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Experiments with the Active Impact of Steam Jet on Atmospheric Electric Field

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Abstract—We present the results of experiments dealing with a study of the effect of artificial vapor-water cloud (VWC) on the atmospheric electric field (AEF). The experiments were performed on September 19, 2006, at Kamchatka heat-and-power water field in the region of the operational Mutnovskaya power plant. We had simultaneously measured the AEF intensity (by three sensors), air electroconductivity, the electric potential of drill hole, and the meteorological parameters in the immediate vicinity of geothermal drill holes, which were opened and closed for duration of the observations. It is found that the dependence of the intensity of the electric filed on the liquid water content in the vapor-water mixture of the drill hole varies throughout the duration of the VWC persistence. Models are proposed and the results of the experiment are discussed.

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INTRODUCTION

In September 2006, the authors had the opportunity to repeat an experiment dealing with the active action on the atmospheric electric field (AEF) of an artificial vapor-water cloud (VWC) formed as the suspended geothermal well was open during the technologic exhaust of superheated steam. In the first (2004) experiment [1], we found that the AEF intensity E during the formation of VWC had decreased (by $\Delta E \approx$ 100–200 V/m) without any change of polarity and then returned to its previous value. In [1] we also noted that the formed artificial cloud possessed an electric charge, though the sign of the charge and its physics were not well understood. The period of a single measurement at the drill hole in the 2004 experiment was set by us to be unequal: at one drill hole, the measurements lasted a little longer than one hour, and at the other two they were 10 min long, which was found to be insufficient for processing. In the 2004 experiment, we used only one AEF sensor which was carried from one location to another during observation. This was very inconvenient and prevented us from obtaining the full pattern of the phenomenon of active action on the AEF. We took into account all these shortcomings and did all we could to overcome them in repeated experiments.

EXPERIMENTAL

The 2006 experiments were performed in the region of the operational Mutnovskaya power station at two drill holes of heat-and-power water (vaporhydrotermas); at one (first) of them, the AEF variations were measured in the 2004 experiment. The vertical AEF component E_z was measured by three Gradient M3 electric fluxmeters, an Elektroprovodnost-2 electrical air conductivity sensor, and a system for signal digitization and digital recording. The electroconductivity sensor is assembled in the form of a double aspiration measuring capacitor. The sensor consists of a cylindrical plate, an internal collecting plate, an entrance pipe, and an aerosol protector. Voltage is applied to the plates and the current is measured. One capacitor measures the conductivity of positive lightweight ions, and the other measures the conductivity of negative ions. Each capacitor measures the conductivity in the range ±25 F cm m^{-1}.

One of the AEF sensors, namely Gradient M3, was installed in the immediate vicinity of the drill-hole nozzle at the upper area segment of the metallic casing; the others were 20 and 40 m away from the drill hole. The Elektroprovodnost-2 device, data digitization system, and computer were 20 m away from the drill hole. Thus, the maximum separation of the electrometer from the drill hole was 40 m, because the measurement cable was as short as 20 m. It was hypothesized that the larger the height of the vapor exhaust is, the greater the distance at which its influence on AEF will be significant. However, when the drill hole was opened, it had been clear that this separation was underestimated. The exhaust height at the first drill hole was much higher in the 2006 experiment than 2004 (150, as opposed to 30 m high steam jet). This was not the only difference in the hole's characteristics in the 2006 experiment. The first and second drill holes substantially differed in that the

Table

	I	II	III	IV
λ_+	↑	↑	↓	=
λ_-	↓	↑	↓	↓
E	↓	↑	↑	↑

Note: ↑ indicates growth, ↓ indicates decrease, and = indicates constancy.

injection rate of vapor-water mixture was 115 kg/s with 22% vapor content at the first drill hole and 14–15 kg/s of 100% pure (water-free) vapor at the second drill hole. At the moment that the first drill hole was opened, the percentage ratio of the vapor in the course of the experiment increased; then the drill hole rapidly saturated into its main characteristics, and the emission rate and, correspondingly, liquid water content of the steam jet increased. At this point, a huge amount of water fell on the instrumentation, and the experiment had to be stopped. In the paper, we use only the fragment of the records for which the amount of liquid water in the vapor-water mixture had decreased. The steam jet in the second drill hole was practically dry. This provides the opportunity (unlike in the 2004 experiment, when all three drill holes were "water-contaminated") to compare the results of the action of both dry and wet steams on AEF, and, of course conditionally, to consider the experiment with the dry drill hole as if it were a continuation of observations at the first drill hole, which contained 78% of water.

