22. A. I. Vyskrebentsev, "Method of effective accounting for radiation energy transport equations in one-dimensional problems of radiation gasdynamics," Inst. Fiz. Zemli, Akad. Nauk SSSR, Dep. in VINITI, No. 2691-79 (1979).
23. A. I. Vyskrebentsev, "Method of numerical solution of transport equations in one-dimensional gasdynamics problems," Zh. Vychisl. Mat. Mat. Fiz., 21, No. 5, 1206-1214 (1981).
24. A. P. Golub', "Finite-difference approximation for averaged radiation transport equations," Inst. Fiz. Zemli, Akad. Nauk SSSR, Dep. in VINITI, No. 282-79 (1979).

AN EXPERIMENTAL INVESTIGATION OF EGD FLOW OF GAS IN A CORONA DISCHARGE AND ITS INFLUENCE ON THE MOTION OF DISPERSED PARTICLES

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The procedure and results of an experimental investigation of the EGD gas flow accompanying a corona discharge — the electric wind — are presented. It is shown that the motion of dispersed particles in a corona discharge is determined mainly by the electric wind.

The motion of gas-dispersed streams in the field of a corona discharge takes place in a number of technological devices. Such devices include electric filters, electrostatic separators, devices for depositing various coatings, etc. The processes taking place in such devices are extremely complicated, and their description is often associated with great mathematical difficulties. Therefore, experiment still remains the principal method of investigating these processes.

The most often encountered method of analyzing the behavior of dispersed particles in the field of a corona discharge, placed at the foundation of the design of such apparatus, is based on the determination of the Coulomb forces acting on particles charged through ion sorption and the forces of hydraulic drag (Stokes forces) [1-3]. In the simplest form this approach yields the following equation of motion of a spherical charged particle in an electric field:

$$m\frac{d\bar{v}}{dt} = q\bar{E} - 6\pi\mu a\bar{v} \pm m\bar{g}. \qquad (1)$$

Different variants of Eq. (1) are possible, allowing for nonuniformity of the electric field, variability of the particle charge, etc. However, such an approach does not allow for the influence on the motion of the dispersed particles of the EGD flow accompanying a corona discharge in gases — the electric wind. The mechanism of its generation is this. In a unipolar corona discharge, when the corona-forming electrode is the cathode, negative gas ions are formed near the latter. Under the action of the electric field they move toward the oppositely charged electrode and, in the process of motion, in colliding with the neutral gas molecules they impart kinetic energy to them: $\varepsilon_i = m_i\bar{v}_i^2/2$.

The energy obtained by a neutral molecule in a collision with an ion is determined by the relation $\varepsilon_n = (m_n m_i^2(1-\cos\theta)\bar{v}_i^2/(m_i + m_n)^2$.

In air, in particular, the masses of the O_2^-, O_3^- and other ions formed in a corona discharge are close to the mass of a neutral molecule. Therefore, an estimate of the efficiency of kinetic-energy transfer provides a basis for assuming that in each collision act, the energy of an ion is fully transferred to a neutral molecule. The collision frequency is determined by the gas density and the ion velocity, which depends in turn on the gas temperature and the magnitude of the electric field. Mass motion of the gas directed away from the

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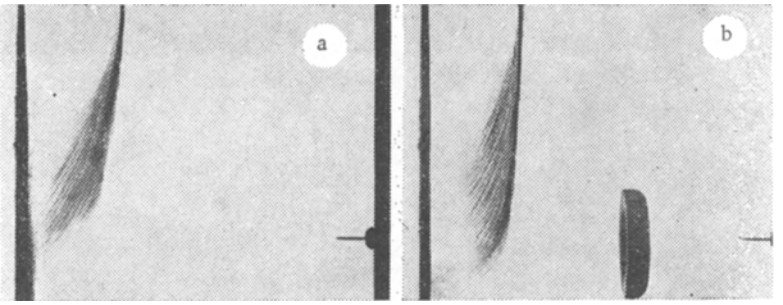

Fig. 1. Destruction of a stream of spheres: a) by an electric wind in a spike—plane gap; b) by a stream of neutral gas initiated by the electric wind in a spike—ring gap.

corona-forming electrode develops as a result of such an interaction — an electric wind, the velocity of which can reach 5-10 m/sec or more [4, 5], whereas the technological velocity of motion of gas-dispersed streams in such devices as an electric filter, e.g., does not exceed 1-2 m/sec. The influence of the electric wind on the destruction of a freely falling stream of glass spheres $1 \cdot 10^{-4}$-$1.25 \cdot 10^{4}$ m in diameter in the field of a coronal discharge in a spike—plane electrode system is shown in Fig. 1a. It is seen that at sufficiently high voltages and correspondingly high velocities of EGD flow a region free of particles forms between the electrodes. An analysis of the particle trajectories shows that the particle motion is determined mainly by the jet flow of the electric wind, while their velocity is five to seven times higher than what they could acquire in an electric field due only to the Coulomb force with a realistic amount of particle charge.

