STRUCTURE FORMATION IN AN ELECTRODYNAMIC FLUIDIZATION SYSTEM

S. I. Zhebelev

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A diffusion mechanism is examined for forming structures during electrodynamic fluidization (EDF) in an electric field. The characteristics of nonuniform structures and their dependence on various EDF process factors are determined.

The formation of nonuniform structures have been observed in multiple experiments on electrodynamic fluidization (EDF), in which the concentration of microparticles is not identical at various points in the interelectrode gap. Here structure formation is related to the growth of the number of microparticles introduced into the EDF process.

Data have been presented [1] on string-like structures during the fluidization of graphite, and the formation of structures has been described [2, 3] during electromechanical convection of suspensions of various minerals. Several models [2] have been proposed to explain these experiments. Here we examine a diffusion mechanism for structure formation and estimate the dimensions of nonuniformities in the EDF system, which can take place in this case.

The self-diffusion of microparticles transverse to the electric field in the EDF process has been examined [4]; this diffusion is caused by interparticle collisions. It was shown that when the microparticle concentration exceeds $n_D = 4^{1/3} n_{in} = 1/(\beta d)$, the EDF process is transversely unstable. A local concentration increase in this case leads to its further growth. This behavior of the EDF system is explained by the concentration-dependence of the coefficient of transverse self-diffusion $D_\perp$, which is determined by the diffusion flux of microparticles:

$$J_{D_\perp} = -\frac{\partial (D_\perp n)}{\partial n} \frac{\partial n}{\partial x_\perp}, \tag{1}$$

where $x_\perp \perp E$. In the limiting cases of small and large concentration, we have [4]

$$D_\perp^* = \left(\frac{\pi}{8}\right)^2 \frac{V_{q_M}^3 \tau_r^2}{d} \frac{n}{n_{in}}, \tag{2}$$

$$D_\perp^{**} = \frac{1}{2}\left(\frac{\pi}{4}\right)^2 \frac{V_{q_M}^3 \tau_r^2}{d} \left(\frac{n_{in}}{n}\right)^2. \tag{3}$$

The total dependence of the self-diffusion coefficient on the concentration can be set equal to $1/D_\perp = 1/D_\perp^* + 1/D_\perp^{**}$. Here n_D is determined by the maximum of the product $D_\perp n$, which characterizes the magnitude in the direction of the diffusion current. According to the inequality $\partial(D_\perp n)/\partial n < 0$ for $n > n_D$, the concentration nonuniformity should grow without bound (electrodynamic collapse). However, in the EDF system there is a mechanism which limits further growth in the concentration. As shown in [5], the microparticle concentration cannot be larger than $n_{cr} \simeq 2n_{in}$. Increasing the number of particles in the interelectrode gap leads only to thickening the precipitation layer on the electrode.

As a whole, the process of forming a nonuniform structure should be described by the transient diffusion equation which considers the longitudinal instability of the EDF system. However, estimating the characteristics of the nonuniformity which is already formed requires examining the equilibrium state of the EDF system in the absence of a transverse flux of particles. The possible steady states of the EDF system in this case are the separate regions of the interelectrode gap with concentrations n_D and n_{cr} (Fig. 1). In the region $n = n_D$, there is no transverse flux, due to the zero derivative $\partial(D_\perp n)/\partial n = 0$. In the region $n = n_{cr}$, there is no diffusion flux because the concentration is constant and $\partial n_{cr}/\partial n = 0$.

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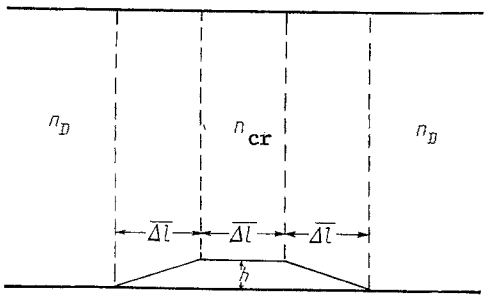

Fig. 1. Steady-state structure of the EDF system for a diffusion instability.