During our experiments, we measured the potential at the upper edge of the metallic casing of the drill holes. In both cases, the initial potential before the hole opened was approximately 300 mV. After the holes were opened, the potential decreased on average by 100 mV. This means that, at the edge of the hole at work, an additional positive electric charge was created. It should be noted that, sometimes during hole operation, the potential started rapidly changing in value and even sign. This was seemingly due to variations in the parameters of the steam jet, such as water concentration among others. An estimate of the density of the additional electrical charge in an exhaust cloud that we derived earlier from AEF variations [1] showed that the density of the charge is in the range 10^{-9}–10^{-10} C/m^3. For cloud with a volume of $\approx 10^4$ m^3, its electric charge will be $\approx 10^{-6}$ C. Since the characteristic time of increase (decrease) in E as the hole opens (closes) is approximately 5 min, the electric current of the hole varies in the range 10^{-7}–10^{-9} A.

It was especially interesting to verify the deduced electric current by direct measurements. Of importance here is not only the value of the current but also its "direction," which is indicative of the sign of the charge. If we could record the variations of the direction and value of the current of the drill hole, it would confirm our speculation about the change of the water regime of steam release. So far we can only presume that when the E field increases and the positive electric conductivity predominates, the drill hole injects "dry" steam. This means that, at the edge of the pipe, a positive charge had to appear, which was precisely what our galvanometer recorded. Subsequently, the positive charge was discharged to ground via the steel pipe of the drill hole.

RESULTS

Data of both experiments are depicted in Fig. 1, which presents the time variations of AEF at distances of 20 and 40 m and data of electroconductivity measurements at a distance of 20 m from the drill hole. The data of AEF recording from the sensors, which were installed in the immediate vicinity of the output pipe, are not presented in view of their small information content. Figure 1 distinguishes four stages of the first experiment: (0) behavior of AEF parameters before hole opening and sensor calibration; (I) decrease (↓) E, increase (↑) λ_+, and decrease of λ_-; (II) beginning of the increase of E, λ_+, and λ_-; and (III) further increase of E and decreases of λ_- and λ_+. At this moment the experiment was terminated due to an abrupt blowout of water onto the instrumentation. On the right-hand side of Fig. 1 there are the data obtained at the second "dry" drill hole. As will be shown below, in principle, they can be conditionally viewed as the final stage of the experiment, initiated with the first drill hole; therefore they are designated as stage IV of the experiment, in which AEF continues to increase for lowering λ_- and almost constant λ_+ (see Fig. 1 and table).

Variations of E_z recorded by two sensors located at distances l equaling 20 and 40 m from the drill hole provide a crude estimate of the $E(l)$ dependence. It appears that, at the dry drill hole, the field decreases: $E \sim l^{-1}$ in the first case and $E \sim l^{-1/2}$ in the second case. However, this estimate rather shows the charge distribution inside the zone of influence of the vapor cloud and not the variation of the field far from the source of AEF perturbation; therefore, this does not bear on the character of the E_z field drop with the distance from its perturbation source. For instance, we showed earlier that the AEF variation with distance r from the cyclone has well-defined quadratic dependence $E_z \sim 1/r^2$ [2].

A preliminary analysis of the experimental results presented in Fig. 1 shows that the variations of the electroconductivity λ_+ and λ_- practically always coincide in time with variations of the field E, although, as follows from Fig. 1 and the table, these relations are not unique. This is probably because the AEF param-

