Peculiarities of the electric field calculation of the artificial thunderstorm cells

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***Abstract*—**Method of the calculation of the formation dynamics of the electric fields of a single and a system of two artificial thunderstorm cells is considered in paper. Method of the electric field calculation of the fully developed charged aerosol flow is based on the theoretical and experimentally measured parameters of a turbulent jets. Method of the calculation of the dynamics of the electric field formation of the turbulent charged submerged aerosol flow is based on the method of "big particles". Application of these methods for calculation of the electric fields of single artificial thunderstorm cell and for the system of two vertically disposed artificial thunderstorm cells has been considered in paper. It was established that near the second is required for the creation of the fully charged artificial thunderstorm cell. It is shown that the maximal electric field strength will achieve in the space between the artificial thunderstorm cells of the different polarity. It is found that the maximal electric field strength will be 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 (from powerful streamers to clear observed return strokes) between the charged clouds and between the artificial thunderstorm cells and the ground. Received results could help to find the methods of the artificial lightning initiation in thunderclouds.

***Keywords*—**Electric field calculation, dynamics formation, method of equivalent charges, charged aerosol, artificial thunderstorm cell, positive and negative polarity, lightning, thundercloud, model hydrometeors, discharge.

I. INTRODUCTION

APPLICATION of the artificial thunderstorm cells (clouds of strongly 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 [2]. Method of an electric field calculation of the fully developed submerged charged aerosol turbulent flows has been proposed in [3]. 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 [4, 5]. It could connect the dynamics formation of the electric field inside such cell and in a space near its boundaries with the space-temporal characteristics of the discharge phenomena changing in a place of their appearance and along their trajectories. A model of the formation dynamics of artificial thunderstorm cells created by a charged aerosol generator of a condensate type and a method of calculation of the electric field near boundaries and inside the forming charged part of the cloud are presented.

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 [6, 7]. Such task is requiring the calculation 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 calculation 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 FULLY DEVELOPED ARTIFICIAL CHARGED AEROSOL TURBULENT FLOW

Method for electric field calculation of a turbulent charged water aerosol flow has been proposed in [3-5]. 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 [3]. Method suggests that an electric field strength E of artificial thunderstorm cell depends on the parameters of a turbulent charged aerosol flow as in

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

where I_{out} – outlet current of charged aerosol generator of a

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

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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 [8], distribution of the volume charge density $\rho_m(p)$ in the axis direction of the charged turbulent jet will be the following:

$$\rho_m(p) = (5.35 d_0 \rho_0)/p . \tag{2}$$

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:

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

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:

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

where r – coordinate in the radial direction of the charged aerosol 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 [3]:

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

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, 8], change of the volume charge density on the jet axis $\rho^*_m(p)$ has considered in the method as:

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

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).

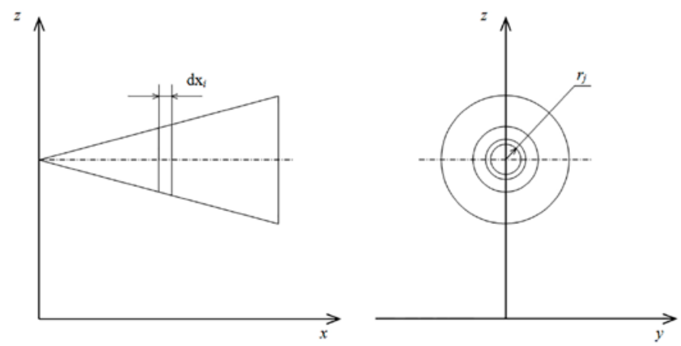

Fig. 1. Scheme of separation of volume charge of charged aerosol region

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:

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

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

Volume charge density of the circle has calculated as:

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

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:

