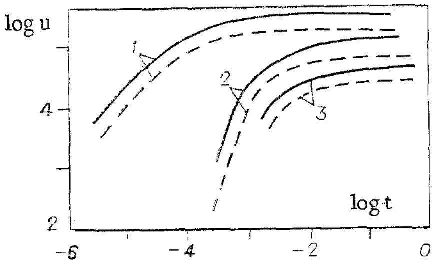

Fig. 3

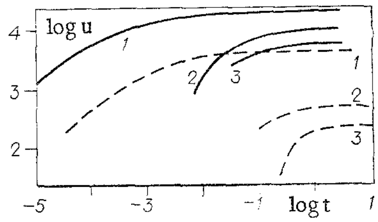

Fig. 4

In Fig. 4 we show the results of a similar calculation but for a lower initial density ($\rho_0 = 2\cdot10^{-4}$ kg/m^3). A regime close to the regime of "total freezing" occurs in this case. It is seen that the time of the start of dispersal for the real value of $\gamma(t, m)$ increases by an order of magnitude compared with the value calculated for $\gamma = 1.4$, while the velocity of dispersal for $\gamma = 1.4$ is five times higher than for the actual function $\gamma(t, m)$.

The method proved to be sufficiently effective in the examples considered. The function $\gamma(t, m)$ was determined by the method of successive approximations. Two iterations provided an accuracy of $\sim$5%, indicating rapid convergence. The system of CK equations was calculated at five points in space, which was sufficient to achieve an accuracy of $\sim$5% in the interpolations of γ. It will be interesting to extend the described method to a wider class of gasdynamic problems with strong nonequilibrium.

In conclusion, the authors sincerely thank I. A. Devyaterikov, E. A. Ivanov, and V. P. Kudryavtsev for useful discussions in the course of the completion of this work.

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ELECTROHYDRODYNAMIC PROBING OF HIGH-VELOCITY AEROSOL FLOW BY MEANS OF A CORONA DISCHARGE

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The charging of disperse aerosol particles as they move through a uniform, unipolar corona discharge whose electric field is directed along the aerosol flux was investigated in [1]. The effect of gas motion on the corona discharge characteristics, which is considerable at aerosol velocities $u \gtrsim bE$, where E is the electric field strength and b is the ion mobility, was taken into account in these investigations. On the basis of the results obtained in [1], we investigate here the macroscopic electrohydrodynamic methods of calculating the mean parameters of high-velocity aerosol fluxes in a uniform corona discharge that do not require complex microscopic measurements.

1. Consider the steady-state flow of aerosol consisting of a gas and disperse liquid particles between two flat, round grid electrodes, positioned perpendicularly with respect to the aerosol flux. Assume that in order to produce a corona discharge a system of points oriented along the aerosol flux and starting to display corona at the emitter potential $\Phi_0 > 0$ is mounted on the emitter electrode; the collector electrode is grounded (its potential

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 52-58, May-June, 1985. Original article submitted September 6, 1983.

0021-8944/85/2603-0347$09.50

is used as the zero potential); the aerosol moves through the interelectrode gap from the emitter to the collector. Approximating the corona points by semiellipsoids of revolution, we shall estimate the initial electric field strength at which the corona discharge is fired. As is known [2-4], a corona discharge develops in sharply nonuniform fields if the condition for a self-maintained gas discharge is satisfied:

$$\int \alpha(E)\,ds = K, \tag{1.1}$$

where α is the effective ionization coefficient. For air at normal atmospheric pressure and temperature, the dependence of α on the electric field strength E can be approximated by the expression [3-5]

$$\alpha(E) = A(E - B)^2, \tag{1.2}$$

which provides good agreement with experimental values up to $E = 1.2\cdot10^7$ V/m [3-5]. The experimentally obtained values of the coefficients $B = 24.5\cdot10^5$ V/m and $\sqrt{K/A} = 6.5\cdot10^4$ V/m$^{1/2}$ are given in [3].

