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 $\sim (\overline{\Delta l})^2/(3\overline{\Delta l})^2 = 1/9$. 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 $n \approx 10\%$ [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

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UDC 621.319

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-

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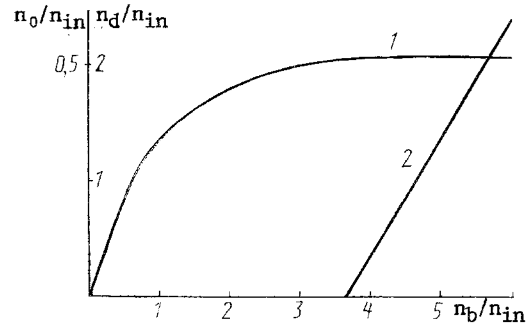

Fig. 1

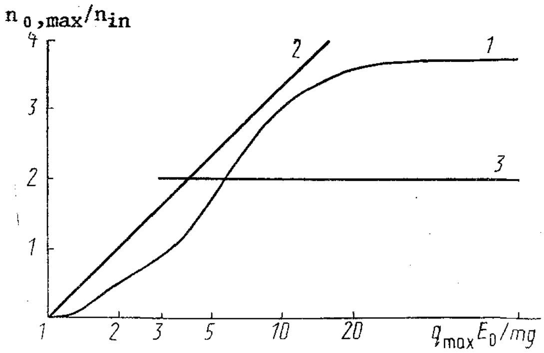

Fig. 2

Fig. 1. Relative concentrations of 1) fluidized particles n_0/n_{in} and 2) particles in the precipitation layer n_d/n_{in} versus the relative bulk concentration n_b/n_{in}.

Fig. 2. Maximum relative concentration of fluidized particles $n_{0,max}/n_{in}$ as a function of the parameter $q_{max}E_0/mg$: 1) according to the calculation considering the force of gravity; 2, 3) for a homogeneous system from data in [4].

charge distribution function and the maximum concentration considering a recombination mechanism. However, the EDF system was assumed to be uniform in this case. Here results are presented for a nonuniform EDF system considering the force of gravity and the charge recombination of the particles during collisions, and the effect of these factors on the maximum concentration is examined.

We use the Boltzmann kinetic equation, whose use in macroscopic systems has been discussed [5], to describe the EDF system. For an EDF process which has a relatively small concentration, the use of the kinetic equation is based on the short time between particle collisions compared to the free flight time. In the general case, the phase variables of the system — the coordinate $\mathbf{x}$, the velocity $\mathbf{V}$, and the charge q — determine a unique distribution function $f(\mathbf{x}, \mathbf{V}, q)$. We limit ourselves to the longitudinally nonuniform $x \parallel E$, which consists of high-conductivity particles of the EDF system, in which the velocity of a particle is determined by its charge $V(x) = [qE(x) + mg]/s$. As in [4], this means that the free flight time is much longer than the impulse relaxation time $\tau \gg \tau_r = m/s$, and the distribution function depends only on the longitudinal coordinate and the charge: $f = f(x, q)$. In order to discretize the problem we divide the interelectrode gap into M parallel layers, and consider the EDF system uniform in each of them. The maximum concentration has been determined [4, 5] by equating the chemical potentials of the fluid and the solid phases of the EDF system. Here it is possible to introduce a direct description of the layer of deposits on the surface of the lower electrode into the equation for conserving the number of particles

$$n_b = n_d + n_s + n_0,$$
$$n_0 = \frac{1}{M}\sum_{m=1}^{M} n_m, \qquad (1)$$

where n_b is the bulk particle concentration; n_d is the particle concentration in the precipitation layer; n_s is the particle concentration in the precipitation surface; and n_m is the particle concentration in the m-th layer, ratioed to a unit volume of the layer. Here the maximum concentration in the surface layer of the precipitation is determined by the volume concentration of a monolayer: $n_{s,max} = 1/[(2r)^2 d]$.

For a discrete charge spectrum of EDF particles, we obtain

$$f(x, q) = \sum_i f_{m,i}\delta(q - q_i), \quad m = s, 1, \ldots, M. \qquad (2)$$

Substituting (2) into the kinetic equation gives

$$d_m \frac{\partial f_{m,i}}{\partial t} = 2\frac{n_m}{n_{in,m}} \sum_{k,j} |V_{m,k} - V_{m,j}| f_{m,k} f_{m,j} - \frac{n_m}{n_{in,m}} \sum_{j \neq i} |V_{m,i} - V_{m,j}| f_{m,i} f_{m,j} - |V_{m,i}| f_{m,i} \qquad (3)$$

$$+\frac{n_{m-1}}{n_m}\underset{V_{m-1,i}>0,\ m>n}{|V_{m-1,i}|\,f_{m-1,i}}+\frac{n_{m+1}}{n_m}\underset{V_{m+1,i}<0,\ m<M}{|V_{m+1,i}|\,f_{m+1,i}}+\sum_{V_{m,j}>0}|V_{m,j}|\,f_{m,j}\delta(q_i-q_{\max,M})\,\delta(m-M), \tag{3}$$

where $n_{in,m} = 1/(\beta d_m)$ is the initial particle concentration in the m-th layer, and $V_{m,i}$ is the particle velocity with charge q_i in the m-th layer.

