where the interelectrode distance is greatest. In turn the layer of deposits can result in compensation of the initial nonuniformity. Therefore the EF system can have a stationary nonuniform structure in the form of regions with different concentration of the fluidized microparticles in the interelectrode space. In the general case the dynamics of the development of the nonuniformity in the EF system, taking into account both the transverse and longitudinal instability, requires a special analysis in which the nonstationary diffusion equation is solved. However, based on the estimate made, namely, of the transverse instability of the EF system at high concentrations it is possible to explain the formation of nonuniform regions and the existence of jet flows, which were noted in [2], under conditions of electrodynamic fluidization of fine powders.

NOTATION

Here r is the radius of a microparticle; ρ is the density of a microparticle; E is the electric field strength; q_M is the maximum charge of a microparticle; $\beta = 4\pi r^2$ is the scattering cross section; m is the mass of a microparticle; g is the acceleration of gravity; n is the concentration; d is the interelectrode distance; and, s is the resistance of the medium per unit velocity of a microparticle.

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FLUIDIZATION OF MICROPARTICLES IN ELECTRIC FIELD

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The results of statistical modeling of the electrodynamic fluidization of microparticles in an electric field are outlined. The dependence of the current density and charge distribution function of the microparticles on the microparticle concentration is discussed. The limiting attainable microparticle concentration in the interelectrode space is considered. The dependence of the concentration of fluidized microparticles on their bulk concentration is considered.

Electrodynamic fluidization (EDF) of conducting powders, in which microparticles of the material move in a sufficiently strong electric field, is currently of interest as a method of fluidizing disperse materials with the aim of intensifying technological processes. On account of recharging at the electrodes, the particles perform oscillations in the interelectrode space.

In the experimental investigation of this process, it is established, in particular, that there is some limiting concentration of microparticles involved in fluidization. This limiting concentration depends on the size of the microparticles, but does not depend on the magnitude of the electric field [1]. The current density of the EDF system tends to saturation with increase in microparticle concentration.

In [2], the existence of a limiting concentration was explained by the influence of gravitational forces, which lead to asymmetry of the particle distribution in the interelectrode space limiting the EDF-particle concentration. This mechanism applies for large particles (radius $r = 100-500 \cdot 10^{-6}$ m).

In [3], the existence of a recombination mechanism limiting the EDF-particle concentration as a result of microparticle collisions was noted. However, only a few estimates were made.
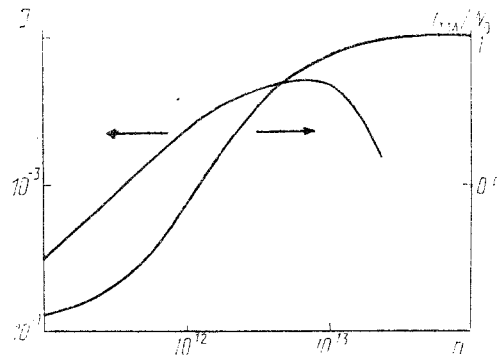
Fig. 1. Dependence of the current density J, A·m^{-2}, and the relative number of interparticle collisions N_M/N_0, rel. units, on the microparticle concentration n, m^{-3}.
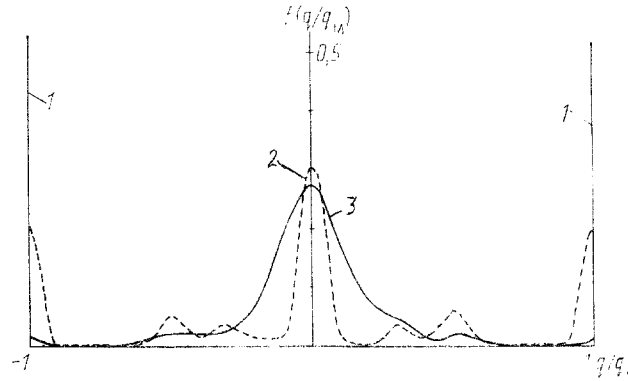

Fig. 2. Charge distribution function of microparticles obtained for a microparticle concentration of $1\cdot10^9$ (1), $1\cdot10^{12}$ (2), and $1\cdot10^{13}$ (3) m^{-3}.

