ELECTRODYNAMIC FLUIDIZATION OF MICROPARTICLES WITH A FINITE ELECTRICAL CONDUCTIVITY

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We report the results from statistical simulation of the electrodynamic fluidization of microparticles in an electric field with allowance for their finite electrical conductivity. The maximum attainable microparticle concentration is estimated and the form of the charge distribution function of the particles is discussed.

Experimental studies of electrodynamic fluidization (EDF) [1, 2] determined that the maximum attainable concentrations of particles of the same size vary greatly for different materials. In [2], for example, the maximum attainable concentration in the fluidization of stainless steel and graphite particles differs by roughly two orders of magnitude.

As shown in [3], the maximum attainable concentration of microparticles is the critical concentration at which the current density and potential energy of EDF particles have a maximum. The particles were assumed to have a finite conductivity; the conditions of the charge transfer and interaction of these particles were not changed by the finite time of their charge transfer at the electrodes and the finite time of interparticle collisions with allowance for the recombination mechanism limiting the concentration.

We report the results of statistical simulation of the motion of microparticles with allowance for their finite electrical conductivity and we consider the effect of this limitation on their maximum attainable concentration. The effect that the finite conductivity of a microparticle has on its contact charging at the electrodes was considered in a number of studies [1, 2, 4, 5]. It was shown that the ratio τ_c/τ_σ, where τ_c is the contact time and $\tau_\sigma = \varepsilon\varepsilon_0/\sigma$ is the charge relaxation time, appears in the charging expression when the finite conductivity is taken into account. In our statistical simulation of microparticle motion we assumed that the finite conductivity of the microparticle material affects the fluidization process in two ways. First, during contact charging a microparticle with charge q_i acquires a charge

$$q_i' = q_M + (q_i - q_M)\exp(-\tau_c/\tau_\sigma), \tag{1}$$

where the maximum charge q_M is determined by a familiar formula [1]. Second, we made allowance for the fact that when two particles with charges q_i and q_j interact the charge of particle i after collision is

$$q_i' = \frac{q_i + q_j}{2} + \frac{q_i - q_j}{2}\exp(-\tau_c/\tau_\sigma). \tag{2}$$

As the ratio $\tau_c/\tau_\sigma \to 0$ the charge of the particle remains unchanged; in the opposite case $\tau_c/\tau_\sigma \to \infty$ we have $q_i' = (q_i + q_j)/2$, which corresponds to the condition adopted in [3]. The contact time was assumed to be equal to the collision time [6]. When two identical particles collide the contact time is

$$\tau_c = 4.53\left[\frac{\sqrt{2}\delta m}{\sqrt{r\tilde{V}}}\right]^{2/5}, \tag{3}$$

where $\delta = (1 - \mu^2)/\pi E_0$ is a material constant and $\tilde{V}$ is the relative velocity of the colliding bodies. When a particle collides with an electrode the contact time differs from (3) by the factor $2^{1/5}$. Since τ_c depends on the size of the particle and its relative velocity as $\tau_c \sim r/\tilde{V}^{1/5}$ during simulation the variation of the microparticle parameters was taken into

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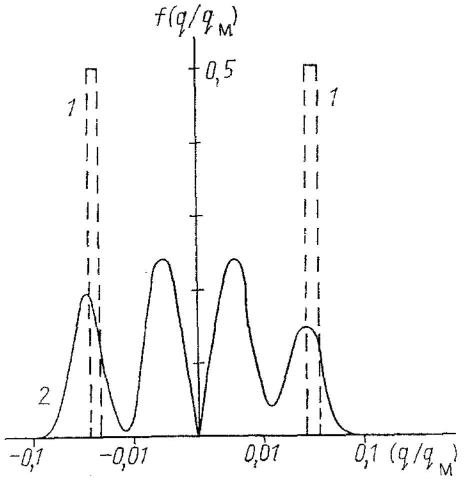

Fig. 1

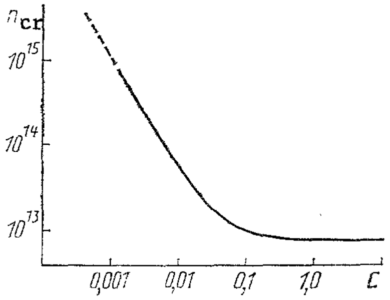

Fig. 2

Fig. 1. Charge distribution function for particles $r = 2\cdot10^{-6}$ m at $E = 10^6$ V/m, calculated for the concentrations $1\cdot10^{11}$ (1) and $5.26\cdot10^{13}$ m^{-3} (2).

