N91-32729

EXPERIMENTAL MODELLING OF LIGHTNING INTERACTION PHENOMENA WITH A FREE POTENTIAL CONDUCTING OBJECTS

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Abstract

A laboratory experiments has been conducted to investigated the physical processes of the development of long air discharge and their interaction with a free potential conducting objects.Space-time development of the lightning phenomena in the gaps was registered by the moving-image camera and optoelectronic transducer.The electric field in the different points of a gap was measured using a Pockels device both in the leader stage and the stage of return stroke.Experimental results of the streamer zone length measurements in the gaps with length of up to 65 meters are presented.Extrapolation on the lightning case shows that the streamer zone length of the leader in the lightning composes only the few tens meters.A physical processes of the interaction of a positive and negative long sparks with the isolated objects are investigated.In particularly the striking probability of isolated conducting spheres with different diameters in the dependence on the location in the gap is investigated.It is obtained that the striking probability of the spheres smaller than the critical size equal to zero near the electrode.The striking probability of the spheres with the diameters greater then the critical is the unity near the electrode.The physical picture of the observed effects is supposed.

1 Introduction

It is well known that both the lightning and the spark discharge in a long air gap are characterized by the leader mechanism of the propagation.Therefore a series of properties of lightning discharge are displayed also in the long air gap discharge.This allows to put the task of modelling of lightning orientation processes on the objects in the laboratory.The different factors influence on the spark discharge channel orientation:a gap geometry,parameters of a leader,atmosphere conditions and others.Many papers was suggested to the investigation of striking probability of a free potential objects(see,for example,[1-3]).In[1] it is shown that the striking probability is increased with the growth of conductivity and capacity of the object.In[2]the striking probability of the objects in the dependence on the its spacing in the gap is investigated.It is shown that near the earth surface the striking probability is incresed.In paper [3] the results of investigation of the polarity effect in the interaction of spark with a free potential object are presented.

The basic effect of the orientation of a leader discharge is connected with the flow of electric field,closed on the object,i.e. the orientation is determined by the degree of field distortion by the object and most probably in the direction of field intensification.However the effects of space charges interaction also influences on the striking probability.The investigation of striking probability dependence on the charge of the leader also is of interest for lightning protection of aircrafts.

In this paper the influence of polarity of the applied voltage and the parameters of the streamer zone on the striking probability of the free potential objects are investigated.

2 Experimental technique

Measurements are carried out in rod-plane and toroid-plane gaps.Impulses with the duration τ_i = 7500 μs and the front duration τ_f from 2 to 1200 μs were forming on an outlet of High-Voltage Generator HVG-9MV and energy capacity 1.35 MJ.The space-time development of the lightning phenomena in the gap was registered by the moving-image camera and optoelectronic transducer.The electric field in the various point of the gap was measured using a Pockels device.The sensor is a primary transducer optically connected by fiber guides of up to 150 m long with a light source and a photodetector.A light source is a semiconductor laser with emission wavelength of 0.86 μm.Recorded frequence band is 50 MHz.

In the experiments the models of aircrafts and metallic spheres with the diameters 4,10, 30.50 cm are used.The objects on the different distance from the high-voltage electrode both inside of the streamer zone and the outside of its are placed.The streamer zone length was measured with the help of a photoelectronic recorder.The trajectories of the spark channel were recorded using a two photocameras,mounted under the angle 90°.The striking probability was determined from 100 breakdowns for each case.The applied voltage was equal to 90% of the breakdown probability. Investigations are carried out in the gaps with the length of up to 25 meters long under application of voltage pulses of positive polarity and of up to 12 meters under negative polarity voltage.The sparks from the HVG top,which is the toroid with the ratio of external radiuses 8/2 m have the length from 50 to 80 meters.

3 Experimental results

3.1 Positive polarity

The main parameters characterized the leader are the streamer zone length,electric field intensity and the space charge of the streamer zone.