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

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

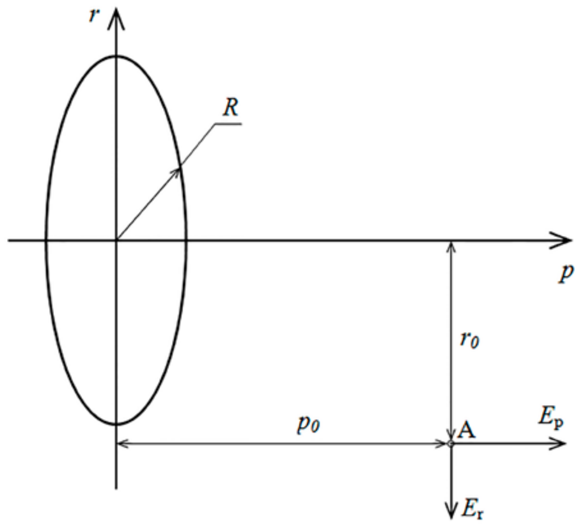

Fig. 2. Scheme of calculation of the electric fields of equivalent ring charge

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. Dynamics of Electric Field Formation Inside Artificial thunderstorm Cell and in a Space near its Boundaries

Because of the turbulent jet charge is concentrated on the aerosol particles, in the nonstationary conditions formation dynamics of the artificial thunderstorm cell could be described by the “big particle” model [9]. So, we consider the action of the hydro-dynamical forces of the turbulent flow on the particles of charged aerosol. We also consider the action of electrical forces of the forming charged part of artificial thunderstorm itself. The fluctuations occurring in the turbulent aerosol flow could be taken into account by the approximation characteristics [8]. Using the lasts, the mean trajectories of the additive particles that determine the formation of the charged aerosol flow can be found. So, the self-coordinated task of the charged aerosol particles motion in high-speed gas-dynamical turbulent flow and in the electric field created by the charged part of jet with continuously changed boundaries and charge density distributions is solved.

The process of the non-charged aerosol jet propagation in time was quite detail considered in [8] where the turbulent jet boundary contours under its development in time were obtained. The auto model profiles of the velocities and the additives concentrations in the jet were used. However, it is impossible to use this method for the self-coordinated task solving of the charged parts formation dynamics of jet because the location and the distribution of the space charge and the force action on the aerosol particles are changed with jet charged part development. So, the different approach in the formation dynamics task solving of the charged part of the axi-symmetrical jet was considered [4]. There the model of “big particles” was used. It was supposed that a main charge in jet is transported by the charged aerosol drops. The charged aerosol particles move under the influence acting on them forces. The motion equation of the charged particle was written the following:

$$m\frac{dV}{dt}=\sum F \tag{10}$$

m - mass of the aerosol particle; V - its velocity vector; ΣF - sum of the forces acting on the particle.

In gas dynamical turbulent jet, the forces acting on the charged spherical aerosol particles are:

a) the Stock’s force of flow resistance F_S:

$$F_S=-6\cdot\pi\cdot\mu\cdot K_h\cdot a\cdot(V-U) \tag{11}$$

b) the electric force F_E:

$$F_E=q\cdot E \tag{12}$$

where a, q - the radius and the charge of the water drop; U - the gas dynamical turbulent flow velocity; μ - the viscosity coefficient for air; E - the electric field in the point where water drop is situated in that moment; K_h - Koeningam corrector factor (was used for particles less than the micron dimension).

The force of gravity acting on the aerosol particle doesn’t consider because it is very less in comparison with others for the aerosol particles less than 1 μm.

Equation of motion (10) has been solved analytically on every time step. That has allowed to coordinate the solution with the electric field calculation equation from the space charge of the forming charged part of the jet.