We shall consider the case where the following inequalities are satisfied:

$$h \gg l \gg \Delta, \tag{1.3}$$

where h is the spacing between the corona points of the grid emitter, l is the length of the points, and Δ is the meshsize in the grid. The distribution of the electric field strength around each point is then close to the field distribution around a single corona point, fastened to an infinitely large metal plate. We write the equation for determining the electric field strength causing firing of the corona discharge in the case of a single corona point by using Eqs. (1.1) and (1.2) and the corresponding approximate expressions for the distribution of the field strength E near corona electrodes of any shape that have been derived in [3]:

$$\int_0^{x^*} A\left[E_l\frac{r^2}{(r+x)^2} - B\right]^2 dx = K. \tag{1.4}$$

Here E_l is the electric field strength at the tip of the point, r is the principal curvature radius at the end of the semiellipsoid of revolution approximating the point, x is the distance from the end of the point along the normal to it, and x* is the value determined from the condition

$$\alpha(x^*) \equiv A\left[E_l\frac{r^2}{(r+x^*)^2} - B\right]^2 = 0.$$

After performing the integration in (1.4), we obtain an equation for determining the electric field E_l causing firing of the corona discharge:

$$E_l^{*2} - 6E_l^* + 8\sqrt{E_l^*} = 3\left(\frac{K}{AB^2r} + 1\right),\ E_l^* = \frac{E_l}{B}. \tag{1.5}$$

For instance, assume that the thickness and the length of the corona point are equal to $2m = 2\cdot10^{-3}$ m and $l = 5\cdot10^{-3}$ m, respectively. Then $r = m^2/l = 2\cdot10^{-4}$ m. We find $E_l^* \simeq 4.9$ from (1.5) and, thus, $E_l \simeq 1.2\cdot10^7$ V/m and $E = E_l r^2/(r + x)^2 \leqslant 1.2\cdot10^7$ V/m.

Before the corona discharge firing, the electric field distribution around a single point having the shape of a semiellipsoid of revolution fastened to a metal plate coincides with the electric field distribution in the case of an uncharged conducting ellipsoid of revolution, located in an external uniform electric field whose strength is directed along the ellipsoid's major axis and is equal to the strength E_0 of the electric field remote from the metallic flat surface with the point. Therefore, the electric field strength at the tip of the point E_l is expressed in terms of E_0 by means of the equation [6]

$$E_l = \frac{2e^3E_0}{(1-e^2)\left(\ln\frac{1+e}{1-e} - 2e\right)},\quad e \equiv \sqrt{1 - \frac{m^2}{l^2}}. \tag{1.6}$$

If we know the dimensions of the corona point m and l and the value of E_l, we can readily determine by means of expression (1.6) the electric field strength E_0 at the distance $L \gg l$ from the electrode at which the corona discharge is fired. For instance, let $E_l = 1.2\cdot10^7$ V/m. Then, for the above values of m and l, we have $E_0 = 6.74\cdot10^5$ V/m. If the inequality $H \gg L$, where H is the spacing between the grid electrodes, is satisfied, it can be considered that E_0 is the mean strength of the electric field near the grid emitter (in comparison with the spacing H). If, instead of inequalities (1.3), the weaker conditions $h \gtrsim l \gtrsim \Delta$ are satisfied, expression (1.6) can only be used for estimating the order of magnitude of the mean field strength at the grid emitter E_0 at which a corona discharge is fired.

2. During their movement in the region of a unipolar corona discharge between grid electrodes, disperse aerosol particles acquire a positive electric charge as positive ions settle on them. We shall limit our considerations to the case of fairly strong electric fields and low particle concentrations, which is important in practice, where it is possible to neglect the influence exerted on the charging of particles by the thermal motion of ions and by the electric field and ion concentration perturbations caused by neighboring particles. For this, it is sufficient that the following inequalities be satisfied [7]:

$$a \ll \delta \lesssim \lambda \ll H \ (\delta \sim bEa^2/D,\ \lambda \sim n^{-1/3}). \tag{2.1}$$

Here a is the particle radius, δ is the characteristic path traveled by ions under the action of the electric field during the time $\tau \sim a^2/d$, i.e., during the time necessary for their displacement over the distance $\sim a$ as a result of thermal motion, λ is the characteristic distance between particles, n is the particle concentration, E is the mean electric field strength throughout a physically infinitesimal volume containing a sufficiently large number of particles, and b and D are the mobility and the diffusion coefficient of ions, respectively ($b \simeq 1.7 \cdot 10^{-4}$ m²/(V·sec) and $D \simeq 4.6 \cdot 10^{-6}$ m²/sec); the permittivity of the aerosol is assumed to be equal to unity. The latter inequality in (2.1) is based on the assumption that the motion of aerosol in an electric field can be described within the framework of the mechanics of continuous media [8].