3.1.1 The streamer zone length

It is important to reproduce the stage of free development of leader with the chance distortions of the channel trajectory in the experiments on the modelling of lightning striking of the aircrafts.This is ensured in the case when the streamer zone length ℓ_{str} of developing leader is much shorter then the gap length d .It is known that the streamer zone length of leader in the its initial phase of development ℓ_{in} depends on the front duration of the applied voltage.

At the sharply impulse front the streamer zone length occupies the significant part of the gap already in the initial phase of leader development. The dependences of streamer zone length on the front duration of the applied voltage for different gaps obtained using photoelectronic transducer are presented in fig.1. It can been seen that the discharge at the τ_f = 2 μs is characterized by

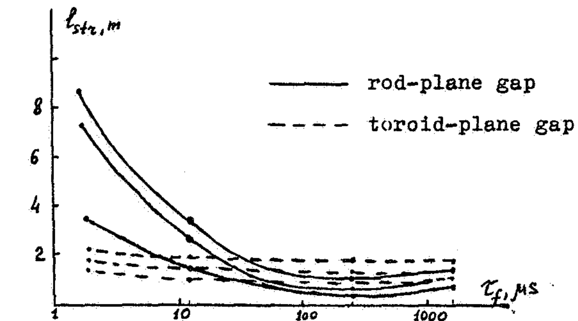

Fig.1. The variation of streamer zone length l_{str} as a function of voltage front duration τ_f. 1- d =5m; 2- d =10m; 3- d =15m.

significant length of streamer zone and for the gap with length d =4 m consists from only one final stage. The critical duration of voltage front τ_{fcr} is exist at which the streamer zone length takes the minimum value. Note, that the breakdown voltage is minimal at the critical duration of the front. It is seen from fig.1 that the change of streamer zone length in the gap rod-plane essentially more then in the gap toroid-plane. The streamer zone lengths versus from the gap length at the critical front duration τ_{fcr} of the applied voltage are presented in the fig.2.

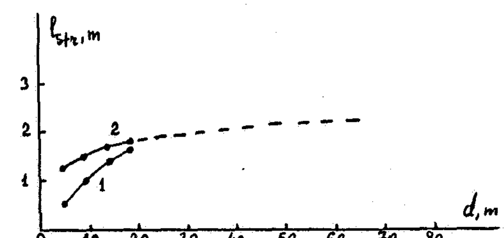

Fig.2. The variation of streamer zone length l_{str} as a function of gap length d.

The streamer zone length l_{str} in the gap rod-plane in the dependence on the gap length d is described by the expression

$$l_{str} \simeq 0.18\, d^{3/4}, [m] \qquad (1)$$

In the gap toroid-plane this dependence have the form

$$l_{str} \simeq 1 + 0.15\, d^{1/2}, [m] \qquad (2)$$

Approximation of the streamer zone length on the large length of gaps by formula (2) is represented in the fig.2 with the drawing line. It is seen that the streamer zone length is saturated at the large gap length. So, at the gap length d =100 m the streamer zone length, calculated by the formula (2), is equal to $l_{str} \simeq$ 2.5 m. Note, that the streamer zone length of leader developing from the HVG top is equal to $l_{str} \simeq$ 2.8 m at the influence of impulse (2/7500μs), when the breakdown take place with the overstrain.

3.1.2 The electric field intensity

Oscillograms of the electric field intensity change are represented in figs.3-6. Figures 3 and 4 correspond to gap breakdown case of d =6 m and d =12 m under application of voltage pulse (300/7500μs). Maximum value

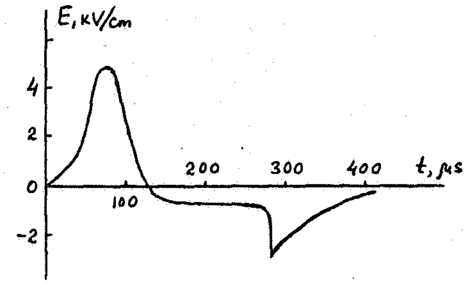

Fig.3. Electric field in the streamer zone of leader. d = 6 m, h = 0.6 m.

