rho(p_i, r_j) = \frac{5.35 d_0 \rho_0}{p_i}\left[1-\left(\frac{r_j}{R_i}\right)^{1.5}\right]^2\left[\frac{R_i(p)}{R_i^*(p)}\right]^{0.5} \qquad (8)$$

where $R_i(p)$ – radius of the disc i without jet expansion, $R^*_i(p)$ – radius of the disc i after charged aerosol jet expansion, p_i – axis coordinate of the disc i, r_j – radial coordinate of the ring j of the disc i.

Potential and electric field strength induced in point A (Fig. 2) by the given ring charge could be calculated using the following formulas:

$$\begin{aligned} E_r &= \frac{Q_k}{8\pi^2\varepsilon_0(R\cdot r_0)^{0.5}}\frac{k}{r_0}\left[K(m)+\left(\frac{r_0-R}{2R}\frac{k^2}{k'^2}-1\right)E(m)\right] \\ E_p &= \frac{Q_k p_0}{16\pi^2\varepsilon_0(R\cdot r_0)^{1.5}}\frac{k^3}{k'^2}E(m) \\ U(r_0,p_0) &= \frac{Q_k K(m)}{2\pi^2\varepsilon_0\left[p_0^2+(R+r_0)^2\right]^{0.5}} \end{aligned} \qquad (9)$$

where $k^2 = m = (4r_0R)/\left[p_0^2+(R+r_0)^2\right]$, $k'^2 = 1-k^2$, $K(m)$ – complete elliptic integral of the first kind, $E(m)$ – complete elliptic integral of the second kind.

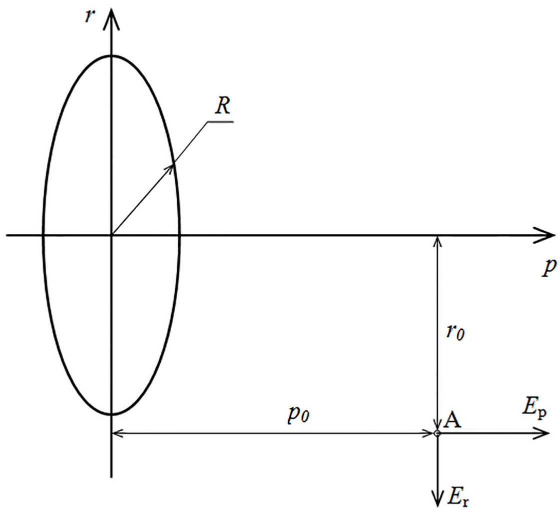

Fig. 2. Scheme of calculation of the electric fields of equivalent ring charge

Further, electric field of a whole charged aerosol cloud (artificial thunderstorm cell) has computed as a superposition of the electric fields from the totality of the ring charges considering their mirror reflection in the ground and in the conducted walls of the aerosol chamber (it has a form of the rectangular parallelepiped).

III. Computation of Electric Field of System of Artificial Thunderstorm Cells

Computations of the electric fields of system of two vertically disposed artificial thunderstorm cells of the same and different polarity have carried out for the case of an aerosol chamber of rectangular parallelepiped. Sizes of the chamber are 4.0*4.3*3.5 m. Height of the nozzle creating the bottom artificial thunderstorm cell was 0.75 m above the grounded screen. Height of the nozzle creating the upper artificial thunderstorm cell was 1.7 m above the grounded screen.

The aim of the fulfilled computations was to connect the electric field distribution with the form of the electrical discharges initiated by the groups of model hydrometeors (for example, hails). One of the typical picture of these cells and model hydrometeors disposition in the aerosol chamber is shown in Fig. 3.

Fig. 3. Variant of disposition of artificial thunderstorm cells and model hydrometeor array in aerosol chamber

Calculations have been carried out for every separate artificial thunderstorm cell of positive/negative polarity. Then, a common electric field distribution in the gap “two artificial thunderstorm cells - ground” has been found through superposition of the calculation results for every artificial thunderstorm cell. Two variants of the disposition of the artificial thunderstorm cells that could be characteristic to the real thundercloud situation have been used for the electric field calculations.