Equation of motion of the aerosol particle in the axial and radial directions had the following form:

$$\begin{aligned}
&\frac{d^2z}{dt^2}=\frac{\sum F_z}{m}=w_z\\
&\frac{dz}{dt}=v_{z0}+\frac{d^2z}{dt^2}\Delta t=v_z\\
&z=z_0+v_{z0}\cdot\Delta t+0{,}5\cdot w_z\cdot(\Delta t)^2\\
&\frac{d^2x}{dt^2}=\frac{\sum F_x}{m}=w_x\\
&\frac{dx}{dt}=v_{x0}+\frac{d^2x}{dt^2}\Delta t=v_x\\
&x=x_0+v_{x0}\cdot\Delta t+0{,}5\cdot w_x\cdot(\Delta t)^2
\end{aligned} \tag{13}$$

where v_{z0}, v_{x0} - the charged water aerosol particle velocity on the previous time step into the axial and radial directions; w_z, w_x - the charged water aerosol particle accelerations on that time step; ΣF_z, ΣF_x - the acting in both directions forces; Δt - time step.

The mean trajectories of the charged particles that are situated on the boundary of the charged turbulent flows was computed for the following parameters of the charged aerosol generator used in experiments: flow velocity in the nozzle section u_0 = 400 m/s; the outlet current of generator I = 120 μA; the nozzle diameter d_0 = 6 mm; height of the nozzle x = 0.8 m; the aerosol particle radius a = 0.4 μm; the charge of aerosol particle $q = 4 \cdot 10^{-17}$ C; the average space charge density in the beginning cross-section of the main part of jet $\rho_m = 2.3 \cdot 10^{-4}$ C/m^3; length from the generator screen and the grounded wall 3,3 m.

Results of the calculation of dynamics of the electric field formation (electric field strength and potential) in the single bottom artificial thunderstorm cell of the negative polarity have been presented in Fig. 3-6 for the different period that has passed after the charging beginning.

During first tens of millisecond potential of the cloud rises to some hundred kV (Fig. 4) and electric field strength near the nozzle screen increases to 9-10 kV/cm (Fig. 3). At the same time, electric field strength on the grounded plane beneath the artificial thunderstorm cell is less than 1 kV/cm. In such situation discharge phenomena could appear before near the nozzle screen than near the charged cell boundaries.

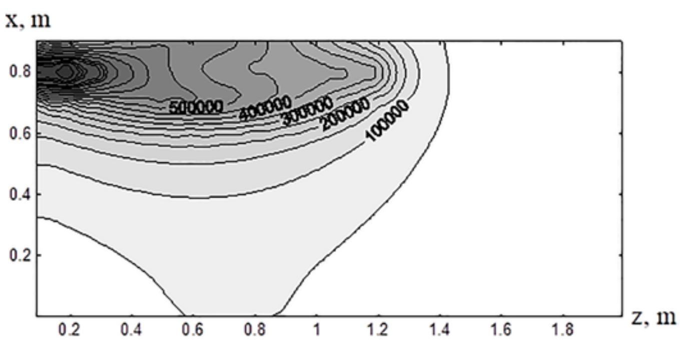

Fig. 3. Distribution of electric field strength (V/m) in the vertical cross-section of the gap "artificial thunderstorm cell – grounded plate" passing through jet axis for 50 ms time period after the charging beginning

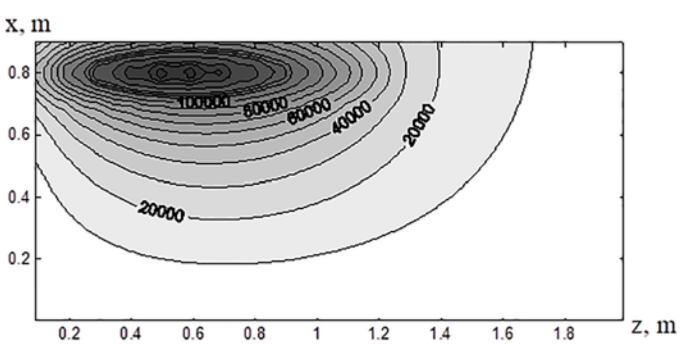

Fig. 4. Distribution of electric field potential (V) in the vertical cross-section of the gap "artificial thunderstorm cell – grounded plate" passing through jet axis for 50 ms time period after the charging beginning