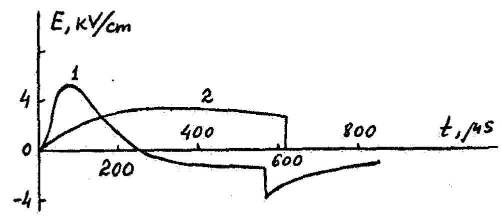

Fig.4. Electric field in 12 m rod-plane gap. 1- h = 0.8 m; 2- h = 4 m.

of electric field intensity is achieved at sensor placing on the longitudinal axis of streamer zone and is equal to 5 kV/cm, time of attainment of this maximum at change of sensor position in gap being determined by velocity of leader propagation. Curves 1 correspond to case of streamer zone passage through the sensor. It is seen from the figures that the polarity of electric field intensity is changed. In the oscillograms one can separate two stages corresponding to different physical processes. First stage corresponds to leader one of discharge development, second stage corresponds to neutralization of the space charges. Time of discharge forming grows with increase of gap length and is defined by leader propagation velocity v_l ($t = d/v_l$). Field intensity is decreased moothly after breakdown. Half-decay time or neutralization time of the space charge τ grows with increase of gap length. So, at the length d =6 m, time $\tau \simeq$ 100 μs, and at d =12 m τ is 400 μs. In case when the sensor is beyond a leader cover the neutralization stage is not registrated by the sensor (fig.4, curve 2).

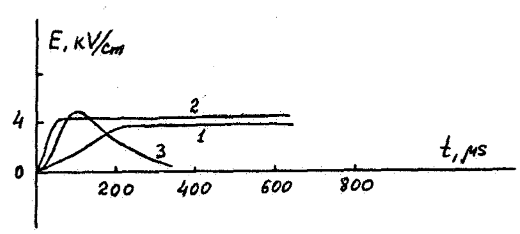

Fig.5. Electric field in 18 m rod-plane gap. 1- h =4m; 2- h =0.8m; 3- h =1.6m. 300/7500μs.

At absence of breakdown the field oscillogram was changed depending on availability or absence sence of uncompleted leader in gap (fig.5). In last case the sensor placing beyond a streamer corona from the rod end reproduced change of electrode field in rod-plane gap (fig.5, curve 1). Inside the streamer corona at absense of leader the electric field repeats form of applied voltage however velocity of field growth is defined not by the steepness of voltage rise, but a dynamics of the space charge in the streamer zone and depends on distance from the rod end (fig.5, curve 2). A availability of the uncompleted leader in the gap the field change inside the streamer corona takes place analogically to breakdown case. However change of field polarity is not observed in this case (fig.5, curve 3). Change of front duration of applied voltage (15/7500 μs) is not affected on the qualitative picture of field behaviour (fig.6). Note only that for-

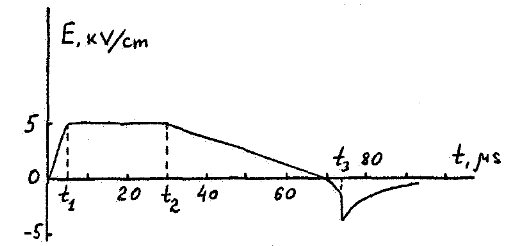

Fig.6. Electric field in 4 m rod-plane gap. h = 0.7 m; τ_f/τ_i = 15/7500 μs.