Fig. 2. Critical concentration of an EDF system versus C for particles $r = 2\cdot10^{-6}$ m. n_{cr}, 1/m^3.

account by introducing a dimensionless parameter C in the form

$$\tau_c/\tau_\delta = C(r/10^{-6}\,\mathrm{m})(1\,\mathrm{m/sec}/\bar{V})^{1/5}. \tag{4}$$

The distribution function and the macroscopic characteristics of the EDF system were calculated for a number of values of C that ensured satisfaction of both the condition $\tau_c/\tau_\sigma \gg 1$ and the reverse relation. For a small value of C ($\tau_c/\tau_\sigma \ll 1$), when the particle does not manage to obtain a substantial charge on the electrodes, the spectrum of the charges of the EDF system lies mainly at charges smaller than q_M even in the absence of collisions. At the same time the number of intervals N into which the entire range of the charge from $+q_M$ to $-q_M$ can be divided in order to obtain the distribution function is limited by the power of the computer. To increase the accuracy of the computation and reveal the distinctive features of the distribution function at small charges, therefore, we used a nonuniform scale in the form

$$q[i] = q_M\left[\frac{2(i-1)}{N-1} - 1\right]^{2k+1}, \quad i = 1, \ldots, N, \; k = 0, 1, \ldots, n. \tag{5}$$

The use of nonuniform scale enables us even at k = 1, 2 to "consider" the details of the distribution function at small charges, while leaving the limits of possible charge states unchanged. Figure 1 shows the charge distribution function, calculated for microparticles with $r = 2\cdot10^{-6}$ m, $\rho = 7.8\cdot10^3$ kg/m^3, $E = 10^6$ V/m, $d = 10^{-2}$ m, and C = 0.01 for EDF system concentrations $1\cdot10^{11}$ 1/m^3 and $5.62\cdot10^{13}$ 1/m^3. As in [9] (the case $\tau_c/\tau_\sigma \gg 1$) the distribution at a low concentration consists of two delta-shaped peaks that determine the particle charges in the absence of collisions. In this case the charge of a microparticle is determined by self-consistent oscillatory motion with velocity $V = V(q)$, which in turn also determines its charge through the relation $\tau_c = \tau_c(V)$. At $\tau_c/\tau_\sigma \ll 1$ this charge can be evaluated from (1): $q \simeq q_M/2(\tau_c/\tau_\sigma)$. With increasing concentration the EDF system becomes weakly charged as a result of recombination of charges. A distinctive feature of the distribution function in this case is a gap in the density of charged states at q = 0. The explanation for this is that the recombination is not complete and, therefore, neutral particles cannot exist in the EDF system. We must point out that since τ_c/τ_σ is always finite the gap in the density of charge states exists at $\tau_c/\tau_\sigma \gg 1$ as well. Naturally, the gap width is determined by the value of τ_c/τ_σ. When $\tau_c/\tau_\sigma \gg 1$ the gap halfwidth $\Delta/2$ can be estimated by assuming it to be equal to the residual charge when particles with charges $+q_M$ and $-q_M$ collide. From (2) we have $\Delta \simeq 2q_M \exp(-\tau_c/\tau_\sigma)$. The situation is more complicated at $\tau_c/\tau_\sigma \ll 1$ since in this case we must find the residual charge of the particles after a large number of collisions. Another approach can be taken, however, by assuming that the residual charge of the particles is equal to the charge acquired by the introduced neutral particle in one collision with a particle of the EDF system with charge $q_M/2(\tau_c/\tau_\sigma)$. Then from (2) we obtain $\Delta \simeq q_M/2(\tau_c/\tau_\sigma)^2$. From the estimates we see that in both limits the gap width decreases (as $\tau_c/\tau_\sigma \to \infty$ in one case and as $\tau_c/\tau_\sigma \to 0$ in the other), whereby the gap width has a maximum which obviously is at $\tau_c/\tau_\sigma \simeq 1$.

The dependence of the current density J and the potential energy E of the EDF system on the concentration n is similar in form to that in [3]. As C decreases the current density and the energy of the EDF system also decrease. The maxima of J(n) and E(n) shift to higher concentrations. Figure 2 shows the critical concentration $n_{cr}[E(n_{cr}) = \max E(n)]$ versus C.

At a large value of C (C = 1-10), when $\tau_c/\tau_\sigma \gg 1$, the critical concentration is constant and is equal to the value calculated earlier [3]. It increases as C decreases. At C = 0.01-0.05, when $\tau_c/\tau_\sigma \ll 1$, n_{cr} is an order of magnitude higher than the value calculated for particles with infinite conductivity. As C decreases further to ~0.001 the oscillatory motion of the microparticles breaks off under the force of gravity. In this case the charge acquired by a particle at the electrode is insufficient to raise it. This situation manifests itself in an abrupt asymmetry of the distribution function and the lack of a maximum of the potential energy of the EDF system. As τ_c/τ_σ increases the maximum attainable concentration, determined by n_{cr}, increases.