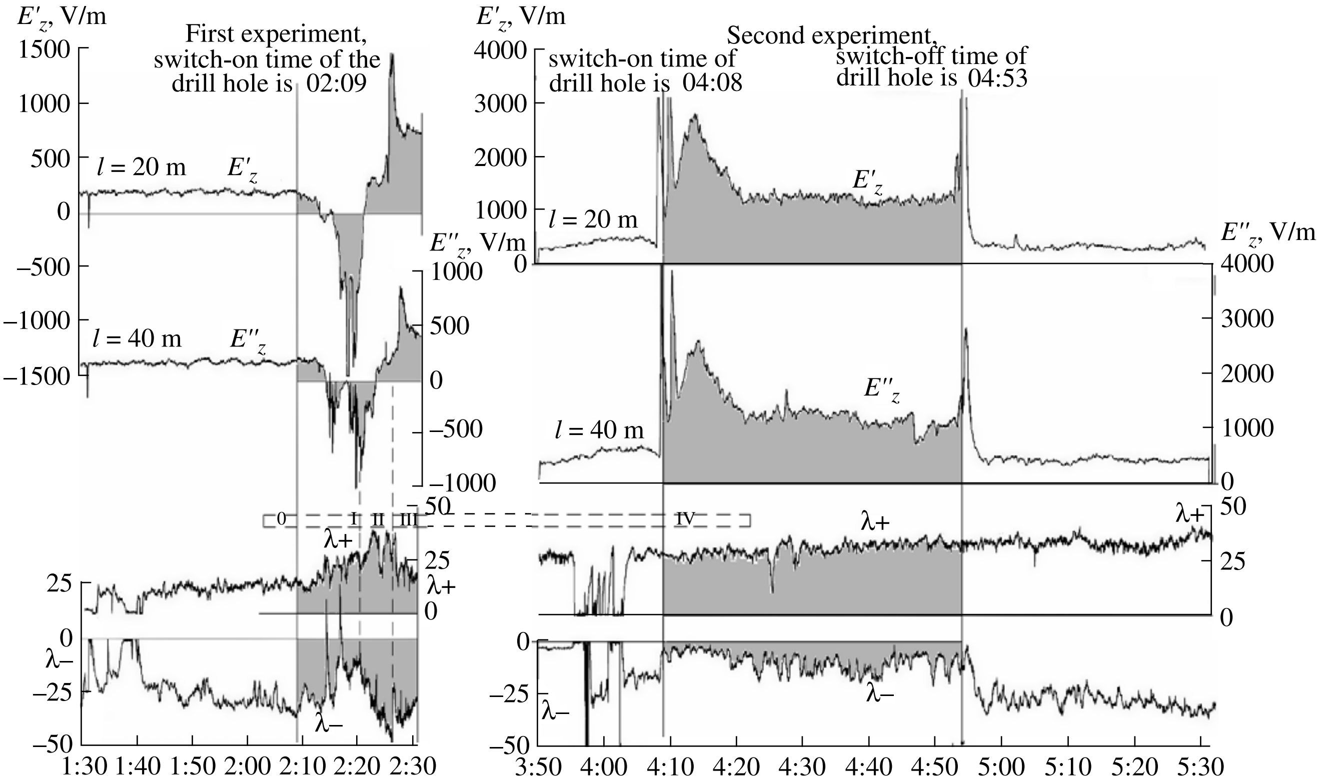

Fig. 1. Results of E_Z, λ_+, and λ_- measurements at two thermal drill holes.

eters were measured in the immediate vicinity of the ground or, in other words, the sensors were located on the ground (except for the sensors of the field, which were installed at a height of 7 m on well-conducting protective casings). However, these sensors supplied no additional information because, when the drill hole was opened, they were quite rapidly covered by falling water. We note that we studied only two first stages in the 2004 experiment (I and II), and then the observations were stopped. In these experiments, the field E decreased almost to zero, but the sign of the field did not change.

INTERPRETATION OF RESULTS

The measurements of the AEF variations in the near-ground region are especially difficult to interpret because in this region the so-called electrode effects (EEs) [3] occur, caused by the proximity of the studied conducting atmospheric layer to the well-conducting earthís layer ("electrode"). In what follows, the obtained results will be interpreted using the theory developed for describing EE and keeping in mind that the variations of electric field and conductivity observed in the experiment are explained primarily by the effects of charge separation in the vapor-water mixture and by the interaction of ions with mixture constituents and only secondarily by the interaction with the Earth's surface (i.e., by the proper electrode effect). There is no general theory of atmospheric electricity, so we will use the theory of electrode effects for a preliminary interpretation of results. This theory conventionally uses (instead of the electroconductivity λ_+ and λ_-) the concentration of light-weight positive n_1 and negative n_2 ions and heavy-weight ions N_1 and N_2 respectively:

$$\lambda_+ = eu_1n_1, \quad \lambda_- = eu_2n_2,$$

where e is the electron charge and u (cm^{-2} s^{-1} V^{-1}) is the mobility of light-weight ions.