Assume also that the spacing between the points of the grid emitter h, the spacing between the electrodes H, and the electrode radius R satisfy the inequalities

$$R \gg H \gg h. \tag{2.2}$$

Then we consider that the aerosol flow is one-dimensional and calculate the electric parameters of the flow by means of the expressions derived in [1]:

$$E_H = \frac{1}{b}\left[\frac{3}{4}\left(\frac{b\Phi}{H} - u\right) - \frac{bE_0}{2} + \sqrt{\frac{9}{16}\left(\frac{b\Phi}{H} + u\right)^2 + \frac{3}{4}(u + bE_0)\left(\frac{b\Phi}{H} - bE_0\right)}\right]; \tag{2.3}$$

$$j = \frac{1}{8\pi bH}\left[(u + bE_H)^2 - (u + bE_0)^2\right]; \tag{2.4}$$

$$Q_H = 3a^2 E_H F\left(\mathrm{Pe}_E, \mathrm{Pe}_E^0\right),\ \mathrm{Pe}_E = \frac{u}{bE_H},\ \mathrm{Pe}_E^0 = \frac{u}{bE_0},$$
$$F = \frac{K_2\left(\sqrt{1/\mathrm{Pe}_E^0}\right) I_2\left(\sqrt{1/\mathrm{Pe}_E}\right) - I_2\left(\sqrt{1/\mathrm{Pe}_E^0}\right) K_2\left(\sqrt{1/\mathrm{Pe}_E}\right)}{K_2\left(\sqrt{1/\mathrm{Pe}_E^0}\right) I_0\left(\sqrt{1/\mathrm{Pe}_E}\right) - I_2\left(\sqrt{1/\mathrm{Pe}_E^0}\right) K_0\left(\sqrt{1/\mathrm{Pe}_E}\right)}. \tag{2.5}$$

Here Φ is the emitter potential ($\Phi > \Phi_0 \equiv E_0 H$), u is the aerosol velocity, E_0 and E_H are the values of the field strength at the emitter and the collector, respectively, j is the density of the ion current between the electrodes, Q_H is the charge of an aerosol particle emerging from the interelectrode gap, and I_0, I_2, K_0, and K_2 are modified Bessel functions. The electric current transported by disperse particles J_p and the electric ion current J are respectively calculated by means of the expressions

$$J_p = \pi R^2 unQ_H,\ J = \pi R^2 j. \tag{2.6}$$

In deriving Eqs. (2.3)-(2.5), it was assumed [1] that the effect of the electric field on the motion of the gas and the disperse particles is slight, the gas and particle velocities are constant and equal to each other, and the concentration of disperse particles is sufficiently low ($nQ_H \ll q$, $J_p \ll J$), so that the effect of particles on the electric field strength E and the density of the electric charge of ions q can be neglected. It should be noted that, if the weaker relationship $h \lesssim H \lesssim R$ is satisfied instead of inequalities (2.2), expressions (2.3)-(2.6) can be used for estimating the order of magnitude of the parameters in question.