ming time of breakdown is decreased essentially because of increase of leader propagation velocity and increase of streamer zone length in the final stage. Fig.6 corresponds to the gap length d =4 m. Time moment t =0 coinsides with the beginning of voltage application, t_1 coinsides with contact moment of the streamer zone with the sensor. When the sensor is placed inside the streamer zone time t_1 is determined by propagation velocity of ionization front of the streamer corona $t_1 = h/v_{str}$. Velocity is constant at different distances from the rod end and is equal to v_{str} =$2\cdot 10^7$ cm/s. Electric field intensity is not changed also along the full length of the streamer zone and is equal to E_{str} =5 kV/cm. Electric field intensity begins to decrease after the leader head. Time interval $\Delta t = t_2 - t_1$ is defined by velocity of leader propagation. In this case leader velocity is equal to $v_\ell \simeq 3\cdot 10^6$ cm/s. The leader reaches the plane at the moment time t_3. Further the change of electric field intensity is connected with the processes of neutralization of charges accumulated in the discharge gap. Time of charges neutralization is correlated with the streamer zone length and the gap length.

3.1.3 Space charge of streamer zone

Using the Gauss theorem we can to evaluate the value of space charge, carried out by leader:

$$Q_{str} = \varepsilon_0 \oint E_{str}\, dS \simeq \varepsilon_0 E_{str} \ell_{str}^2 \Omega, \qquad (3)$$

where ε_0 =$8.85\cdot 10^{-12}$ F/m is the dielectric constant, E_{str} is the electric field in the streamer zone, ℓ_{str} is the streamer zone length. On the known intensity of electric field in the streamer zone the potential of leader head also may be obtained:

$$\varphi_\ell \simeq E_{str}\cdot \ell_{str} \qquad (4)$$

Setting in (4) the expression (2) for streamer zone length ℓ_{str}, we have

$$\varphi_\ell \simeq E_{str}(1 + 0.15\, d^{1/2}),\ [V] \qquad (5)$$

At the characteristic gap length $d \simeq 3$ km for the lightning it is followed from here, that the potential of the leader head composes $\varphi_\ell \simeq 4.6$ MV, and the streamer zone length equal to $\ell_{str} \simeq 9.2$ m. This is not contradicted with the experimentally observing value of streamer zone length in the lightning[4]. In fig.7 the per unit length charge $q \simeq 2\pi\varepsilon_0 E_s \ell_s$ versus from the gap length is presented. It is seen from figure, that the per

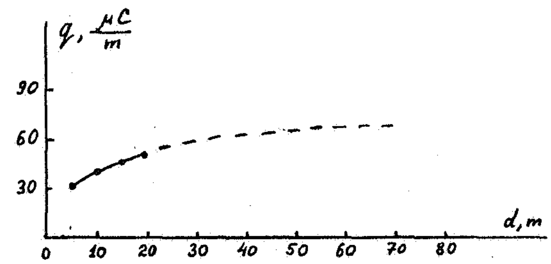

Fig.7. The charge per unit length as a function of the gap length.

unit length charge of leader is saturated at the growth of gap length. It is known[4], that the space charge distributed around the lightning channel is neutralized in the return stroke stgge and is composed

$$Q = \int i\, dt \simeq 1\ C$$

for the mean current $i \simeq 20$ kA with the duration $\Delta t \simeq 50$ μs. Approximately a such charge is followed at the evaluating of $q \simeq 2\pi\varepsilon_0 E_s \ell_s$ using the expression (2) for the lightning channel length $d \simeq 3$ km:

$$Q = q\cdot d \simeq 300\,\frac{\mu C}{m}\cdot 3000\,m = 0.9\ C$$

3.1.3 Striking probability of aircraft models

Lower the experimental dependences of striking probability of aircraft models in the gap rod-plane are resulted. In figs.8,9 the dependences of striking probability P of models with length ℓ_m=1.15 m on the distance h_m up to high-voltage electrode at the different value τ_f and d are presented. It is