Time variations of light-weight ion concentration are described by the equations [3, 4]:

$$dn_1/dt = q - \alpha n_1n_2 - \eta_{12}n_1N_2 - \eta_{10}n_1N_0,$$

$$dn_2/dt = q - \alpha n_1n_2 - \eta_{21}n_2N_1 - \eta_{10}n_2N_0.$$

Here, q is the ionization rate, α is the recombination coefficient between light-weight ions, η_{12} is the rate of sticking of light-weight positive to heavy-weight negative ions, η_{21} is the rate of sticking of light-weight negative to heavy-weight positive ions, η_{10} is the rate of sticking of light-weight positive ions to neutral molecules, etc. All three terms following in the equation after q quantify the rate of decrease of ions of the corresponding sign.

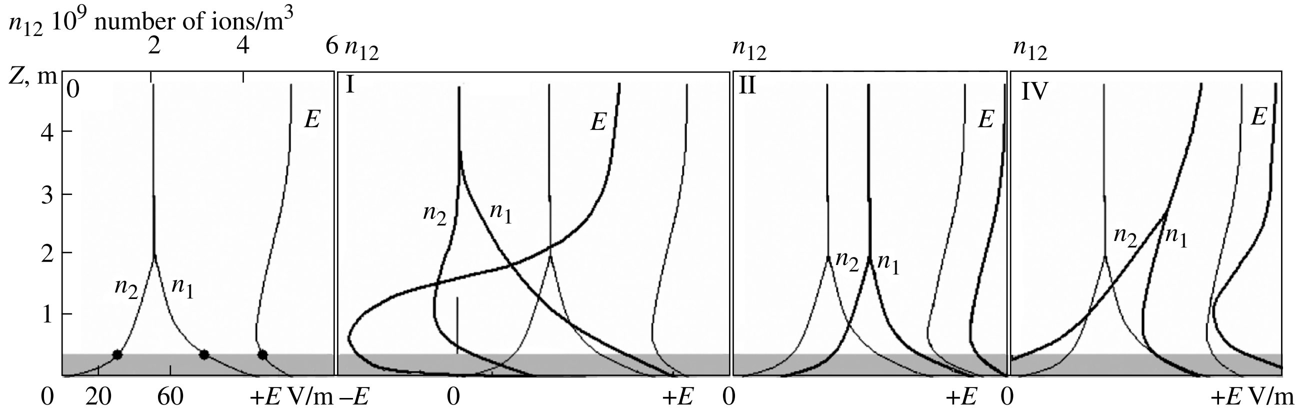

Fig. 2. Altitude distributions of AEF (E) and concentrations of positive (n_1) and negative (n_2) light-weight ions for four situations: initial situation (0), situations (I, II), depicted in Fig. 1 for the first experiment, and the final stage (IV) of the second experiment. The dark strip shows the altitude region where the electrode effect is manifested and where the measurements were performed. Closed circles in situation (0) indicate the initial AEF parameters.

Changes of the field E with height (z) and time (t) in EE region are described by the equations

$$dE/dz = e/\varepsilon_0(n_1 - n_2 + N_1 - N_2),$$

$$dE/dt = ze/\varepsilon_0(dn_1/dt - dn_2/dt + dN_1/dt - dN_2/dt)$$
$$= he/\varepsilon_0(dN_1/dt + \eta_{21}n_2N_1 - dN_2/dt - \eta_{12}n_1N_2).$$

From these equations it follows (replacing h by z) that AEF increases along with an increasing n_2 and N_1, and vice versa. The field E increases with the appearance of dry vapor with a positive charge in the atmosphere, and it decreases when negatively charged water droplets appear. This conclusion was confirmed, though it should be remembered that the instruments in our experiments could measure the conductivity only of light-weight ions. In addition, according to the conditions of the experiment, we only recorded the time variations of the AEF parameters and could not study their variations with height. Moreover, it is obvious that such a replacement is valid only if the concentrations are homogeneous in space. The theory of electrode effects considers the variations of the parameters E, n_1, and n_2 with height. Let us use the formula for dE/dt, which will allow us to interpret the results of variations of AEF parameters in time by means of the EE model in the form dE/dz [3, 4].