If in the same electrode system one places one more ring electrode, at the same potential as the plate, directly in front of the corona-forming spike (Fig. 1b), all the negative ions will recombine on it, which is confirmed by the absence of current from the plane electrode. Thus, the same stream of spheres placed between the ring and plane electrodes will be in a region free of the space charge of ions and in the absence of an electric field. However, the average-mass velocity acquired by the gas in the gap between the spike and the ring electrode proved to be high enough that the trajectories of the spheres remained practically the same as those observed in the first case. This confirms the assumption that the influence of the mechanical action of EGD flow on the dispersed particles overwhelms the Coulomb influence.

In the next step we determined the excess of total pressure on the plane electrode due to the impingement on it of the jet of electric wind in the spike—plane electrode system. The distance L between the electrodes along the axis of the system was 0.05, 0.075, 0.10, and 0.125 m, while the voltage was varied from 20 to 70 kV with a step of 10 kV. As the corona-forming electrode we used a polished tungsten needle with a radius of rounding of the point of 10^{-5} m. A copper plate, which could be moved in its own plane, served as the anode. The total head of the stream of electric wind was determined with a capillary, soldered to the center of the plate, with an inlet opening $6 \cdot 10^{-4}$ m in diameter and connected to an MKV-250-0.02 micromanometer. The experiment was run on air at a temperature of 19 ± 1°C and a humidity of 50 ± 2%. The high-voltage source had an applied-voltage instability of no more than 1%.

The values obtained for the pressure excess over atmospheric allow us to estimate, using the Bernoulli equation, the average-mass velocity of the air stream — the electric wind — or, more precisely, of the component V_x normal to the surface of the plane electrode.

The distribution of the ionic current density over the plane electrode was determined by measuring the current with an F-116/1 instrument from each of concentric rings etched in the copper coating of the dielectric from which the plane electrode was made in this case. The width of the rings was $4 \cdot 10^{-3}$ m and the gap between them was $1 \cdot 10^{-3}$ m. The corona-forming electrode was mounted opposite to the plane electrode in such a way that the axis of the system passed through the spike and the center of the concentric rings.

A comparison of the data on the velocity V_x of the electric wind and the distribution of current density j (Fig. 2) shows their good correlation. As is seen from the functions presented, the region of the plane electrode lying directly opposite the corona-forming spike

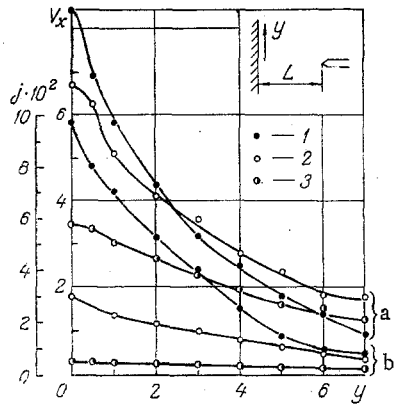

Fig. 2. Distribution over the surface of the plane electrode of: a) the normal component V_x of the electric wind (m/sec); b) the ionic current density j (A/m^2): 1) L = 0.05 m; 2) 0.075 m; 3) 0.125 m; U = 60 kV; y, 10^{-2} m.

is characterized by the highest values of the normal component of the velocity of the gas stream and the current density. Their values decrease rapidly with greater distance from this region, which allows us to speak of a certain localization of the effect. When a system of spikes is present, as is observed in the majority of actual devices, overlapping zones with high velocities of electric wind should exist, leading to the development of closed vortices, greatly complicating the hydrodynamic pattern in the interelectrode space. It should be noted, however, that in the vicinity of the point y = 0 the influence of neighboring spike electrodes will be unimportant, and this can be considered as a characteristic point for the electrode system being studied. The measurement results presented in Fig. 3 show that the velocity V_0 of the electric wind at the axis of the discharge gap depends linearly on the applied voltage U and depends on the square root of the current density j in the investigated range of the parameters.