In the present work, the possibility of statistical modeling of the motion of the microparticle system in electrodynamic fluidization in an electric field is considered, taking account of interparticle collisions; EDF is analyzed for small microparticles, in conditions where taking gravitational forces into account cannot lead to limitation of the fluidized-microparticle concentration.

Below, it is assumed that the system of EDF microparticles consists of identical spherical particles (radius r) with a density ρ. With gas filling of the interelectrode space, the resistance of the medium to microparticle motion is determined by solving the Navier—Stokes equation. In a motionless medium at small Reynolds numbers, the equation of microparticle motion takes the form [4]

$$m\mathbf{V}' = F_E + F_g + F_c + F_n,$$
(1)

where $m = 4/3\pi r^3 \rho$ is the particle mass; $\mathbf{F}_E = q\mathbf{E}$ is the force acting on a particle of charge q in an electric field $\mathbf{E}$; $\mathbf{F}_g = mg$ is the gravitational force; $= -6\pi\eta r\mathbf{V} = -s\mathbf{V}$ is the drag force of the medium for a microparticle of velocity $\mathbf{V}$; F_n is the term due to nonsteady motion of the microparticle. Confining attention to the case where the microparticle motion between collisions occurs at constant velocity, it follows from Eq. (1) when $\mathbf{V}' = 0$ that

$$\mathbf{V} = \frac{q\mathbf{E} + mg}{s}.$$
(2)

This means that $\tau_p/\tau \ll 1$, where $\tau_p = m/s$ is the time constant of the particle; τ is the mean free-flight time.

The maximum microparticle charge acquired at the electrode is determined by its radius [5]
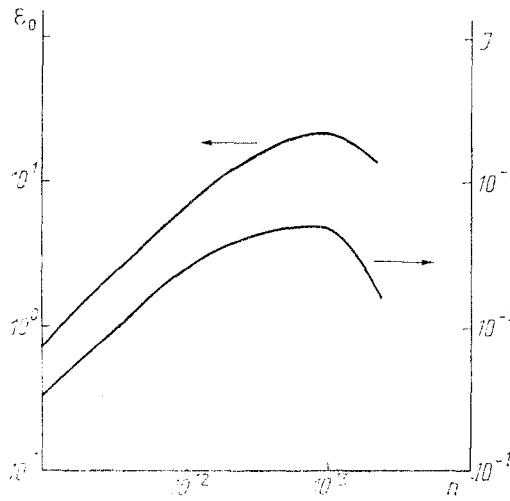
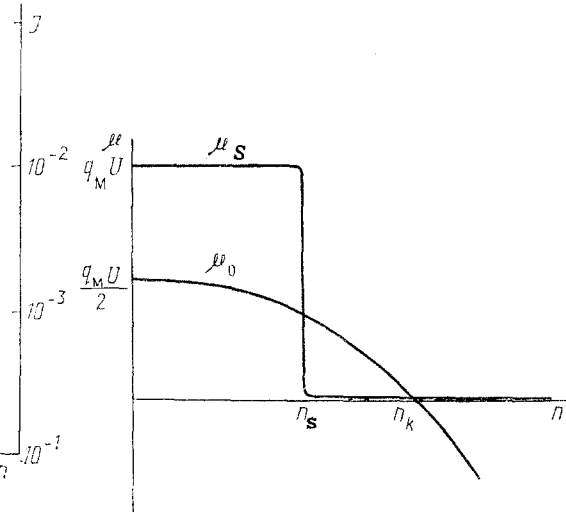$$q_M = 2/3\pi^3\varepsilon_0\varepsilon r^2 E.$$
(3)

55

Fig. 3

Fig. 4

Fig. 3. Dependence of the potential energy E_0, J·m^{-3}, and the current density J, A·m^{-2}, on the concentration of fluidized microparticles for $r = 2 \cdot 10^{-6}$ m, $U = 2 \cdot 10^4$ V, $d = 10^{-2}$ m.

Fig. 4. Dependence of the chemical potential of the solid μ_S and liquid μ_0 phase of the EDF system on the microparticle concentration n, m^{-3}; μ, J.