Figure 2 (0) presents the typical distribution of the parameters E, n_1, and n_2 characteristic for EE [3]. It is usually considered [3, 4] that the EE region (in other words, the region of anomalous behavior of AEF parameters) is confined from above by a 3 m height, as is shown in Fig. 2 (0). Figure 2 shows possible static situations corresponding to the dynamic development of the process of VWC action on the AEF parameters in the EE zone; these situations correspond to separated time intervals (I–IV):

In situation I, $n_1 \sim \uparrow$, $n_2 \sim \downarrow = E(\downarrow) \longrightarrow (n_1 + N_1) < (n_2 + N_2) \longrightarrow N_1\downarrow, N_2\uparrow$. There is a growth in the concentration of heavy negative ions and decrease in the concentration of heavy positive ions. This phenomenon is due to the injection of a large amount of water; it introduces, through the split of water (the so-called Lenard effect), the negative charge into the air. A situation analogous to ours is observed near waterfalls, such as near Victoria Falls. Due to a split in the water, an electric field of the opposite sign and an intensity of up to 25 kV/m appears (http://class-fizika.narod.ru/w21.htm). In our experiment the field E also changed in sign and reached (1.5–2) kV/m,

In situation II, $n_1 \sim \uparrow$, $n_2 \sim \uparrow = E(\uparrow) \longrightarrow (n_1 + N_1) > (n_2 + N_2) \longrightarrow N_1\uparrow, N_2\uparrow$. The electric field increased, and E passed from the region of negative to positive values. This was seemingly because of the growth of the relative concentration of positive (both light- and heavy-weight) ions. Situation II becomes similar to the initial situation (0), but with higher AEF parameters. The field E reaches the value of +1500 V/m.

In situation III, $n_1 \sim \downarrow$, $n_2 \sim \downarrow = E(\uparrow) \longrightarrow (n_1 + N_1) > (n_2 + N_2) \longrightarrow N_1\uparrow, N_2\downarrow$. The field E starts to gradually decrease, remaining positive and quite large. Positive and negative conductivities both decrease, tending to their initial values.

In situation IV, $n_1 \sim =$, $n_2 \sim \downarrow = E(\uparrow) \longrightarrow (n_1 + N_1) \geqslant (n_2 + N_2) \longrightarrow N_1\uparrow, N_2\downarrow$. The field E remains quite large and positive, and the concentration $n_2 \sim$ decreases, seemingly by recombining with the positive light-weight ions, whose concentration, like the heavy-weight ion concentration (N_1), increases until reaching the saturation of the counter of the positive ions. Again, this situation echoes the initial situation; however, it differs in that both the field E and the concentration of the positive ions are greater than in the free atmosphere. This may signify that the dry steam consists of a considerable amount of heavy-weight positive ions. The generation of an additional positive charge from dry steam jet leads to increase of the field E and $dE/dz = e/\varepsilon_0(n_1 - n_2 + N_1 - N_2)$.

Thus, the introduction of an additional positive charge into the atmosphere by the dry steam jet leads to an increase of AEF, making it possible to take another look at the AEF model. Suppose that a decrease in the concentration of the positive ions ($n_1 + N_1$) reduces the field E in such a way that when the concentration ($n + N_1$) becomes equal to the ion concentration of the unperturbed atmosphere, E will also return to its steady-state value. This suggests that AEF is controlled not only (and not very much) by lightning, as was convincingly shown recently [5], but mainly by the generation and separation of charges immediately in the atmosphere itself. This conclusion supports the main idea of the cardinally new AEF model [6], which is based on the use of the well-known Frenkel model of separating the electric (heavy negative and light positive) charges in the gravity field [7].

As was already noted above, the opening of the drill hole is accompanied by a decrease in the negative potential (ΔU) by approximately 100–150 mV (ΔU = +100 mV): the sensor measured (300–350) mV before the drill hole opening, and the value being measured then decreased to –200 mV. This means that the steam jet carries the positive charge. The fact that, when the drill hole is opened, a negative charge is generated in the atmosphere does not contradict this statement because the negative charge is probably created beyond the drill hole as a result of a spray of water into small droplets. After the drill hole is opened, the value ΔU = +100 mV remains practically unchanged throughout the experiment. At the same time, a separation of the charges, which is accompanied by a generation of the field $E^* \approx \Delta U/R$, where R is the transverse pipe extent ($R \sim 0.3$ m), associated with charge separation ($Q = \varepsilon_0 R^2 E^* = \varepsilon_0 R^3 \Delta U$), probably takes place at the pipe output. Substituting known values, we obtain $dQ = 3 \times 10^{-13}$ C. This charge is removed from the pipe at the steam injection rate $v \approx 100$ m/s or, in other words, steam with a volume of $\approx R^3$ is injected into the atmosphere per time $t = R/v = 3 \times 10^{-3}$ s, which is equivalent to the current $i = dQ/dt = 10^{-10}$ A.