Table 1 provides the calculated values of the parameters E_H, J, Q_H, and J_p for three sets of flow conditions and different dimensions and concentrations of disperse aerosol particles. The initial strength for corona discharge firing E_0 for the first set of flow conditions corresponds to points with $l = 5 \cdot 10^{-3}$ m and $2m = 2 \cdot 10^{-3}$ m on the basis of the calculations given in paragraph 1. For the second and third sets of flow conditions, the assigned value of E_0 is correspondingly smaller by one and two orders of magnitude. A reduction in E_0

TABLE 1

H, m	R, m	E_0, kV/m	Φ, kV	a, m	n, m^{-3}	E_H, kV/m	J, A	Q_H, C	J_p, A	δ_0, m	δ_H, m	λ, m
$5 \cdot 10^{-2}$	$12,5 \cdot 10^{-2}$	$6,74 \cdot 10^{2}$	33,8	10^{-6}	10^{10}	$6,78 \cdot 10^{2}$	$4,2 \cdot 10^{-6}$	$0,6 \cdot 10^{-17}$	$2,9 \cdot 10^{-8}$	$24,4 \cdot 10^{-6}$	$24,6 \cdot 10^{-6}$	$4,6 \cdot 10^{-4}$
$5 \cdot 10^{-2}$	$12,5 \cdot 10^{-2}$	50	3	10^{-5}	10^{8}	70	$3,3 \cdot 10^{-6}$	$1,6 \cdot 10^{-16}$	$7,85 \cdot 10^{-9}$	$1,8 \cdot 10^{-4}$	$2,5 \cdot 10^{-4}$	$2 \cdot 10^{-3}$
$5 \cdot 10^{-2}$	$12,5 \cdot 10^{-2}$	5	0,5	10^{-4}	10^{7}	15	$9,8 \cdot 10^{-7}$	$1,52 \cdot 10^{-15}$	$7,45 \cdot 10^{-9}$	$1,8 \cdot 10^{-3}$	$5,3 \cdot 10^{-3}$	$4,6 \cdot 10^{-3}$

involves much sharper corona points. It should be noted that there are no simple analytical expressions relating E_0 to the corona point dimensions for the second and third sets of flow conditions. In calculating the flow parameters, the values of Φ and E_0 were assigned so that the ion current and the current of disperse aerosol particles satisfied the relationships

$$J \sim 10^{-6}\ \mathrm{A} = 1\ \mu\mathrm{A}\ ,\ J_p \lesssim 10^{-8}\ \mathrm{A} \ll J. \tag{2.7}$$

One can assume that disperse particles do not affect a corona discharge. It is also evident from Table 1 that inequalities (2.1) are satisfied for the analyzed flow conditions.

3. Let us determine the mean dimension of disperse particles. We shall first consider only the case of monodisperse aerosol. Then, the mean mass charge of aerosol particles z upon their emergence from the interelectrode gap is related to their radius by the expression

$$z = Q_H/m_p = 9E_H F(\mathrm{Pe}_E, \mathrm{Pe}_E^0)/(4\pi\rho a), \tag{3.1}$$

where m_p is the mass of an aerosol particle and ρ is the density of its material. If we know the mean mass charge of particles z, we can find the particle radius a from Eq. (3.1):

$$a = 9E_H F(\mathrm{Pe}_E, \mathrm{Pe}_E^0)/(4\pi\rho z). \tag{3.2}$$

To determine the mass charge of particles we can use, for instance, a sampling data unit, mounted beyond the grid collector [3, 9]. The data unit consists of a cylindrical capacitor, which includes a grounded electrode, a lining made of an insulating material, and a filter with conducting fibers, which is connected to an electrometer and a pump. The pump sucks the aerosol into the data unit, where it is passed through a filter. An electrometer is connected to the filter in the data unit. The electrometer determines the electric potential of the filter Φ_f arising as charged aerosol particles settle on the filter. The mass of the particles settled on the filter M_f is then measured by means of an analytical balance, while the mass charge of particles z is determined by means of the expression [3, 9]

$$z = C_f \Phi_f / M_f, \tag{3.3}$$

where C_f is the capacitance of the mass charge data unit. The total mass discharge of disperse particles W in the aerosol flow is often known in laboratory investigations. For instance, this discharge could be equal to the liquid discharge in the spray nozzle. The value of M_f can then be calculated by using the equation

$$M_f = WtkS/S_a, \tag{3.4}$$

without resorting to measurements of the increment in the filter mass by means of an analyticalbalance. In the above equation, k is the capture coefficient of the data unit, S is its opening area, S_a is the cross-sectional area of the aerosol jet, and t is the deposition time.