We must point out that in itself the insufficient charge received by the microparticles at the electrodes does not affect n_{cr} since the mean free path of a particle does not depend on the magnitude of its charge. The increase in the maximum permissible concentration of microparticles, therefore, is due only to the fact that at a low τ_c/τ_σ when microparticles collide they do not lose charge rapidly and as a result the energy of the EDF system is reached at high concentrations.

For an engineering estimate of the critical concentration of microparticles we consider the concentration dependence of the potential energy of the EDF system. It can be estimated as $E = \bar{q}E(d/2)n$, where $\bar{q}$ is the average charge of an EMF particle. In the case $\tau_c/\tau_\sigma \gg 1$ at a low particle concentration $E^* = q_M E(d/2)n$ [3]. At a high concentration a probe particle with charge q_M collides mainly with weakly charged particles, losing half its charge in each collision. When the probe particle undergoes M collisions in the flight in the interelectrode space $M = d/\ell$, $\ell = 1/\beta n$ is the mean free path, the average charge is

$$\bar{q} = \frac{q_M}{M} \sum_{k=0}^{M} 1/2^k \simeq 2q_M/(d\beta n). \tag{6}$$

The potential energy of the EDF system in this case is $E^{**} = q_M E/\beta$. Equating the estimates E^* and E^{**}, we find $n_{cr} = 2/(d\beta) = 2n_{np}$. This value of the critical concentration differs from the result of numerical experimentation [3] by a factor of roughly two.

In the other limiting case $\tau_c/\tau_\sigma \ll 1$ we use the circumstance that τ_c depends weakly on the microparticle velocity and, therefore, on its charge. We take the same value of τ_c/τ_σ, therefore, for each collision of the probe particle. At a low particle concentration we set $\bar{q} = q_M/2(\tau_c/\tau_\sigma)$, whereupon $E^* = (q_M/2)E(d/2)(\tau_c/\tau_\sigma)n$. At a high concentration a neutral probe particle, thrown against the electrode, acquires a charge $q \simeq q_M(\tau_c/\tau_\sigma)$, according to (1). In each collision with weakly charged particles of the EDF system, according to (2), it loses a charge $\Delta q \simeq q/2(\tau_c/\tau_c)$. Then in M collisions, $M = d\beta n \gg 1$, the average charge of the probe particle is

$$\bar{q} = \frac{1}{M} \sum_{k=0}^{M} q_M(\tau_c/\tau_\sigma)\left[1 - \frac{1}{2}\frac{\tau_c}{\tau_\sigma}\right]^k \simeq q_M(\tau_c/\tau_\sigma)\left[1 - d\beta n\left(\frac{\tau_c}{\tau_\sigma}\right)\Big/ 4\right]. \tag{7}$$

The potential energy of the EDF system at a high concentration is $E^{**} = q_M E(d/2)(\tau_c/\tau_\sigma) \times [1 - d\beta n(\tau_c/\tau_\sigma)/4]$. Equating E^* and E^{**}, we obtain

$$n_{cr} = 2n_{np}/(\tau_c/\tau_\sigma). \tag{8}$$

The critical concentration of the EDF system thus increases as τ_c/τ_σ decreases. Considering that τ_c varies little for various materials and $\tau_\sigma \sim 1/\sigma$ we can conclude that the maximum attainable concentration of microparticles is inversely proportional to the electrical conductivity of their material.

The force of gravity causes the current of the EDF system to be limited. The maximum concentration at which the current of the EDF system ceases was calculated in [3] for the case $\tau_c/\tau_\sigma \gg 1$: $n_{pr} = n_{np} \ln(q_M E/(mg))/\ln 2$. In the case $\tau_c/\tau_\sigma \ll 1$, on limiting the number of collisions of the probe particle to the number M' calculated with the condition qE = mg, $q = q_M(\tau_c/\tau_\sigma)[1 - {}^1/_2\, \tau_c/\tau_\sigma]^{M'}$, we obtain

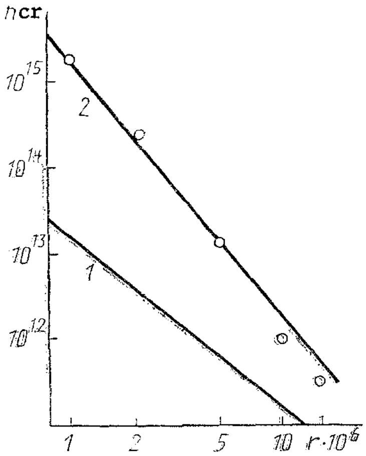

Fig. 3. Critical concentration of the EDF system vs. the particle size on condition that $\tau_c/\tau_\sigma \gg 1$ (1) and $\tau_c/\tau_\sigma \ll 1$ (2): the points represent the experimental data of [1]. r, m.