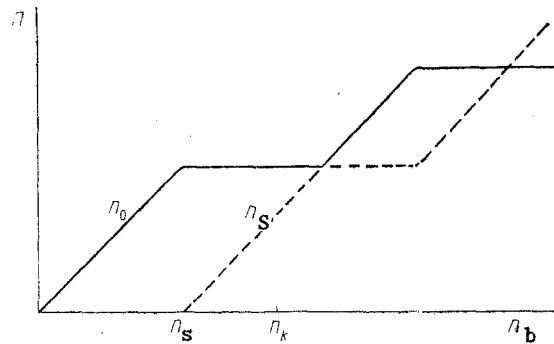Fig. 5. Dependence of the concentration of fluidized microparticles n_0, m^{-3}, and concentration of microparticles deposited at the electrode n_S, m^{-3}, on the bulk concentration n_b, m^{-3}.

In the general case, the state of the microparticle is characterized by spatial coordinate x, velocity V, and charge q.

Considering a microparticle as an element of a statistical ensemble, it is assumed that the distribution function f(x, V, q) determines the statistical properties of the EDF system, i.e., f(x, V, q)$dxdVdq$ is the probability of finding the microparticle in the states x, x + dx, V, V + dV, and q, q + dq. According to Eq. (2), the phase variables V and q are uniquely related; therefore, f(x, V, q) = f(x, q) in this approximation. In addition, an equiprobable charge-independent microparticle distribution in the volume of the EDF system is assumed. Then f(x, q) — f(x)f(q) = f(q)/d, where d is the interelectrode distance. Thus, taking account of all the given assumptions, the statistical properties of the EDF system are determined solely by the charge distribution of the microparticles. It is obvious that, at a small microparticle concentration, when collisions between them may be neglected, only particles with charge $q = \pm q_M$ exist.

Taking account of the normalization $\int\limits_{-q_{\mathrm{M}}}^{+q_{\mathrm{M}}} f(q)\,dq = 1$, it is simple to show that

$$f(q) = \frac{1}{2}\left(1 - \operatorname{sign} q\,\frac{mg}{q_{\mathrm{M}}E}\right)\delta(|q| - q_{\mathrm{M}}),$$
(4)

which reflects the slower upward motion of the microparticles. It is assumed that the upper electrode is positively charged. For microparticles of micronic size, $mg/q_{\mathrm{M}}E \simeq 10^{-2}$, and hence the distribution of positively and negatively charged microparticles is in fact equiprobable. With increase in microparticle concentration as a result of collisions, microparticles with any intermediate charge may appear.

The current density of the EDF system is determined by the motion of the whole set of particles

$$\mathbf{J} = \sum_i q_i \mathbf{V}_i \Delta n_i,$$
(5)

where Δn_i is the quantity of particles with charge q_i and velocity $\mathbf{V}_i$. Using Eq. (2) and converting to integration, it is found that

$$\mathbf{J} = \frac{nq_{\mathrm{M}}^2 E}{s}\int\limits_{-1}^{+1}\left[\left(\frac{q}{q_{\mathrm{M}}}\right)^2 + \frac{q}{q_{\mathrm{M}}}\,\frac{mg}{q_{\mathrm{M}}E}\right]f\left(\frac{q}{q_{\mathrm{M}}}\right)d\left(\frac{q}{q_{\mathrm{M}}}\right),$$
(6)

where n is the EDF particle concentration; $f(q/q_{\mathrm{M}})$ is the normalized charge distribution function of the microparticles. Substituting Eq. (4) into Eq. (6) gives an expression for the current density of EDF particles with low concentration

$$\mathbf{J} = \frac{nq_{\mathrm{M}}^2 E}{s}\left[1 - \left(\frac{mg}{q_{\mathrm{M}}E}\right)^2\right].$$
(7)

When $mg/q_{\mathrm{M}}E \ll 1$, the well-known expression of [1] is obtained.