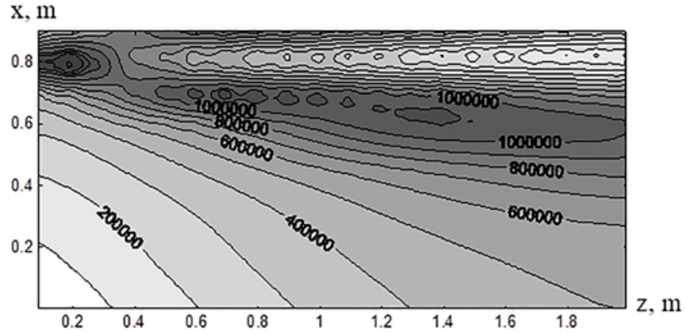

Fig. 5. Distribution of electric field strength (V/m) in the vertical cross-section of the gap "artificial thunderstorm cell – grounded plate" passing through jet axis for 900 ms time period after the charging beginning

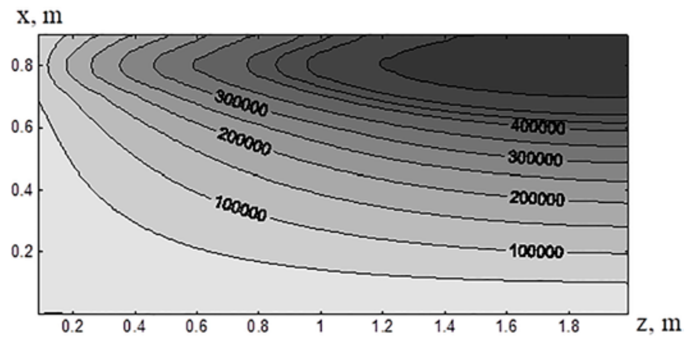

Fig. 6. Distribution of electric field potential (V) in the vertical cross-section of the gap "artificial thunderstorm cell – grounded plate" passing through jet axis for 900 ms time period after the charging beginning

For a second after the charging beginning potential of the artificial thunderstorm cell reaches more than five hundred kV (Fig. 6). Electric field strength near the nozzle screen and on the boundary of the charged parts of the artificial thunderstorm cell is 10-12 kV/cm (Fig. 5). And for that time, electric field strength on the grounded plane beneath the charged cell can be more than 5-6 kV/cm. Such conditions are favorite for the discharge occurrence as near the artificial thunderstorm cell boundaries as on the grounded plane.

IV. Calculation of Electric Field of System of Artificial Thunderstorm Cells

Calculations of the electric fields of system of two vertically disposed artificial thunderstorm cells of the same/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 hydrometeors (for example, hails). One of the typical picture of these cells and model hydrometeors disposition in the aerosol chamber is shown in Fig. 7.

Fig. 7. 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. 8).