First variant is two thunderstorm cells of the different polarity in thundercloud that are on the different heights above the ground (Fig. 4). Examples of electric field calculation in the vertical cross-section passing through the upper positive artificial thunderstorm cell and the bottom negative artificial thunderstorm cell have shown in Fig. 5 (the electric field strength distribution) and in Fig 6 (the potential distribution).

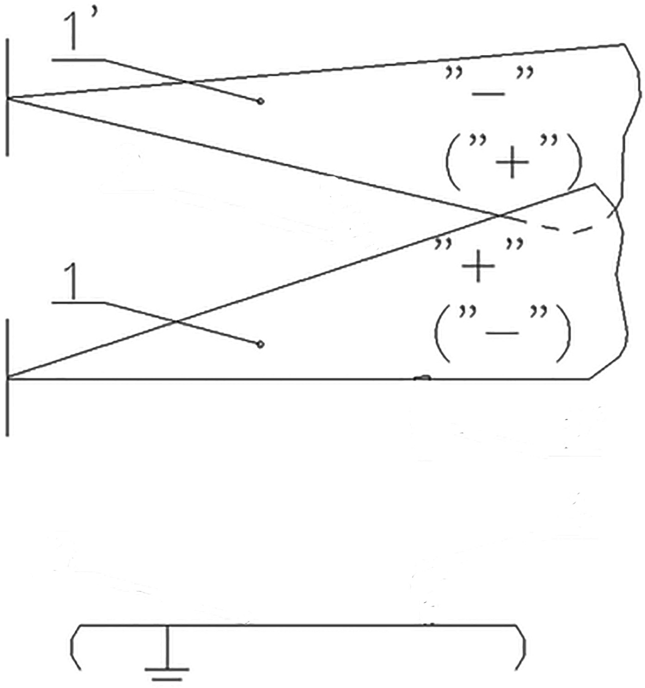

Fig. 4. Calculation scheme characteristic for two artificial thunderstorm cells of a different polarity vertically disposed in aerosol chamber

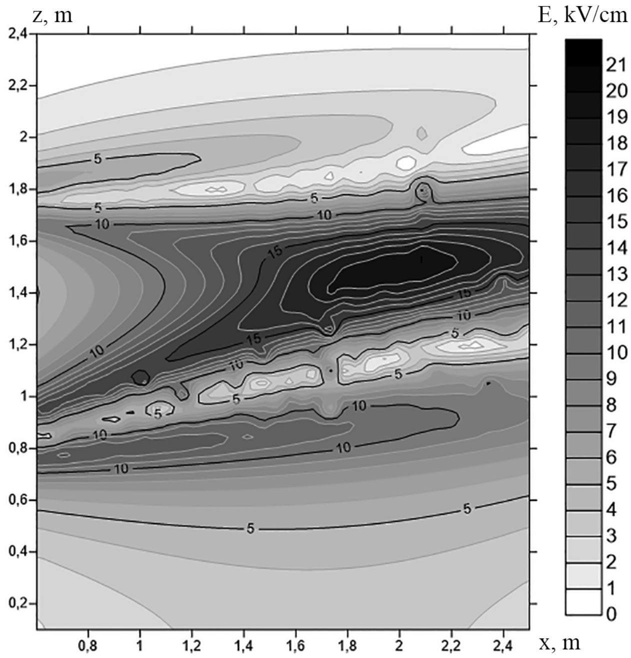

Fig. 5. Electric field strength E distribution in the vertical cross-section of the system of the upper positive artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