In the intermediate region with a characteristic dimension of the average mean free path of the particles $\overline{\Delta \ell}$, the diffusion current directed from the region with $n = n_D$ to the region $n = n_{cr}$ is compensated by a current in the reverse direction, which arises due to the nonuniformity of the electric field in this region. For a small layer thickness, from expressions in [6], this current can be estimated as

$$J_{\Delta E} = n \frac{V_{\bar{q}}^2 \tau_r}{d} \frac{h}{\overline{\Delta l}}, \tag{4}$$

where $V_{\bar{q}} = V(\bar{q})$ is the longitudinal microparticle velocity, which is determined by the average charge of a probe particle. For a large microparticle concentration, when $n \simeq n_{cr}$ [4]

$$\overline{\Delta l} = \frac{\pi}{4} V_{q_M} \tau_r \frac{n_{in}}{n}, \qquad \bar{q} = 2 q_M \frac{n_{in}}{n}. \tag{5}$$

From the condition $J_{D_\perp} + J_{\Delta E} = 0$ for the intermediate region, we obtain

$$h = \frac{1}{8} \left(\frac{\pi}{2} \right)^2 V_{q_M} \tau_r \frac{\Delta n}{n}. \tag{6}$$

By taking $\Delta n = n_{cr} - n_D = 0.4\, n_{in}$ and $n \simeq (n_{cr} + n_D)/2 = 1.8\, n_{in}$, we have $h \simeq 10^{-2} V_{qM} \tau_r$.

The thickness of the precipitation layer required to compensate for the diffusion current is small and is on the order of 10^{-5}-10^{-4} m for micron particles. It is obvious that the appearance of nonuniformity in the EDF system is caused by a nonuniformity in the electrode system, which affects not only the occurrence of the nonuniformity, but also its characteristic dimension. However, in the ideal case of plane parallel electrodes, the structure of the EDF system should consist only of nonuniformities of minimum dimension. The condition for a minimum in the total energy of the system requires minimizing the relative volume of the interelectrode gap with a concentration n_{cr}. Because the minimum dimension of the region with $n = n_{cr}$ is $\sim \Delta \ell(n_{cr})$, the EDF system in this case should consist of cylindrical regions of this dimension, which are separated by gaps of $\sim 2\Delta \ell$. According to (5), the magnitude of $\overline{\Delta \ell}$ should be $1.5 \cdot 10^{-3}$ m for graphite powder with a particle dimension of $r = 2 \cdot 10^{-6}$ m in a field of $2 \cdot 10^{-6}$ V/m for $d = 10^{-2}$ m. Thus, for micron particles the diffusion instability leads to the formation of a transversely nonuniform threadlike EDF system. The characteristic time for forming the nonuniform structure can be estimated as

$$\tau_D \simeq \frac{(\overline{\Delta l})^2}{\Delta n} \frac{1}{\left| \frac{\partial^2 (D_\perp^{**} n)}{\partial n^2} \right|}. \tag{7}$$

By substituting (3), (5), and $\Delta n = n_{cr} - n_D$ into this expression, we obtain $\tau_D = 4.5(d/V_{qM}) = 4.5\tau_d$, where τ_d is the interelectrode flight time.

In [3], a nonuniform structure was observed several seconds after switching on the field in a suspension of diatomite in kerosene with particles of dimension $r = (0.5\text{-}10) \cdot 10^{-6}$ m in a field of $8 \cdot 10^5$ V/m. The estimate (7) for this case is $\tau_D = 2$-10 sec.

In the derivation of (1)-(5) it is assumed [4] that the momentum relaxation time of the pulse is determined by the time $\tau_r \ll \tau$, where τ is the mean free flight time. For a gas filled capacitor, this is true only for micron particles. For larger particles, where gas-transverse momentum cannot relax in the time between collisions, a qualitative estimate can be obtained for the transverse diffusion parameters by replacing τ_r by the characteristic time between collisions for a given particle concentration.