The distribution function is calculated using the Monte Carlo method, i.e., the method of statistical modeling of the microparticle motion under the action of the electric field between two plane horizontal electrodes. The particle-scattering cross section in mutual collisions is assumed to be $\beta = 4\pi r^2$. The basis of applicability of this expression was established in [4] in considering the coagulation of differently charged particles in an electric field, and also in [1, 3]. The intensity of the scattering flux for a particle of charge q_i colliding with a particle of charge q_j is

$$\Delta\Phi_{ij} = \beta\,|\mathbf{V}_i + \mathbf{V}_j|\,\Delta n_j,$$

$$\Delta n_j = nf(q/q_{\mathrm{M}})\,\Delta(q_j/q_{\mathrm{M}}).$$
(8)

Correspondingly, the total flux intensity is

$$\Phi_i = \beta n \sum_j |\mathbf{V}_i + \mathbf{V}_j|\,f(q_j/q_{\mathrm{M}})\,\Delta(q_j/q_{\mathrm{M}}).$$
(9)

After collision, the new particle charge is equal to the mean charge of the colliding particles: $q'_i = (q_i + q_j)/2$. It is obvious that the form of the distribution function $f(q/q_{\mathrm{M}})$ is determined by the scattering intensity, which, in turn, depends on this function. Thus, the problem of determining $f(q/q_{\mathrm{M}})$ is significantly nonlinear. Therefore, for the given microparticle concentration, the form of the distribution function is determined using an iterative procedure in which Eq. (4) is taken as the initial approximation for $f(q/q_{\mathrm{M}})$. In each iteration, the distribution function is calculated from the formula

$$f_h(q_i/q_{\mathrm{M}}) = \Delta t_i^k / \sum_j \Delta t_j^k,$$
(10)

where Δt_i^k is the time that the microparticle is in the ith charge state. The convergence of the iterative procedure is monitored by calculating the norm

$$h_k = \int\limits_{-1}^{+1} [f_k\,(q/q_M) - f_{k-1}\,(q/q_M)]^2\,d\,(q/q_M).$$

(11)

Modelling the EDF system shows that h_k decreases sufficiently rapidly with increase in the number of iterations. The results of modeling an EDF system of microparticles ($r = 2 \cdot 10^{-6}$ m) in the air medium of a plane capacitor with an interelectrode distance of 10^{-2} m on an EC-1060 computer are shown in Figs. 1 and 2. In each iteration, $\sim 10^4$ interparticle collisions are taken into account. The number of iterations for a specified accuracy of 5%: is no more than 20.

The dependence of the current density of the EDF system on the microparticle concentration n is shown in Fig. 1. At a low concentration, J is directly proportional to n and is described by Eq. (7). With further increase in concentration, the current density reaches saturation and there is a maximum at some critical concentration n_{cr}. A numerical experiment gives $n_{cr} = 8 \cdot 10^{12}$ m^{-3} for $r = 2 \cdot 10^{-6}$ m. This behavior of the current density may be explained on analyzing the dependence of the charge distribution function of the microparticles on the concentration (Fig. 2). At a low concentration, the form of $f(q/q_M)$ corresponds to Eq. (4) with two peaks at $q = \pm q_M$. With increase in concentration, particles with zero and fractional charge appear and, at a concentration corresponding to the current maximum, the EDF system consists basically of weakly charged and neutral particles. Thus, within the framework of the given model, the saturation of the current density with increase in concentration is due to particle collisions with the formation of a weakly charged EDF system. The ratio of the number of interparticle collisions N_M to the total number of particle collisions N_0 with one another and with the electrodes N_e ($N_0 = N_M + N_e$) is shown as a function of the concentration in Fig. 1. The ratio N_M/N_0 increases sharply on approaching the critical concentration n_{cr} at which the current density is a maximum. At $n > n_{cr}$, there are basically only interparticle collisions; the microparticles do not undergo charge reversal at the electrodes and hence the current through the EDF system ceases. Thus, an engineering estimate of n_{cr} requires the consideration of the ratio between the free path length of the microparticle and the interelectrode distance. It is evident from Eq. (8) that the estimate of the free-flight time of the microparticle is $\tau = 1/(\beta \tilde{n} \tilde{V})$, where $\tilde{n}$ is the concentration of scattering particles; $\tilde{V}$ is their relative velocity. At a microparticle concentration corresponding to the onset of current-density saturation, it may be assumed that $\tilde{n} = n/2$ and $\tilde{V} = 2V_{q_M} = V(q_M)$. Then the free path length of the microparticle is

$$l = \tau V_{q_M} = 1/(\beta n).$$

(12)