The velocity field of the electric wind in the same electrode system was determined in the next step of the investigation. To obtain reliable data we had to measure the magnitude and direction of the gas velocity in the entire discharge gap without disturbing the electric field configuration or the hydrodynamic flow structure. This was achieved through the use of a multicomponent laser Doppler anemometer (LDA), the optical scheme of which is described in [6]. To make the measurements, a moving platform with the spike–plane electrode system was fastened to the optical bench of the LDA system. The platform could be moved relative to the measurement volume of the LDA, formed by the intersecting beams of an LG-38 laser passing through the stationary optical system. The laser radiation was scattered on smoke particles no more than $0.5 \cdot 10^{-6}$ m in size supplied directly to the corona-forming spike. A calculation by the method presented in [7] shows that the velocities of particles of this size can be fully identified with the velocity of the gas stream at the actual velocities of the electric wind. However, the smoke particles, entering the region of the corona discharge become charged and can move independently toward the plane electrode under the action of the electric field. An elementary analysis of these processes shows that the maximum velocity of charged smoke particles under the influence of Coulomb forces does not exceed $1 \cdot 10^{-3}$ m/sec, which cannot noticeably affect the measurement results.

The axisymmetric geometry of the investigated electrode system allowed us to confine ourselves to the measurement of two velocity components of the EGD stream: that normal to the surface of the plane electrode and that directed along it. The measurements were made in the same range of voltages and interelectrode distances as in the experiments described above.

The results of the measurement of the velocities of the electric wind using the LDA for a distance $L = 12.5 \cdot 10^{-2}$ m between the electrodes and a voltage U = 60 kV, i.e., under conditions characteristic of industrial apparatus, are presented in Fig. 4, where the interaction of the gas-dispersed stream with the electric wind is shown. The air stream, containing spherical glass particles $15 \cdot 10^{-6}$–$40 \cdot 10^{-6}$ m in diameter as the dispersed phase, passed through the vertical chamber from top to bottom at an average velocity of 1.5 m/sec. The

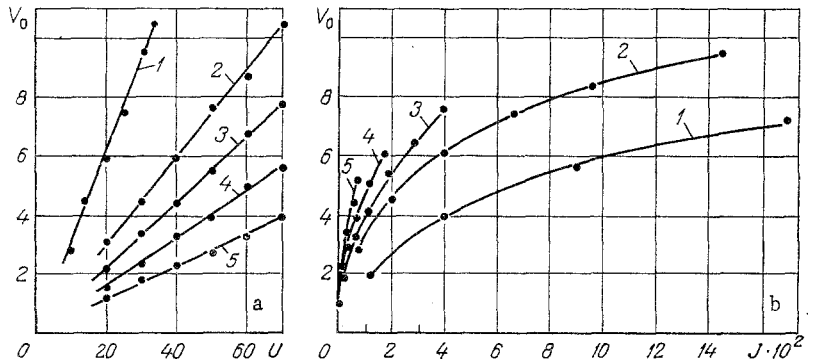

Fig. 3. Dependence of the velocity V_0 of the electric wind (m/sec) at the axis of the discharge gap (y = 0) on: a) the voltage U on the electrodes (kV); b) the ionic current density j (A/m^2): 1) L = 0.025 m; 2) 0.05; 3) 0.075; 4) 0.1; 5) 0.125 m.

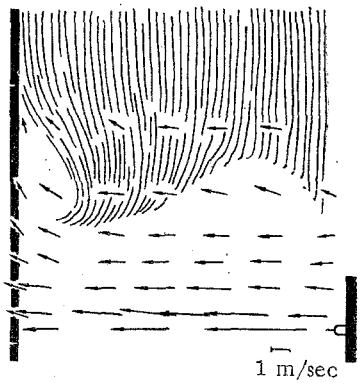

Fig. 4. Superposition of the measured velocity field of the electric wind onto the pattern of its interaction with the gas-dispersed stream.

weight concentration of particles was $3 \cdot 10^{-2}$ kg/m^3. The stream was illuminated through a vertical slit in the plane electrode. The measured velocity field of the electric wind, obtained, however, in the absence of transverse ventilation of the discharge gap, is also shown here. From these data it follows that the velocity of the electric wind in the direction of the plane electrode is rather high even in the peripheral regions of the corona discharge, where the space-charge density and the electric field strength are low.

Thus, the results presented indicate the determining influence of EGD flow on particle motion in gas-dispersed streams in the field of a corona discharge.