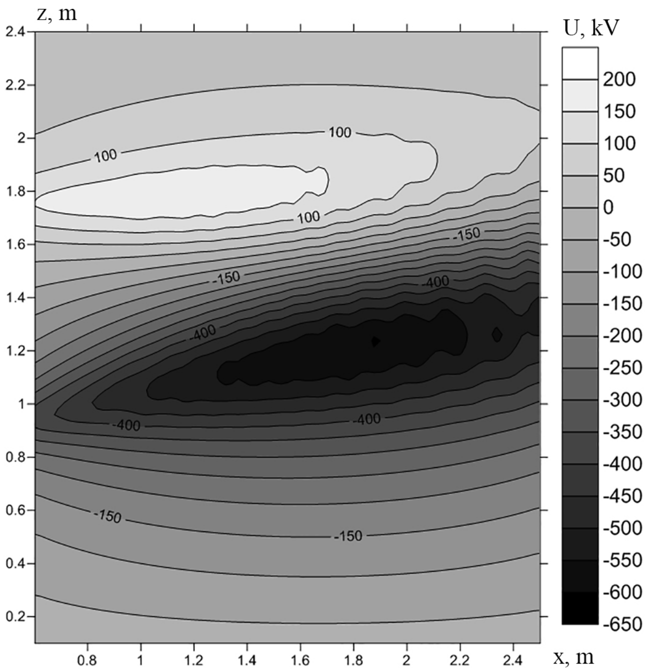

Fig. 6. Potential U distribution in the vertical cross-section of the system of the upper positive artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

According to the calculation results, electric field strength could achieve in the gap between the positive and negative artificial thunderstorm cells the values of 16-20 kV/cm. As a result, group of the model hydrometeors being between the charged aerosol clouds of a different polarity initiates the intensive discharge phenomena (powerful negative and positive streamers) that penetrated in the cells (Fig. 7).

Fig. 7. Powerful streamer discharges initiated by the model hydrometeor array between the positive and negatively charged artificial thunderstorm cells

Second variant simulated two thunderstorm cells of the same polarity in thundercloud that are on the different heights above the ground (Fig. 8). Examples of electric field calculation in the vertical cross-section passing through the negatively charged upper and bottom negative artificial thunderstorm cells have shown in Fig. 9 (the electric field strength distribution) and in Fig 10 (the potential distribution).

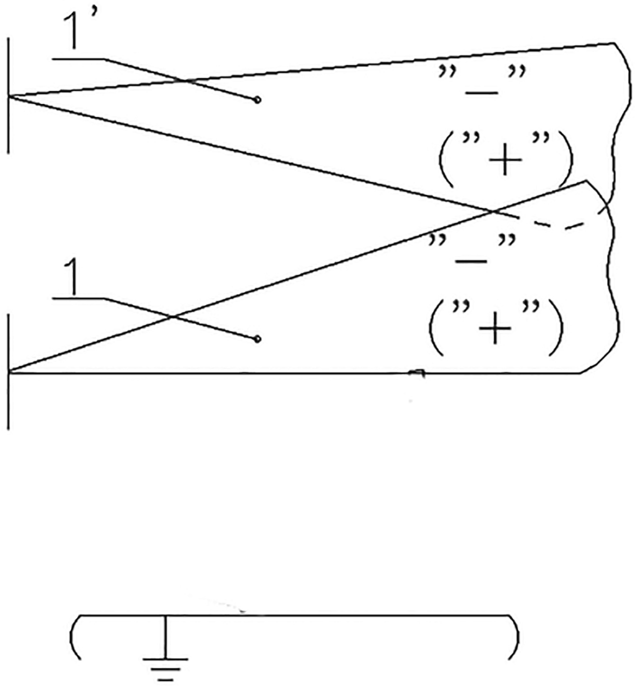

Fig. 8. Calculation scheme characteristic for two unipolar artificial thunderstorm cells vertically disposed in aerosol chamber