Assuming that $l = d$, it follows that $n_{os} = 1/(\beta d)$, the concentration of onset of current-density saturation, is found. On the other hand, at a concentration corresponding to the cessation of current through the EDF system, a microparticle leaving the electrode basically encounters neutral microparticles, losing half of its charge in each collision. The microparticle begins to fall downward, as the force acting on it from the electric field becomes less than the gravitational force: $qE \leq mg$. After M collisions, the microparticle charge will be $q_M/2^M$ and correspondingly $M = \ln(q_M E/mg)/\ln 2$ when $q_M E/2^M = mg$. For this case, $\tilde{n} = n$ and $\tilde{V} = V_{q_M}$. From the condition $Ml = d$, an estimate of the limiting microparticle concentration at which the current through the EDF system ceases is obtained

$$n_{li} = n_{os} \ln\left(\frac{q_M E}{mg}\right)\Big/ \ln 2.$$

(13)

Thus, the critical concentration of the EDF system is limited on both sides: $n_{os} < n_{cr} < n_{li}$. For $r = 2 \cdot 10^{-6}$ m, $E = 2 \cdot 10^6$ V/m, $\rho = 7.8 \cdot 10^3$ kg/m^3, it is found that $n_{os} = 2 \cdot 10^{12}$ m^{-3} and $n_{li} = 2 \cdot 10^{13}$ m^{-3}, these values completely correspond to the results of modeling.

Numerical experiments with various electric fields show that n_{cr} does not depend on E. This agrees with the experimental data in [1], and is not surprising, since the free path length of the microparticle does not depend on the velocity nor correspondingly on the electric field. When $mg/q_M E \ll 1$, the dependence of M on E is weak; therefore, n_{li} may also be regarded as independent of E.

In the statistical modeling of the EDF system, r_p/r is also monitored. Whereas for particles of radius $2 \cdot 10^{-6}$ m this ratio is no more than 0.2 and it may be assumed that the required condition $r_p/r \ll 1$ holds with sufficient accuracy, the inverse relation $r_p/r > 1$ holds for $r \simeq (5\text{-}10) \cdot 10^{-6}$ m. Nevertheless, taking into account that the free path length is independent of the microparticle velocity, it may be assumed that the qualitative behavior of the current density as a function of the concentration is also retained for larger microparticles. However, the numerical experiments conducted have still not answered the question: what is the limiting attainable microparticle concentration in EDF? In [3], it was assumed that the limiting attainable concentration in the recombinational mechanism is determined by a single microparticle collision in some elementary volume of the EDF system. It is assumed that the onset of formation of a deposit layer at the electrodes corresponds to the collision of two differently charged particles in elementary volumes with square or hexagonal bases. In fact, the concentration of onset of current-density saturation is taken as the limiting attainable concentration. This estimate is based only on some physical considerations regarding the character of the recombinational mechanism, i.e., without considering the conditions in which a layer of material may exist at the electrode surface, as well as a region of fluidized microparticles.

To elucidate the conditions of existence of the EDF-system components, the EDF particles and the layer of material at the electrode surface are regarded as two different phases of a single EDF system. In this case, the phase-equilibrium condition [6] requires equality of their chemical potentials. If E_S and E_0 are the energies of the solid and liquid phases in unit volume of interelectrode space and n_S and n_0 are the volume concentrations of these phases, the equilibrium condition is written in the form

$$\mu_S = \mu_0, \tag{14}$$

where $\mu_S = \partial E_S / \partial n_S$ is the chemical potential of the solid phase (layer of material at the electrode); $\mu_0 = \partial E_0 / \partial n_0$ is the chemical potential of the liquid fluid phase (EDF particles). Analysis of this equation entails finding E_S and E_0. In calculating the energy of the EDF particles, note, first of all, that, taking account of the above constraints, the energy of kinetic motion of the microparticles is completely converted into the heat of the gas filling of the interelectrode space and hence only the potential part of the EDF-particle energy need be taken into account in E_0. The potential energy of a single microparticle of charge q_i and spatial coordinate x_i along the direction of the electric field is

$$E_i = mgx_i - q_i E \left[\frac{d}{2} (1 - \operatorname{sign} q_i) - x_i \right]. \tag{15}$$

Averaging the microparticle energy over the ensemble of EDF particles, it is found for unit volume that

$$E_0 = n_0 \int_{-q_M}^{+q_M} \int_0^d \left\{ mgx - qE \left[\frac{d}{2} (1 - \operatorname{sign} q) - x \right] \right\} f(x) f(q) \, dx \, dq. \tag{16}$$