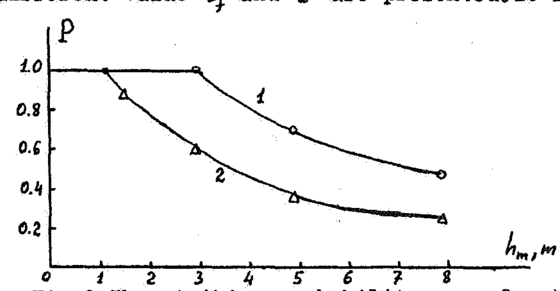

Fig.8. The striking probability as a function of distance from the electrode. 1- τ_f =15 μs; 2- τ_f =600 μs. d = 8 m.

seen from figures that the probabilities P are maximum near the electrode and is decreased with the removing from it. Fig.10 shows a change of striking probability of model placed on the fixed distance h_m from the electrode at the increase of gap length. It can be seen that the striking probability decreases with the increase of gap length. It is known that the essential influence on the striking probability of models turns out the discharge processes beginning from the model. Fig.11

shows the discharge development until the striking of model. It is seen from figure that the positive discharge begins from the model after the contuct of the streamer zone of direct leader with the model. Note that the itself leader channel is finded on the distance ℓ_{str} from the surface of model.

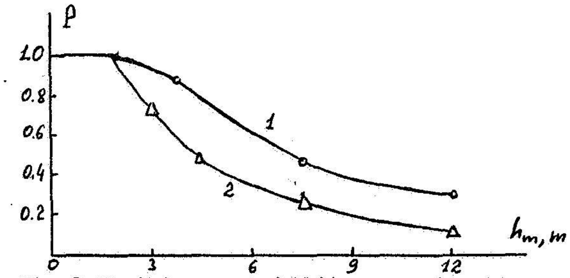

Fig. 9. Striking probability as a function of distance from the electrode. $d=12\,m$; $1 - \tau_f = 15\,\mu s$; $2 - \tau_f = 600\,\mu s$.

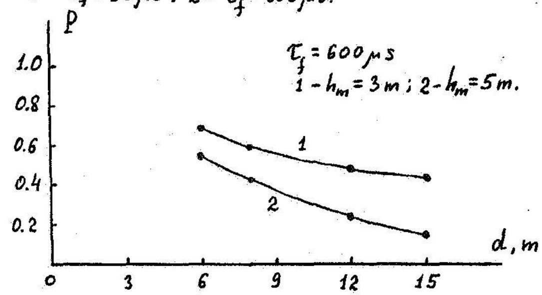

Fig. 10. Striking probability of aircraft model as a function of a gap length.

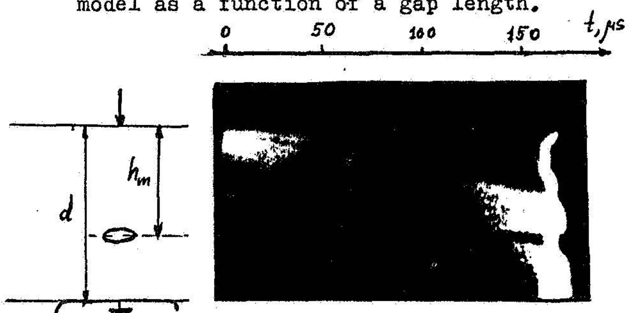

Fig. 11. Discharges development in the gap positive rod-model-plane. $d=8\,m$, $h_m=5\,m$.

3.1.4 Striking probability of metallic spheres

As was shown above the corona discharge processes begin from the objects until the contact its by the leader channel. Elucidation of the role of this processes on the orientation of leader channel is of interest. Lower the results of the investigation of the positive leader orientation to the metallic spheres, from which the corona processes is absent, are presented. Experimental investigations have been carried out in the rod-plane gap. The positive switching impulse voltages (15/7500 μs and 300/7500 μs) were applied to the rod electrode. The striking probability of conducting spheres with different diameters in the dependence on the applied impulse voltage parameters and on the situation of spheres in the gap are measured. The spheres with the diameters D = 4, 10, 30, 50 were used. The spheres were placed in the gap at the different distance from the rod end both inside of streamer zone and outside its.