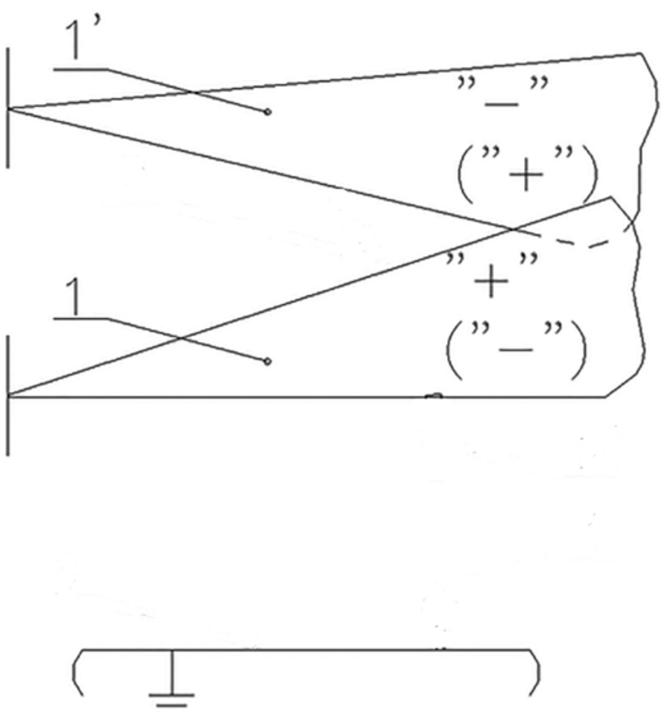

Fig. 8. Calculation scheme characteristic for two artificial thunderstorm cells of a different polarity vertically disposed in aerosol chamber

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. 9 (the electric field strength distribution) and in Fig 10 (the potential distribution).

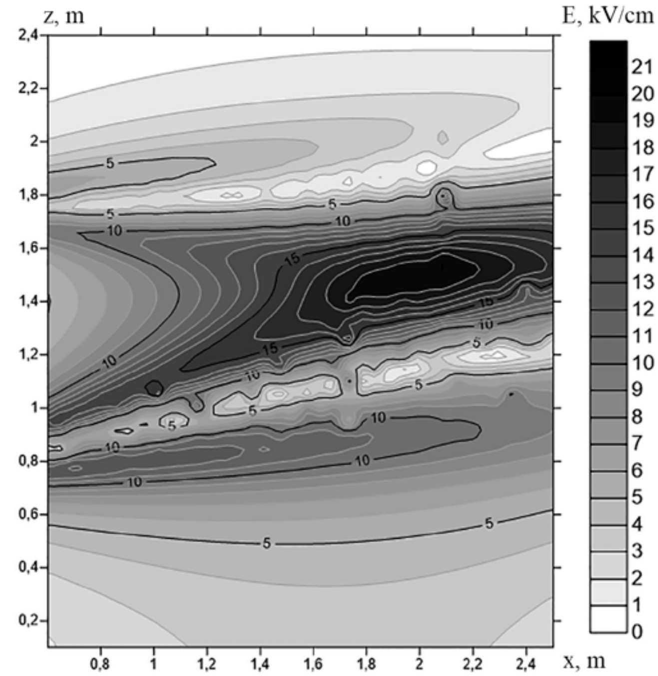

Fig. 9. Electric field strength *E* distribution in the vertical cross-section of the system of the upper positive artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

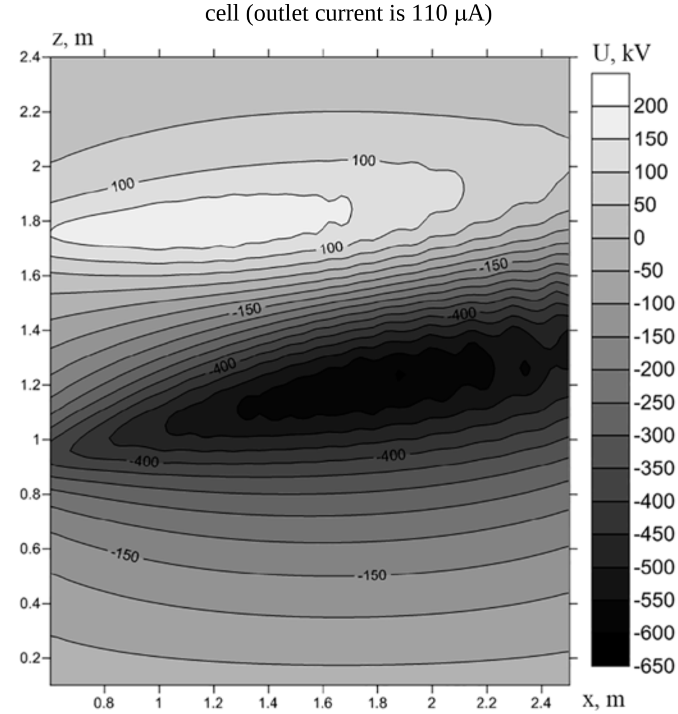

Fig. 10. Potential *U* distribution in the vertical cross-section of the system of the upper positive artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

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. 11).