Using the obvious equality $q \operatorname{sign} q = |q|$ and integrating with respect to the spatial coordinate, it is found, taking account of the relation $f(x) = 1/d$, that

$$E_0 = \frac{n_0 d q_M E}{2} \left\{ \frac{mg}{q_M E} + \int_{-1}^{+1} \left| \frac{q}{q_M} \right| f\left(\frac{q}{q_M} \right) d\left(\frac{q}{q_M} \right) \right\}. \tag{17}$$

At a low microparticle concentration, when collisions between the microparticles may be neglected, the distribution function is determined by Eq. (4). Substituting Eq. (4) into Eq. (17) gives the obvious equality

$$E_0 = n_0 \frac{q_M E d}{2} = n_0 \frac{q_M U}{2}. \tag{18}$$

In this case, the energy of the EDF particles is proportional to their concentration. With increase in the microparticle concentration, the form of the distribution function changes. Interparticle collisions lead to decrease in the charge of the EDF particles and consequently to relative decrease in their energy. The dependence of the EDF-particle energy on the concentration calculated for particles with $r = 2 \cdot 10^{-6}$ m from Eq. (17) using statistical modeling data is shown

in Fig. 3. It is evident that the energy of the liquid phase of the EDF system has a maximum at the concentration n_{cr} at which a maximum of the current density is also observed. Comparison of Eqs. (6) and (17) for J and E_0 shows that, when $mg/q_M E \ll 1$, the concentration dependence of these quantities is determined solely by the form of the charge distribution function of the microparticles. At low concentration, the chemical potential of the liquid phase of the EDF system is $\mu_0 = \partial E_0/\partial n_0 = q_M U/2$ and does not depend on the concentration. With increase in the concentration, microparticle collisions lead to decrease in the energy growth in comparison with Eq. (18). The beginning of this section is defined by the concentration n_{os}. With further increase in concentration, the chemical potential of the liquid phase decreases, passing through zero at $n = n_{cr}$ and becoming negative (Fig. 4).

In calculating the energy of the EDF-system solid phase, it is taken into account that only the upper particles of the layer with a surface concentration of the order of $\gamma_s = 1(2r)^2$ and a volume concentration $n_s = \gamma_s/d$. The potential energy of the solid phase per unit volume of interelectrode space is this

$$E_S = n_S q_M U = \frac{\gamma_s}{d} q_M U. \tag{19}$$

Increase in the number of particles deposited at the electrode does not lead to increase in energy of the layer as a whole. Therefore, when $n_S > n_s$, $\mu_S = \partial E_S/\partial n_S \to 0$. In the case of a low concentration of particles deposited at the electrode, when their surface concentration is less than the monolayer concentration $\gamma_S < \gamma_s$, the energy of the solid phase is $E_S = (\gamma_S/d)q_M U$ and correspondingly $\mu_S = \partial E_S/\partial n_S = q_M U$. Thus, the chemical potential of the solid phase is constant when $n_S < n_s$, and sharply decreases to zero when $n_S > n_s$ (Fig. 4). On the basis of the equal chemical potentials of the liquid and solid phases of the EDF system in the equilibrium state, the dependence of n_0 and n_S on the bulk concentration of microparticles $n_b = n_0 + n_S$ is determined. The condition $\mu_0 = \mu_S$ corresponds to simultaneous intersection of a straight line parallel to the concentration axis with the curves of $\mu_0(n_0)$ and $\mu_S(n_S)$. At a low microparticle concentration, when $n_b < n_s$ and $\mu_S > \mu_0$, the existence of both phases simultaneously is impossible. With a minimum of the total energy, the energy of the EDF system consists solely of liquid-phase particles, i.e., $n_0 = n_b$.

In the range $n_s < n_b < 2n_s$, solid phase appears; the concentration of fluidized particles remains constant ($n_0 = n_s$), while the number of particles deposited on the electrode increases ($n_S = n_b - n_s$). With further increase in bulk concentration, the state of the solid phase is stabilized, and its concentration remains constant: $n_S = n_s$. At the same time, the concentration of fluidized particles increases in direct proportion to the bulk concentration up to the value $n_0 = n_{cr}$. Further increase in the quantity of microparticles introduced in the interelectrode space, i.e., increase in the bulk concentration, does not change the quantity of fluidized particles, but leads only to increase in the number of particles deposited at the electrode. Thus, the limiting attainable concentration in the EDF system is the concentration n_{cr} at which the current density and energy of the EDF particles are a maximum. This conclusion is confirmed by experimental results [1] indicting saturation of the current density with increase in the bulk concentration of microparticles.