The streamer zone length was measured using the moving-image camera. For gap length d = 6m the streamer zone length was equal to ℓ_{str} = 0.6 m and ℓ_{str} = 2 m at the applied voltage impulse τ_f/τ_i = 300/7500 μs and 15/7500 μs accordingly. The trajectories of sparks channel were recorded using a two photocameras, mounted under the angle 90°. In figs. 12 and 13 the dependences of a striking probability of the spheres with different diameters from the distance between the sphere and rod are presented. From figures it can be seen that the striking probability in the dependence on the leader charge Q_ℓ and the inductive charge Q_{in} may be either increasing or decreasing function of distance between the object and high voltage electrode. Striking probability of the spheres smaller than the definite size equal

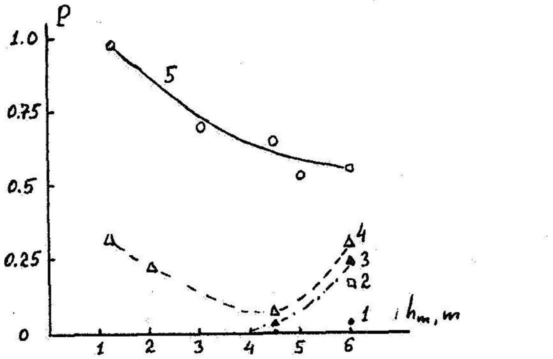

Fig. 12. Striking probability of spheres at the applied voltage 300/7500 μs.

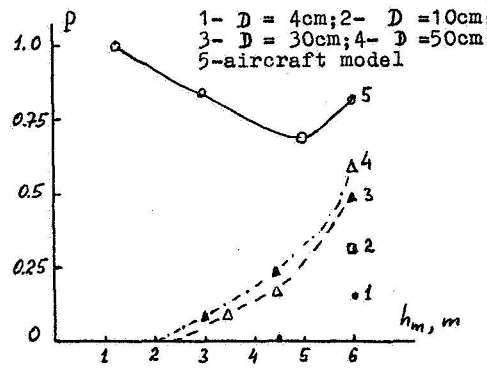

Fig. 13. Striking probability of spheres at the applied voltage 15/7500 μs.

to zero near the electrode. At the exceeding of critical size the striking probability becomes the unit near the rod and decrease with the removing from it. The charge of the streamer zone grows also at the increasing of gap length that must to change the striking probability of object. So, the sphere with the diameter D = 50 cm in the gap with length d = 6m situated on the distance 1m from the rod end is striked with the probability P = 0.3. At the gap length d = 8m this sphere is never striked. The charge of the streamer zone at this is increased two times. The obtained results may be explained proceed from the next physical picture of leader discharge orientation. Propagation of leader takes place mainly in the direction of field intensification, created by the object. At the contact of object by the streamer zone the object is charged with the positive charge. This is increases the flow of electric field, closed on the object. If the charge of streamer zone turns out to be more than the inductive negative charge then the repulsive electric field is appeared.This explaines the existance of critical parameters (critical size of object or critical charge of leader) at exceeding of which the mechanism of leader orientation is changed.

3.2 Negative polarity

The striking probability of objects is increased at the negative polarity of leader approximately on 25% in relation to the positive polarity (fig.14).

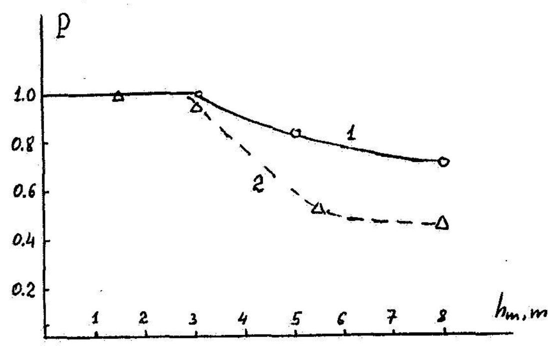

Fig.14.Striking probability of aircraft model as a function of the distance from the electrode. d =8 m;1- τ_f =15 μs;2- τ_f= 600 μs.