For a small concentration, where $n \ll n_{in}$, the free path of the particle is determined by the time for moving between electrodes τ_d. Then

$$D_{\perp}^{*} = \left(\frac{\pi}{8}\right)^2 V_{q_M} d \frac{n}{n_{in}}; \quad \overline{\Delta l} \simeq \frac{\pi}{4} d. \tag{8}$$

At higher concentrations $n > n_{in}$, the mean free flight time is equal to $\tau = \tau_d (n_{in}/n)$ [4]; consequently:

$$D_{\perp}^{*} = \left(\frac{\pi}{8}\right)^2 V_{q_M} d \frac{n_{in}}{n}; \quad \overline{\Delta l} = \frac{\pi}{4} d \frac{n_{in}}{n}. \tag{9}$$

If $n \simeq n_{cr}$, then $\tau = \tau_d/2$ and

$$D_{\perp}^{**} = \frac{1}{8}\left(\frac{\pi}{4}\right)^2 V_{q_M} d \left(\frac{n_{in}}{n}\right)^2; \quad \overline{\Delta l} = \frac{\pi}{8} d \frac{n_{in}}{n}. \tag{10}$$

For a rather wide range of concentrations, it is characteristic that $D_{\perp}^{*} \sim 1/n$; consequently $\partial(D_{\perp}^{*}n)/\partial n \simeq 0$, which indicates the weakness of the diffusion mechanism for equating the concentration and a potential nonuniformity in the EDF system, even starting with rather small n's. The dimension of the nonuniformity in this case is $h \simeq 4.85 \cdot 10^{-3} d$ and $\Delta\overline{l} \simeq 0.22d$, so that for the assumed conditions these quantities do not depend on the material characteristics and are determined only by the interelectrode distance.

Equations (1)-(10) are obtained under the assumption that the electrical conductivity of the particles is large enough, so that the maximum charge q_M can be acquired at the electrode and the particle can recombine its charge with oppositely charged particles during the contact time τ_c; that is, it is assumed that the parameter $\tau_c/\tau_\sigma \gg 1$. The opposite case is examined in [7]. Then for $\tau_c/\tau_\sigma \ll 1$, the average charge of the particles is equal to $\bar{q} \simeq (q_M/2)(\tau_c/\tau_\sigma)$, which tends to lower the average particle velocity. As a result, for the case $\tau_c/\tau_\sigma \ll 1$ we can use (1)-(10) with a multiplier $[(1/2)(\tau_c/\tau_\sigma)]^k$, where k is equal to the exponent for the particle velocity in these expressions.

Besides the formation of a nonuniform structure in an EDF system, the formation of an interelectrode bridge is also noted, which increases the electrorheological effect [2, 3]. These phenomena evidently are caused by particle coagulation, which accompanies the EDF process in the presence of a developed transverse nonuniform structure. In order to determine the features which accompany particle coagulation under these conditions, we note several facts. First, coagulation is enabled by a relatively large particle concentration in cylindrical regions (bundles). This concentration remains constant at n_{cr}. Second, as has been shown [7], at concentrations close to n_{cr}, the EDF system consists mainly of weakly charged particles, where the density of the charged state has a gap at $q = 0$. The width Δ of the gap depends on the ratio t_c/t_σ and is maximized for $t_c/t_\sigma \simeq 1$. Third, the presence of large interparticle cohesion and adhesion to the electrode leads to the separation of precipitates between the electrodes with a layer thickness of h/2. The formation and maintenance of aggregates during a collision of different particles requires a weak charge on these aggregates, that is, the total charge of the colliding particles must be equal to zero.