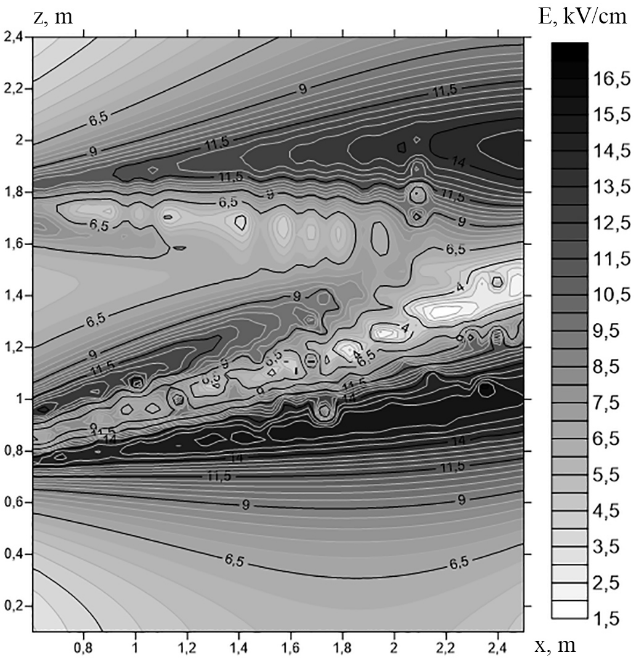

Fig. 9. Electric field strength E distribution in the vertical cross-section of the system of the upper negative artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

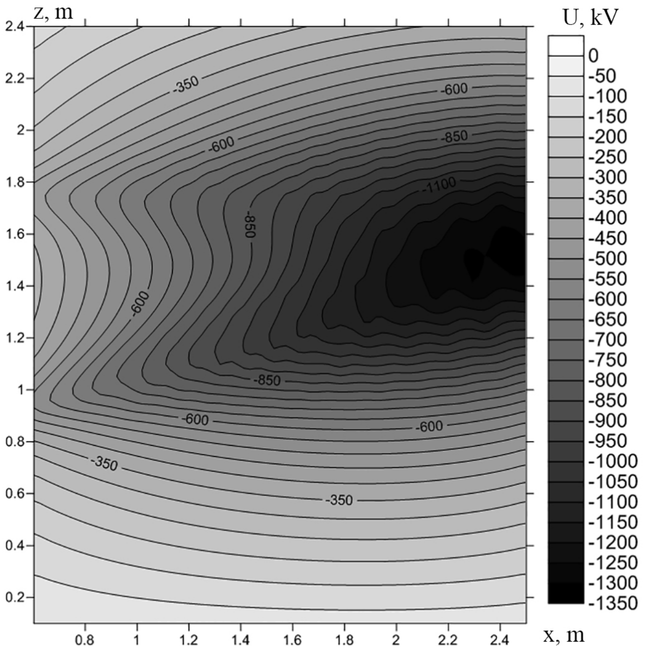

Fig. 10. Potential *U* distribution in the vertical cross-section of the system of the upper negative artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

Common maximal potential of the system of two negatively charged artificial thunderstorm cells could exceed the values of 1300-1400 kV. And, the maximal values of the electric field strength will be beneath the bottom boundary of the bottom artificial thunderstorm cell (up to 16-17 kV/cm) and above the upper boundary of the upper artificial thunderstorm cell (up to 14-15 kV/cm). As a result, powerful channel discharges have been initiated between the bottom artificial thunderstorm cell and the ground and between the upper artificial thunderstorm cell and the ceiling (Fig. 11). At the same time, the electric field strength in the gap between the unipolar artificial thunderstorm cells is not so intensive (Fig. 9) being in the values of some kilovolts per centimeter. And, intensive discharges could develop in the region between the unipolar artificial thunderstorm cells only in the cases when the groups of model hydrometeors have been introduced in the gap (Fig. 11).

Thus, computations of the electric fields of the system of the artificial thunderstorm cells of the different or same polarity with the experimental investigations using the model hydrometeor arrays could help to explain the peculiarities of the processes of lightning initiation and propagation inside the thunderclouds and between the thundercloud and the ground [7], to clarify the role of the large hails in these processes, and to connect the charge and disposition of the thunderstorm cells and their electric fields with the character and intensity of the discharges formed in the thundercloud and near its boundaries and the level of the thundercloud discharging by cloud-to-ground and intracloud lightning [8].