$$n_{\text{pr}} = 2n_{\text{np}} \ln \left(\frac{q_{\text{м}}E}{mg} \frac{\tau_c}{\tau_\sigma} \right) \Big/ (\tau_c/\tau_\sigma). \tag{9}$$

From the estimates we see that in the case $\tau_c/\tau_\sigma \gg 1$ the dependence of the critical concentration on the particle size is of the nature $n_{cr} \sim r^{-2}$. This dependence is stronger, $n_{cr} \sim r^3$, in the other limiting case $\tau_c/\tau_\sigma \ll 1$. Thus, from $n_{cr}(r)$ we can classify the effect of the finite particle conductivity on their fluidization conditions. To compare the expressions obtained with the experiment we took the dependence of the maximum attainable concentration during the fluidization of iron powder on the particle size, which is given in [1]. The experimental points in the range $r = (1 - 15) \cdot 10^{-6}$ m are shown in Fig. 3 along with $n_{cr}(r)$ calculated for the case $\tau_c/\tau_\sigma \gg 1$. The experimental points lie slightly higher and the overall character of the experimental dependence of the maximum attainable concentration on the particle size is close to r^{-3}. Since for metal particles $\tau_c/\tau_\sigma \gg 1$, as a result of the high electrical conductivity this can be attributed only to the effect of the oxide film, which has a substantially lower electrical conductivity. To approximate this experiment, therefore, we used Eq. (8) with the parameters $\mu = 0.28$, $E_0 = 20.6 \cdot 10^{10}$ N/m². The best approximation gives $\tau_\sigma \simeq 1 - 10^{-6}$ sec. For this value of the charge relaxation time on the assumption that the dielectric constant of the oxide film is a few units, we obtain $\sigma \sim 10^{-5}$-10^{-4} S/m. The dependence of the critical concentration on the particle size gives a value of the electrical conductivity of the surface layer of the metal particles that is close to the real value. The charge of particles having an oxide layer was considered in [5]. In this case the charge relaxation time is determined by the conductivity σ_1 of the layer. Accordingly, the maximum attainable concentration should increase when σ_1 decreases. This conclusion is supported qualitatively by experimental data on the electrodynamic fluidization of particles ($r = 7 \cdot 10^{-6}$ m) of stainless steel, bronze and graphite under conditions imitating weightlessness, which are given in [2]. The highest concentration was observed for stainless steel particles and the lowest, for bronze particles. Oxides of chromium, an alloying component, coating the surface of a steel [9] have the lowest electrical conductivity (10^{-13}-10^{-9} S/m [7]) in comparison with copper oxides with $\sigma_c \sim 10^{-2}$-10^{-3} S/m.

An important finding from these experiments is that the maximum attainable concentration depends on the electric field strength. At the same time this dependence does not exist for iron powder [1]. The explanation for this can be that only the static electrical conductivity of the layer plays a role in the case of relatively thick oxide layers. For thin oxide films, however, electron tunneling through the potential barrier formed by the film is an important process [8]. In this case the current density and, hence, the electrical conductivity $\sigma_c \simeq \partial J_c/\partial E_c$ depend on E_c, the electric field strength in the oxide layer, and are determined by both the height of the barrier and the thickness of the film; the conductivity σ_c increases with E_c.

The value of E_C is determined by the charges that the particles acquire at electrodes in the field E and, therefore, the charge relaxation of metal particles with relatively thin oxide films will depend on the field strength in the interelectrode space. An increase in the field should lower the maximum attainable concentration. Indeed, for microparticles a lower concentration corresponds to a strong field [2]. When the particles are larger than 10^{-5} m the influence of the oxide layer decreases as a result of the increased contact time and at $r \sim 10^{-4}$ m the maximum attainable concentration already depends little on the material of the particle.

In summary, during the electrodynamic fluidization of micron particles under conditions when the force of gravity has only a negligible effect the maximum attainable concentration of metal powders is determined by the properties of the oxide layer and increases as its electrical conductivity decreases.

NOTATION

Here q_M denotes the maximum particle charge; ε and ε_0 are the dielectric constants; σ is the electrical conductivity; μ is Poisson's ratio; E_0 is Young's modulus; m is the particle mass; ρ is the particle density; E is the electric field strength; d is the interelectrode distance; n is the concentration; r is the particle radius; Δ is the gap width; $\beta = 4\pi r^2$ is the scattering cross section; E is the potential energy; and J is the current density.

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