Thus, the coagulation process in the EDF system, under conditions where a transverse nonuniform structure is developed, aggregates of bipolar charged particles form with charges $\pm\Delta/2$ in bundles with a concentration of n_{cr}, and then the separate aggregates grow and join. Describing this coagulation process as a whole is a separate problem. Nonetheless, at this stage it is sufficient to examine the problem of the probability of forming the primary aggregates, which consist of particle pairs with initial charges $\pm\Delta/2$. The rate for the formation of these aggregates for $V(\Delta/2) \simeq (\Delta/2)(E/s)$ can be written as:

$$\frac{dn_A}{dt} = \beta\Delta \frac{E}{s}\left(\frac{n_{in}}{2}\right)^2.$$

Then for the case $\tau_c/\tau_\sigma \ll 1$, we have $\Delta \simeq (q_M/2)(\tau_c/\tau_\sigma)^2$, $n_{cr} = 2n_{in}/(\tau_c/\tau_\sigma)$ [7], and $d(n_A/n_{in})/dt = 1/(2\tau_d)$. For the case of high-conductivity particles with $\tau_c/\tau_\sigma \gg 1$, we have $\Delta \simeq 2q_M \cdot \exp(-t_c/\tau_\sigma)$ [7], $n_{cr} \simeq 2n_{in}$, and consequently:

$$\frac{d(n_A/n_{in})}{dt} = \frac{2}{\tau_d} e^{-\tau_c/\tau_\sigma}.$$

Thus, the probability of coagulation for highly conducting particles is exponentially small compared to particles for which the parameter $\tau_c/\tau_\sigma \leq 1$. From these estimates it can be seen that the formation rate for aggregates is proportional to $1/\tau_d \sim E^2 d^{-2}$. Consequently, as the

electric field increases or the interelectrode distance decreases, the coagulation probability increases. This conclusion is confirmed by data [3], where suspensions of minerals exhibited the ability to coagulate for particles with lower electrical conductivity when the field was increased and the value of d was decreased.

It should also be noted that the volume which can be occupied by these coagulated aggregates does not exceed the relative volume of the bundles, which is $\sim (\overline{\Delta\ell})^2/(3\Delta\ell)^2 = 1/9$. Thus, increasing the bulk concentration above 10% does not lead to an increase in the thickness of the bridges and, consequently, to an increase in other effects which are caused by structure formation in the EDF system. Thus, the maximum effective viscosity of suspensions is reached for $n \simeq 10\%$ [2], which evidently is related namely to this fact.

Thus, it can be concluded that the transverse nonuniformity caused by the diffusion mechanism determines the linear and time characteristics of the transverse nonuniform structure in an EDF system.

NOTATION

r, particle radius; d, interelectrode distance; $\beta = 4\pi r^2$, scattering cross section; $n_{in} = 1/(\beta d)$, initial concentration; q_M, maximum particle charge; V_{qM}, maximum particle velocity; s, resistance of the medium per unit velocity; τ_r, momentum relaxation time; τ_c, contact time; τ_σ, charge relaxation time.

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LONGITUDINAL NONUNIFORMITY WITH A CONSIDERATION OF GRAVITY IN AN ELECTRODYNAMIC FLUIDIZATION SYSTEM

S. I. Zhebelev

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Results are presented of a calculation of a system of electrodynamically fluidized particles, considering the force of gravity, during recombination under conditions of a nonuniform concentration and electric field strength between the electrodes. The dependence of the maximum attainable concentration and the features of the particle-charge distribution function are discussed for this case.

Data from series of investigations indicate a significant nonuniformity in an electrodynamic fluidization (EDF) system in the direction parallel to the electric field. This nonuniformity is due to several factors. Thus, a nonuniform concentration and electric field strength were calculated considering the force of gravity for noninteracting particles [1]. A calculation of a step-function division of particles was calculated considering the momentum reduction of the particles after they strike the electrode [2, 3]. Here particle interaction and its effect on the limiting concentration in the presence of a nonuniform electric field were not considered. A statistical model was used [4-6] to obtain the particle-

S. M. Kirov Ural Polytechnic Institute, Ekaterinburg.

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