This analysis assumed identical microparticles with a uniform layer of solid phase of the EDF system. In real conditions, however, there are factors (inhomogeneity of the field, the presence of boundaries, etc.) leading, as a rule, to an inhomogeneous distribution of the particles deposited on the electrode surface. In this case the energy of the solid phase of the EDF system may not be constant with increase in the number of particles deposited at the electrode, and hence the jump in the chemical potential at $n_S = n_s$ may not be so sharp. As a consequence, the increase in concentration of fluidized microparticles is slower. Thus, the curves of $n_S(n_b)$ and $n_0(n_b)$ in Fig. 5 only describe their asymptotic behavior in the absence of inhomogeneity in the EDF system. Nevertheless, it may be concluded that, with increase in bulk concentration, the concentration of the liquid phase (concentration of fluidized microparticles) tends, in any case, to a critical value no greater than its value at any n_b.

The microparticle layer deposited at the electrode appears when $n_b = n_s$. For $r = 2 \cdot 10^{-6}$ m, $n_s = 6.25 \cdot 10^{12}$ m^{-3} and $n_{cr} = 8 \cdot 10^{12}$ m^{-3} are of the same order. Therefore, it is unsurprising that estimates of the limiting attainable concentration of fluidized microparticles are usually associated with the monolayer concentration n_s. Note that the relation between n_s and n_{cr} does not depend on the particle size or the electric field. Thus, the given process of solid-layer formation and the corresponding estimate of the limiting attainable EDF-particle concentration may be regarded as valid also for larger particles (of the order of $\sim 10^{-5}$ m and above), for which the constraints adopted earlier do not hold.

NOTATION

Here r is the microparticle radius; ρ, microparticle density; V, velocity; F_E, force due to electric field; q, charge; E, electric field strength; g, acceleration due to gravity; F_g, gravitational force; m, microparticle mass; F_c, drag force of medium; η, viscosity of medium; F_n, nonsteady term in equation of motion; s, drag force of medium per unit velocity; τ_p, time constant of particle; τ, time of free flight; q_M, maximum charge; ε, ε_0, dielectric permittivity; x, coordinate; f, distribution function; d, interelectrode distance; sign, sign function; δ, delta function; n, concentration; Φ, intensity of scattering flux; β, scattering cross section; t, time; h, norm; N_M, number of interparticle collisions; N_e, number of collisions with electrodes; N_0, total number of collision; $\bar{n}$, scatterer concentration; $\tilde{V}$, relative velocity; l, free path length; $\mu_{0,s}$, chemical potential; $\varepsilon_{0,s}$, potential energy; U, potential difference; J, current density; γ, surface concentration.

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PULSATIONAL CHARACTERISTICS OF THE MODEL OF MASS FLOW
IN A FLOW-THROUGH REACTOR

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UDC 66.023.001.57

Liquid flow in a flow-through reactor and one-dimensional longitudinal turbulent mass transfer is considered. The turbulent mass flux is described by a second-order differential equation including the velocity and spatial scale of the turbulent pulsations. Conditions of pulsed tracer introduction in the reactor are considered, and the inverse problem for experimental determination of the pulsational characteristics is solved by the moment method.

In [1, 2], an inhomogeneous differential equation was obtained for the isotropic one-dimensional turbulent or molecular mass (heat) transfer

$$l^2 \frac{\partial^2 q}{\partial x^2} - \frac{l^2}{u^2} \frac{\partial^2 q}{\partial \tau^2} - \frac{2l}{u} \frac{\partial q}{\partial \tau} - q = ul \frac{\partial C}{\partial x}, \tag{1}$$

which includes the spatial scale l and velocity u of the pulsations.

The model in Eq. (1) differs from those in [3, 4] in that the spatial scale and second derivative of the flux with respect to the coordinate are individually present. This permits the formulation of a boundary problem for the flux q which more correctly reflects the physical picture at the boundaries (walls) of the reactor. The steady (quasi-steady at large u) model