We shall provide two examples of application of the described method for calculating the mean size of disperse aerosol particles. Assume that monodisperse aerosol consisting of water particles suspended in air moves at the velocity u = 10 m/sec through two flat, round grid electrodes, positioned perpendicularly to the flow at the distance $H = 5\cdot10^{-2}$ m from each other. The water density is $\rho = 10^3$ kg/m³.

The electric field strength at the grid emitter E_0 and the emitter potential Φ are assigned as $E_0 = 50$ kV/m and $\Phi = 3$ kV. On the basis of (2.3), we have $E_H = 6.9\cdot10^4$ V/m for $b = 1.7\cdot10^{-4}$ m²/(V·sec). The z value found by means of Eq. (3.3) is $z = 4\cdot10^{-5}$ C/kg. The mean radius of disperse particles determined by means of expression (3.2) is $a = 10^{-5}$ m. Assume now that monodisperse aerosol consisting of water particles suspended in air moves between the electrodes at a velocity of 100 m/sec. The assigned electric field strength at the grid emitter E_0 and the emitter potential Φ are equal to $E_0 = 5$ kV/m and $\Phi = 0.5$ kV. In this case, for $b = 1.7\cdot10^{-4}$ m²/(V·sec), we have $E_H = 1.5\cdot10^4$ V/m on the basis of (2.3). The value of z found by means of Eq. (3.3) is $z = 2.4\cdot10^{-8}$ C/kg. The mean radius of disperse aerosol particles determined by means of (3.2) is equal to $a \simeq 10^{-4}$ m.

Let us consider a polydisperse aerosol flow and write the expression for the mean mass charge of particles

$$z = \frac{C_f \Phi_f}{M_f} = \frac{Q_f}{M_f} = \frac{\int_0^\infty f(a)\, Q_H(a)\, da}{\int_0^\infty f(a)\, m(a)\, da}, \tag{3.5}$$

where Q_f is the charge of particles that have settled on the filter in the data unit, $f(a)$ is the distribution function of particles with respect to the radius, and $Q_H(a)$ and $m(a)$ are the charge and mass of a particle with radius a as it emerges from the interelectrode gap. By substituting in (3.5) the expression (2.5) for the charge of a particle with the radius a leaving the interelectrode gap, we obtain

$$z = \frac{9E_H F\left(\mathrm{Pe}_E, \mathrm{Pe}_E^0\right)}{4\pi\rho} \frac{\langle a^2 \rangle}{\langle a^3 \rangle}, \tag{3.6}$$

where $\langle a^2 \rangle$ and $\langle a^3 \rangle$ are the second- and third-order moments of the distribution function of particles with respect to their radius.

In a cloud or fog, for particles whose radius varies in the range from 0.5 to 20 μm, the distribution function of particles with respect to their radius can be represented by [10, 11]

$$f(a) = \frac{1}{\Gamma(\alpha+1)\beta^{\alpha+1}} a^{\alpha} e^{-a/\beta}, \tag{3.7}$$

where α and β are certain, generally unknown, parameters. Then, the following relationships hold:

$$\langle a^n \rangle \equiv \int_0^\infty f(a)\, a^n da = \beta^n (\alpha+1)\ldots(\alpha+n), \quad \frac{\langle a^2 \rangle}{\langle a^3 \rangle} = \frac{1}{\beta(\alpha+3)} = \frac{\alpha+1}{\alpha+3}\frac{1}{\langle a \rangle}.$$

Here, $\langle a \rangle$ is the first-order moment of the distribution function $f(a)$, i.e., the mean particle radius. After substitution of the expressions for the moments of the distribution function (3.7), Eq. (3.6) assumes the following form:

$$z = \frac{\alpha+1}{\alpha+3} \frac{9E_H F\left(\mathrm{Pe}_E, \mathrm{Pe}_E^0\right)}{4\pi\rho\langle a \rangle}.$$