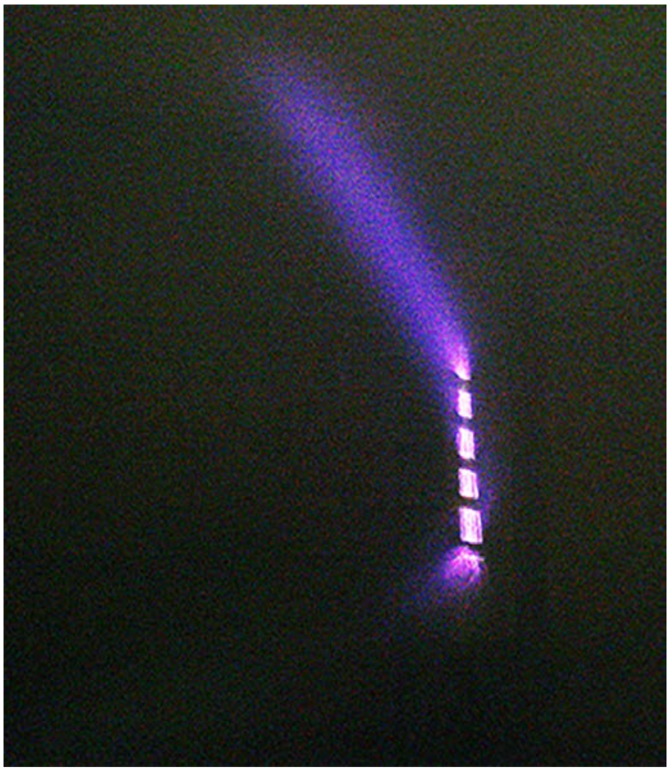

Fig. 11. Powerful streamer discharges initiated by the model hydrometeor array between the positive and negatively charged artificial thunderstorm cells

Second variant simulated two thunderstorm cells of the same polarity in thundercloud that are situated on the different heights above the grounded surface (Fig. 12). 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. 13 (the electric field strength distribution) and in Fig 14 (the potential distribution).

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. 15).

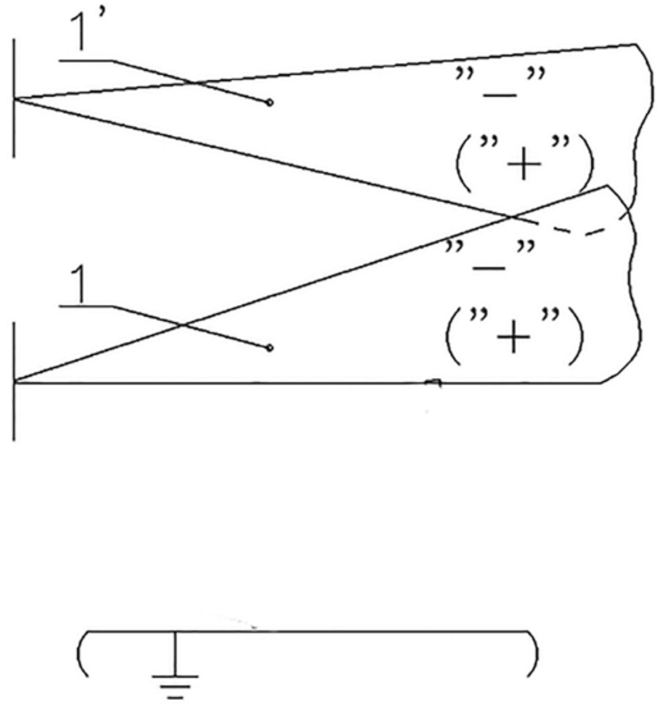

Fig.12. Calculation scheme characteristic for two unipolar (positive or negative) artificial thunderstorm cells vertically disposed in aerosol chamber