We estimate the ion formation rate dQ/dt by letting the VWC charge density [1] $N = 2 \times 10^9$ m^{-3}. We will use the equality $dN/dt = \alpha N^2$ and assume that $N^+ = N^-$. Then, knowing the ion recombination coefficient α, we can estimate the charge formation rate in the atmosphere dN/dt. Using the elementary charge e in the formula, we will obtain the charge accumulation rate $dQ/dt = eV\, dN/dt$, where V is the VWC volume (~5×10^4 m^3, and $N^2 = 4 \times 10^{18}$ m^{-3}). Hence, the value $dQ/dt \approx \alpha \times 4 \times 10^4$ C/s. Thus, letting the recombination rate $\alpha \approx 2.5 \times 10^{-16}$ (m^3 s^{-1}), we get $dQ/dt = 10^{-11}$ A. It turns out that the second estimation yields approximately the same value of the electric current (dQ/dt) through the edge of the pipe.

We compare the results obtained in our work with the data of studies of AEF features by other authors [8, 9]. We will survey the data supporting the main conclusion of our paper that the dry steam predominately carries a positive charge, while the water aerosol carries a negative charge. We turn to [8], which presents the results of the measurements of the electric field in fog. That work showed that the presence of fog leads to a reduction of the electric current density and the electric field intensity, which is usually accompanied by a sign change. It was found that, under fog conditions, the amplitude of the AEF pulsations increased. The fog predominately consists of water aerosols (evidently carrying a negative charge). The authors showed that the turbulence of the fog played a great part in AEF formation.

The authors of [9] studied the distribution of electric charges in volcanic plume during the eruption of the Sakurajima volcano on October 28 and 29, 1995. The plume was in the form of a cloud in which there were differently sized soot particles, water aerosol, and water vapor. The measurements were performed simultaneously for two days at five different locations 3–5 km away from the crater of the volcano. The electric charges in the cloud had a nonuniform altitude distribution: there was a positive charge in the upper part of the cloud, a negative charge in the middle part, and another positive charge in the lower part. In the upper part of the volcanic cloud, the water vapor is present, so the positive charge is concentrated. In the middle part of the cloud, there were very small soot particles carrying the negative charge, and in the lower part there were large positively charged soot particles.

The size of "our" cloud, as was noted above, was $\approx 10^4$ m^3, and its charge $\approx 10^{-5}$ C. Let us compare this result with other estimates. As was shown in [2], the cyclone charge could reach 50000 C and, given its size of $\approx 100 \times 100 \times 10$ km^3 = 10^{14} m^3, the volume density of the electric charges $\approx 5 \times 10^{-10}$ C/m^3. The authors of [9] measured AEF during the eruption of the Sakurajima volcano. The negative charge of the volcanic cloud, which was composed of the water vapor and soot, was estimated to be ~0.1 C. The cloud size (judging from the presented photos) was ≈ 1 km^3, so the charge density was $\approx 10^{-10}$ C/m^3. This comparison shows that our estimates of the charge are quite plausible.

It remains necessary to clarify why the water vapor has a positive charge? As [10] showed, the carriers of the positive charge in the water vapor are water clusters $H_5O_2^+$ and H_3O^+ (hydroxonium ions) which actually exist in the atmosphere up to a height of 80 km.

CONCLUSIONS

In our opinion, the results of the experiment support the model presented in [6]; they substantiate the use of the Frenkel model [7] in the free atmosphere. In conclusion, we note that the active experiments dealing with action on the atmospheric electric field of the jet of vapor-water mixture from the thermal drill hole in the region of the Mutnovskaya hydrothermal power station in Kamchatka reveal marked AEF changes. The dry steam injected into the atmosphere produces an increase in the field *E*. At the same time, the injection of water into the atmosphere and its subsequent split contributes the negative charge, leading to a decrease in the field *E* and even a change of its polarity.

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