Consequently, the mean radius of disperse particles is given by

$$\langle a \rangle = \frac{\alpha+1}{\alpha+3} \frac{9E_H F\left(\mathrm{Pe}_E, \mathrm{Pe}_E^0\right)}{4\pi\rho z}, \tag{3.8}$$

where z is determined by Eq. (3.3) in terms of the measured filter potential in the mass charge data unit and the mass increment of the filter. The difference between Eq. (3.8) for determining the mean radius of particles in polydisperse aerosol and Eq. (3.2) for determining the particle radius in monodisperse aerosol consists in the coefficient $c = (\alpha+1)/(\alpha+3)$, which can vary from 1/3 to 1 as α varies from 0 to ∞. Therefore, if α is not known, it is advisable to use $\alpha = \alpha_0$ for an approximate estimate of $\langle a \rangle$, so that the maximum of the relative error in calculating $\langle a \rangle$ by means of (3.8) occurs at both ends of the range of c values. Hence it follows that $\alpha_0 = 1$, $c(\alpha_0) = 1/2$, and

$$\max_\alpha \left| \frac{\langle a \rangle - \langle a(\alpha_0) \rangle}{\langle a \rangle} \right| = \max_\alpha \left| \frac{c - c(\alpha_0)}{c} \right| = \left| \frac{1/3 - c(\alpha_0)}{1/3} \right| = |1 - c(\alpha_0)| = \frac{1}{2}.$$

Thus, the above method makes it possible to estimate, without resorting to complex measurements, also the mean radius of particles in polydisperse atmospheric aerosols with a relative error of not more than 50% in the case where only the general form, but not the parameters, of the distribution function of particles with respect to size (gamma distribution [10, 11]) is known.

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ANALOGY BETWEEN DENSITY STRATIFICATION AND ROTATION EFFECTS

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UDC 532.5.51+532.5.527

The resemblance (analogy) between the properties of rotating and density-stratified flows was first noted by Rayleigh in 1916 [1]. Since that time, a whole series of studies have been published in which this analogy is successfully employed to solve problems of wave theory and stability theory and to describe secondary regimes and turbulence. Some of these achievements are reviewed in [2, 3].

Although the successes achieved in using the analogy to obtain new results are important, our general understanding of the question is unsatisfactory. One problem is the disconnectedness of the examples with references to which the analogy has been demonstrated. The degree of proximity on the basis of which results from the two domains are considered to be analogous varies from identicalness to very distant similarity. There has been no classification of the examples of the analogy on the basis of general principles. The limits of applicability of the analogy remain unclear. The present study is an attempt to clarify these points.

From the most general standpoint, the analogy between stratification and rotation effects is a consequence of the known principle of mechanics which states that following transition to the corresponding moving frame of reference any part of the true acceleration of an object can be regarded as a "body force" field. This approach is attractive because of its simplicity and universality. However, it turns out that in all nontrivial cases it is useless owing to the velocity dependence of the "body force" field. A good example is provided by the equations of motion of a fluid written in a rotating coordinate system. Here the Coriolis force has to be taken as the "body force." Clearly, the introduction of "body forces" of this sort cannot give any basis for transposing the known results for a uniform gravitational field to a new domain.

At the same time, there are more subtle and also more productive means of explaining the analogy. At present, the only possible way of unifying the theories is mathematical. The motions of a rotating and a stratified fluid will be analogous if they are governed by equations of similar form. The degree of similarity must be such that the description of a certain class of motions in one field makes an important contribution to the solution of a related problem in the other. Given this approach, the analogy question reduces to the problem of classifying the corresponding differential equations. In general form this problem is extremely complex. The present study offers several examples illustrating the possibility of progressing along this path. Two levels of analogy, differing considerably with respect to the rigorousness of the requirements, are examined: 1) the level of similarity of the initial nonlinear equations of motion of the rotating and stratified fluids; 2) the similarity of the linearized equations of motion or their corollaries (e.g., spectral problems for linear waves and stability theory).

Comparison of the equations makes it possible to state that the properties of the motions of a rotating fluid are, generally speaking, much more complex than those of a strati-

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 58-68, May-June, 1985. Original article submitted March 22, 1984.

0021-8944/85/2603-0353$09.50