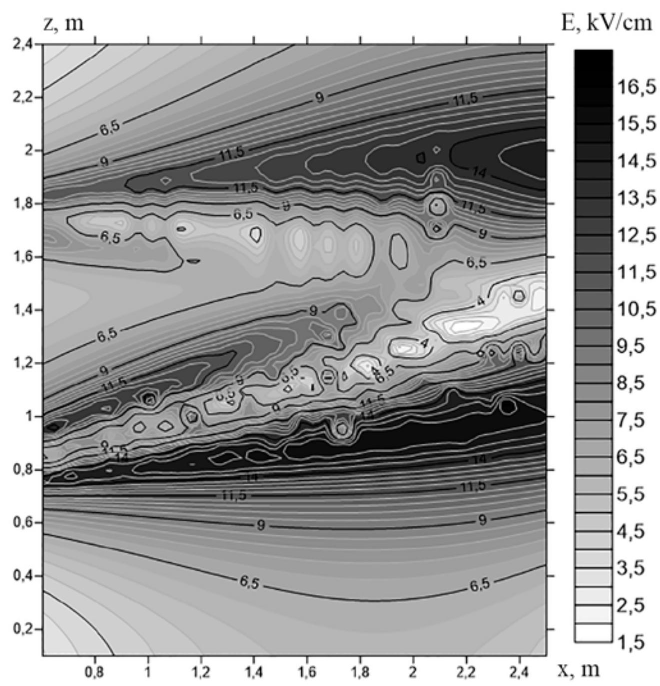

Fig. 13. Electric field strength E distribution in the vertical cross-section of the system of the upper negative artificial thunderstorm cell (outlet current of charged aerosol generator is 70 μA) and bottom negative artificial thunderstorm cell (outlet current of charged aerosol generator is 110 μA)

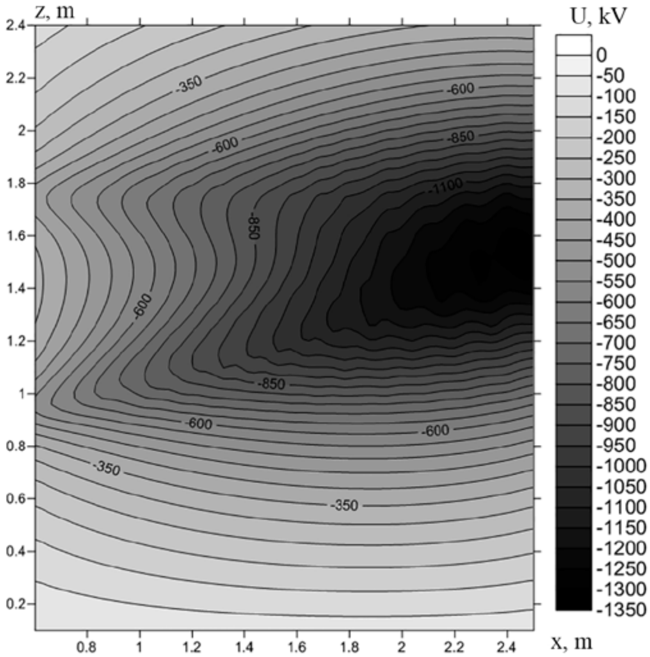

Fig. 14. Potential U distribution in the vertical cross-section of the system of the upper negative artificial thunderstorm cell (outlet current is 70 μA) and bottom negative artificial thunderstorm cell (outlet current is 110 μA)

Fig. 15. 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

At the same time, the electric field strength in the gap between the unipolar artificial thunderstorm cells is not so intensive (Fig. 13) 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. 15).

Thus, computations of the dynamics formation 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 [10], 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 [11, 12].

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