NOTATION

V_x, velocity component of the electric wind normal to the plane electrode; V_0, velocity of the electric wind at the axis of the discharge gap; U, voltage on the electrodes; j, ionic current density over the surface of the plane electrode; L, distance between the electrodes; y, coordinate of the measurement point; m, mass of a dispersed particle; v, velocity of particle motion; t, time; q, particle charge; E, electric field strength; μ, dynamic viscosity of the gas; a, particle diameter; g, free-fall acceleration; ε_i, ε_n, kinetic energy of an ion and of a neutral gas molecule; m_i, m_n, mass of an ion and of a neutral gas molecule; v_i, ion velocity; θ, angle of deviation of an ion after impact.

LITERATURE CITED

1. S. L. Soo, "Dynamics of charged suspensions," in: The Rheology of Suspensions [Russian translation], Mir, Moscow (1975), pp. 140-284.
2. R. Boothroyd, Flowing Gas—Solids Suspensions, Chapman and Hall, London (1971).
3. I. P. Vereshchagin, V. I. Levitov, G. Z. Mirzabekyan, and M. M. Pashin, Principles of the Electrogas Dynamics of Dispersed Systems [in Russian], Énergiya, Moscow (1974), pp. 170-246.
4. A. G. Gagarin and V. Kh. Vigdorchik, "Convective heat exchange between a gas and a flat wall in the field of a corona discharge," Elektron. Obrab. Mater., No. 2, 45-47 (1981).
5. I. B. Rubashov and Yu. S. Bortnikov, Electrogas Dynamics [in Russian], Atomizdat, Moscow (1971).

6. J. E. Rizzo and N. A. Halliwell, "Multicomponent frequency shifting self-aligning laser velocimeters," Rev. Sci. Instrum., 49, No. 8, 1180-1185 (1978).
7. G. L. Grodzovskii, "Motion of fine particles in a gas stream," Tr. Tsentr. Aerogidrodin. Inst., Issue 1755, No. 2, 3-12 (1972).

CHARACTERISTICS OF CHARGE TRANSPORT IN THE DISPERSE PHASE OF ELECTRORHEOLOGICAL SUSPENSIONS

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The role of proton mobility in the polarization and conductivity of electrorheological suspensions is estimated on the basis of measurements of the shearing stress and conductivity of aluminum dihydrotripolyphosphate (AlTP) in transformer oil and of thermal changes in NMR spectra for AlTP.

The mechanical characteristics of suspensions of some substances in dielectric liquids to which an electric field is applied vary in relation to the specifics of development of the disperse phase structure, which, in turn, are determined by the nature of polarization of individual particles and the conditions of charge transport along interelectrode bridges [1-4]. The criteria for deciding upon the disperse phase of electrorheological suspensions have not yet been elaborated; however, it has been noted that variation of the suspension characteristics that have practical importance (e.g., a marked increase in the effective viscosity) at moderate (of the order of $(1-5) \cdot 10^6$ V/m) field strengths is observed in systems whose disperse phase has proton conductivity.

At the present time, the active components used in electrorheological suspensions comprise mainly dielectric materials with a highly developed external surface (Aerosil, diatomite, clays, etc.) carrying an adsorbed protogenic activator (water, amine, or an organic acid) [1]. In correspondence with this, it is assumed that the basic contribution to the polarization of such particles is provided by directional diffusion of protons in the adsorbed layer at the interphase boundary [4]. The principal disadvantage of such suspensions is that the amount of activator adsorbed by the particles depends heavily on the external conditions, which makes it difficult to ensure reproducible suspension characteristics.

It can be assumed that substances with a steady composition and marked proton conductivity are free from this disadvantage. The requirements imposed on the disperse phase of electrorheological suspensions should also be met by weakly hygroscopic layered hydroxides, where charge transport within individual microcrystals can occur in the interlayer space at a rather high rate, since it is not accompanied by diffusion of the basic structure-forming elements of the material. In correspondence with this, our aim is to elucidate the role of proton transitions in the conductivity and polarization of certain hydrated substances of constant composition.

We investigated aluminum dihydrotripolyphosphates with the composition $H_2AlP_3O_{10} \cdot 2H_2O$ (AlTP) and a layered structure, which were synthesized in accordance with [5], and also some simple hydrates — aluminum and iron dihydrophosphates and nickel and cobalt selenites. The suspensions based on mineral oils (in particular, transformer oil) with mass concentrations of particles equal to 5 and 10% were prepared by mechanical grinding with subsequent ultrasound dispersion. The mean size of microcrystals in the suspension was equal to 5 μm, while the theoretical external surface area was equal to 0.2 m^2/g. The surface area of AlTP specimens dehydrated at 473°K, determined with respect to low-temperature adsorption of nitrogen, was approximately equal to 5 m^2/g. Specimens characterized by an intermediate degree of hydration in comparison with the above formula unit were obtained by moistening to the re-

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