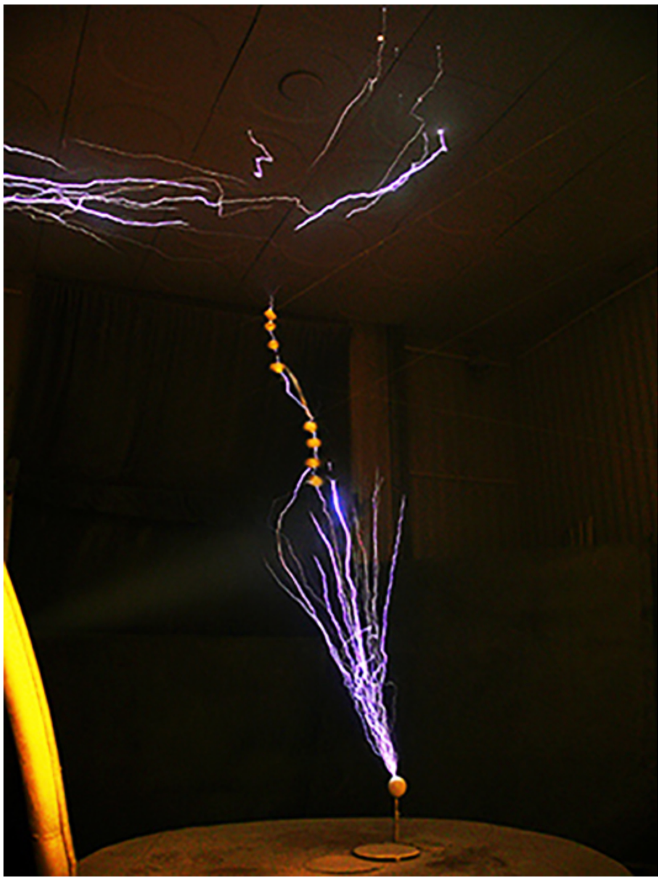

Fig. 11. Powerful channel discharges initiated by the model hydrometeor arrays in the system of the negatively charged artificial thunderstorm cells and between the cells and the grounded parts of the aerosol chamber

References

[1] A. G. Temnikov, "Using of artificial clouds of charged water aerosol for investigations of physics of lightning and lightning protection," *IEEE Conference Publications: Lightning Protection (ICLP)*, 2012 International Conference on, 6344279, 2012.

[2] A. G. Temnikov A. V. Orlov, "Determination of the electric field of a submerged turbulent jet of charged aerosol," *Electrical technology*, no. 3, pp. 49-62, 1996.

[3] I. P. Vereshchagin, A. G. Temnikov, A. V. Orlov, V. G. Stepanyanz. "Computation of mean trajectories of charged aerosol particles in turbulent jets," *J. of Electrostatics*, no. 40&41, pp. 503-508, 1997.

[4] A. G. Temnikov, "Dynamics of electric field formation inside the artificially charged aerosol cloud and in space near its boundaries," *in Proc. 12th Intern. Confer. on Atmospheric Electricity*, Versal, France, 2003.

[5] A. G. Temnikov, L. L. Chernensky, A. V. Orlov, O. S. Belova, N. Y. Lysov, T. K. Gerastenok, D. S. Zhuravkova, "Influence of Hydrometeors on Formation of Discharge between Artificial Thunderstorm Cell and Ground," *IEEE Conference Publications, 2016 International Conference on Lightning Protection (ICLP)*, p. 157.

[6] A. G. Temnikov, L. L. Chernenskii, A. V. Orlov, N. Yu. Lysov, O. S. Belova, I. E. Kalugina, T. K. Gerastenok, D. S. Zhuravkova, "The Influence of Artificial-Thunderstorm Cell Polarity on Discharge Initiation by Model Hydrometeor Arrays," *Technical Physics Letters*, 2017, Vol. 43, No. 2, pp. 197–200.

[7] J. R. Dwyer, M. A. Uman, "The Physics of Lightning," *Physics Reports*, 534(4), 2014, pp. 147–241.

[8] N. Pineda, T. Rigo, J. Montanyà, O. A. van der Velde, "Charge structure analysis of a severe hailstorm with predominantly positive cloud-to-ground lightning," *Atmospheric Research*, 2016, Vol. 178–179, pp. 31–44.