Explanation of this may be obtained from the analysis of discharge photochronograms presented in figs.15,16.It is seen from figures that the contrary positive leader develops from the object.It is noted that the condition of the development of contrary positive leader is the touching of object by the front of streamer zone.In the lower part of gap the discharge develops in the form of slow corona. In table 1 the experimental values of the velocities of contrary v_+ and direct v_- leaders,the develop time up to its close Δt , the channel length of direct leader ℓ and the streamer zone length of negative leader ℓ_{s-} in the beginning of the final jump phase of discharge are presented.Note that the parameters of the direct negative leader and the contrary positive discharge practically is not depended from the front duration of the applied voltage impulse τ_f and the gap length d .These parameters not depends also on the effective velocity of the stepped negative leader development in the upper part of gap,which at the d =12 m grows up to $5-10$ cm/μs.Note,that the development of the contrary leaders takes place in the unbroken form.The velocity v_- coincides with the velocity of negative leader,developing in the "pure" gap,and the value v_+ agrees with the measurements values of positive leader head velocity of leader developing from the volume.In all case the aircraft model participates in the formation of new leader step.The step formation time not depends on the presence of the model and composes in average 30-35 μs.It is seen from table,that the length of direct leader channel ℓ in the moment of birth of contrary leader at the constant distance between the model and high voltage electrode depends on the τ_f ,that may be caused by the different value of space charge or the streamer zone length.By this reason the value ℓ must to increase at the growth of gap length that is observed in the experiments.It is noted that the development of the contrary leader takes place from the moment of contact of the streamer zone of direct leader.However,the growth of distance $(h_m-\ell)$ is observed with the increasing of gap length and for the gap length d =12 m the the value $(h_m-\ell)$ coincides with the streamer zone length of negative leader in the final jump phase.

Table 1.Characteristics of discharge in the gap negative rod-model-plane

d/h_m, m/m	τ_f μs	v_+ cm/s	v_- cm/s	Δt μs	ℓ m	ℓ_{s-} m
8/3	15	$3.7\cdot10^6$	$0.8\cdot10^6$	35.0	0.7	2.7
	300	$3.3\cdot10^6$	$0.6\cdot10^6$	30.0	1.15	2.4
12/7	15	$3.3\cdot10^6$	$1.0\cdot10^6$	31.0	4.1	2.9

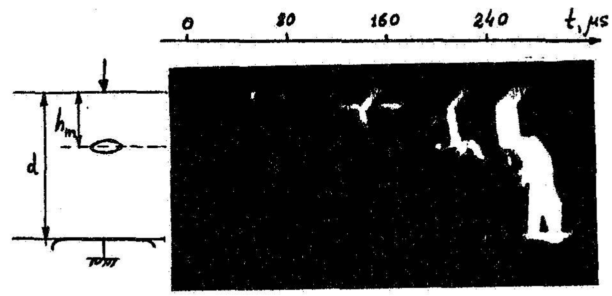

Fig.15.Photochronogram of discharge processes in the gap negative rod-model-plane. d = 8 m; -300/7500 μs; h_m = 3 m.

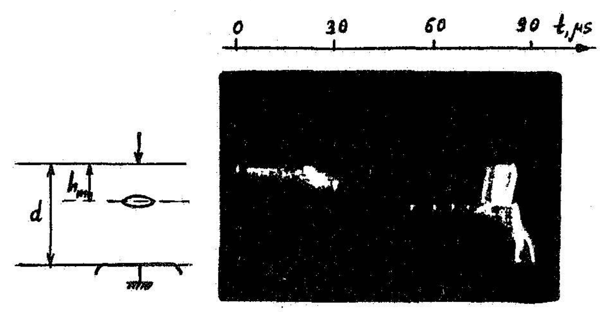

Fig.16.Photochronogram of discharge processes in the gap negative rod-model-plane. d= 8 m; -15/7500 μs; h_m = 3 m.

4 Discussion

The results adduced above are related to the object striking in laboratory discharge gap. Elucidation of the role of obtained effects in lightning striking of real objects is of interest. Let us evaluate a characteristics of objects and lightning at which the repulsion effect turns out to be essential. The charge carried by the streamer zone of leader may be evaluated on the known value of electric field in the streamer zone using the Gauss theorem:

$$Q_{str} = \varepsilon_0 \oint E_{str} dS \approx 2\pi\varepsilon_0 E_s \ell_s^2 (1-\cos\theta_0) \quad (6)$$

where ℓ_{str} is the streamer zone length, θ_0 is the top angle of the streamer zone, E_{str} is the electric field in the streamer zone, ε_0 is the dielectric constant.

The electric field in the streamer zone E_{str} approximately is 5 kV/cm. The angle θ_0 is equal as a rule to 30°- 90°. The value of inductive charge Q_{in} depends on the capacity of the object or of its geometrical sizes. So, for the sphere with a diameter D we have:

$$Q_{in} = \frac{3\pi}{4} \varepsilon_0 E D^2 \quad (7)$$

From (6) and (7) we obtain that

$$\frac{Q_{str}}{Q_{in}} \sim \frac{8}{3} \frac{\ell_s^2 (1-\cos\theta_0)}{D^2} \geq 1,$$

i.e. the essentially repulsion effect takes place for the objects with the linear size smaller than the streamer zone length

$$D \leq \sqrt{\frac{8}{3}(1-\cos\theta_0)}\, \ell_{str}$$

At the length of gap d = 6 m and the front durations of applied voltages τ_f = 300 μs and τ_f = 15 μs the streamer zone length is equal to ℓ_s = 0.6 m and ℓ_s = 2 m, accordingly. The charges of streamer zones are equal to Q_s = 3.5 μC and Q_s = 34 μC. In lightning the streamer zone length composes a few ten meters. At the length of streamer zone ℓ_s=10 m the charge approximately is equal to $Q_s \approx$ 150 μC. The repulsion effect of this leader must take place for the objects with the size $L \leq 5$ m.

Note that the physical picture of leader orientation described above not accounts a series of effects influencing on the striking probability of object. In particularly the corona discharges from the sharp projections of objects are not take into accounted. Experiments show that the striking probability of sphere with a projection of rod form essentially depends on the location of projection on the sphere. The projection that is the cathod electrode, not influences on the striking probability of sphere. So, the sphere of the diameter D = 50 cm with the cathod projection by length of 10 cm was not in the least striked, and with the anode projection the striking probability becomes 100%. Essential influence of the anode projection on the striking probability is noted also in paper[3].

5 Conclusion

Thus, the values of the streamer zone length of leader in the gaps with length up to 80 meters are experimentally obtained. Extrapolation of these results on the lightning shows that the streamer zone length of lightning with a channel length $L \approx$ 3 km composes only 9.2 m.

Electric field intensity in the streamer zone of positive leader composes $E_s \approx$ 5 kV/cm and not depends on the gap length. This allows to calculate the potential of leader head in lightning. So, at the streamer zone length ℓ_{str} = 10 m the potential of leader composes φ_ℓ = 5.0 MV.

A next characteristics essentially influence on the striking probability of objects: position of object in the discharge gap, degree of field distortion byobject and degree of compensation of inductive charge by the charge of streamer zone. It is necessary to take into account these effects at the determining of the orientation height of leader.

It is shown that the contrary discharges, developing from the object, also essentially influence on the striking probability.

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