In (3) the first two terms on the right side determine the change in the charge state of the particles due to the recombination mechanism; the third, fourth, and fifth determine the exchange of states between layers, and the sixth the charge transfer to particles at the upper electrode. For the precipitation layer surface we have

$$d\frac{\partial f_{\mathrm{s},i}}{\partial t}=\sum_{V_{\mathrm{s},j}<0}|V_{\mathrm{s},j}|\,f_{\mathrm{s},j}\delta(q_i+q_{\max,\mathrm{s}})-|V_{\mathrm{s},i}|\,f_{\mathrm{s},i}+\frac{n_1}{n_{\mathrm{s}}}\underset{V_{1,i}<0}{|V_{1,i}|\,f_{1,i}}, \tag{4}$$

where the first term on the right side determines the charge transfer to the particles, and the others the exchange with the lower layer of fluidized particles. Integration of (3) and (4) gives a balance equation for the concentrations:

$$d_m\frac{\partial n_m}{\partial t}=n_{m-1}\sum_{V_{m-1,j}>0,\ m>n}|V_{m-1,j}|\,f_{m-1,j}+n_{m+1}\sum_{V_{m+1,j}<0,\ m<M}|V_{m+1,j}|\,f_{m+1,j}-n_m\sum_j|V_{m,j}|\,f_{m,j}. \tag{5}$$

In each layer m, m = 1, ..., M, the charge density is determined as $\rho_m=n_m\sum\limits_i q_i f_{m,i}$. Then for the piecewise constant charge density in the layer, Poisson's equation with boundary conditions for the potential gives the piecewise linear strength of the electric field, whose value $E_{m-1,m}$ at the boundary between layers is determined as

$$E_{m,m+1}=E_{m-1,m}-\frac{d_m\rho_m}{\varepsilon_0} \tag{6}$$

for

$$E_{\mathrm{s},1}=E_0+\frac{d_m}{\varepsilon_0 M}\sum_{m=1}^{M}\rho_m\left(M+\frac{1}{2}-m\right), \tag{7}$$

where $E_0 = U/d$ is the strength of the initially uniform electric field. The particle velocity in the layer is determined by the average field strength in the layer:

$$\begin{gathered}V_{m,i}=(q_i\bar{E}_m+mg)/s,\\ \bar{E}_m=(E_{m-1,m}+E_{m,m+1})/2.\end{gathered} \tag{8}$$

For the charge transfer, we take for the upper electrode $Q_{\max,M} = q(E_{M-1,M})$. In the surface deposit layer $q_{\max,s} = q(E_{s,1})$; $V_{s,i} = V(E_{s,1})$, where the dependence of the charge on field strength is computed from the standard formula [7]. The system of equations (3)-(5) considering (6)-(8) for $d_m = d/M$, is solved by the equilibration method [6] with the use of the characteristic parameter T_m, is the average flight time of a particle in the m-th layer: $T_m=C\frac{d_m}{V_m}$; $V_m=\sum\limits_i|V_{m,i}|f_{m,i}$, C < 1. The solution of this system reduces to an iteration procedure

$$\begin{bmatrix} f\\ n\end{bmatrix}^{s+1}=\begin{bmatrix} f\\ n\end{bmatrix}^{s}+\frac{C}{V}\{\ldots\}^{s}, \tag{9}$$

where {...} is the right side of Eqs. (3)-(5), computed for the s-th time step. For a given bulk concentration n_b, a normalization is done at each step:

$$n_{\mathrm{s}}^{s+1}=\begin{cases}n_{\mathrm{s}}^{s}+n_{\mathrm{d}}^{s}, & n_{\mathrm{s}}^{s}+n_{\mathrm{d}}^{s}<n_{\mathrm{s},\max},\\[2ex] n_{\mathrm{s},\max}, & n_{\mathrm{s}}^{s}+n_{t}^{s}>n_{\mathrm{s},\max},\end{cases} \tag{10}$$

$$n_{\mathrm{d}}^{s+1}=\begin{cases}0, & n_{\mathrm{s}}^{s}+n_{\mathrm{d}}^{s}<n_{\mathrm{s},\max},\\ n_{\mathrm{b}}-\frac{1}{M}\sum n_m^{s}-n_{\mathrm{s}}^{s+1}, & n_{\mathrm{s}}^{s}+n_{\mathrm{d}}^{s}>n_{\mathrm{s},\max}.\end{cases}$$

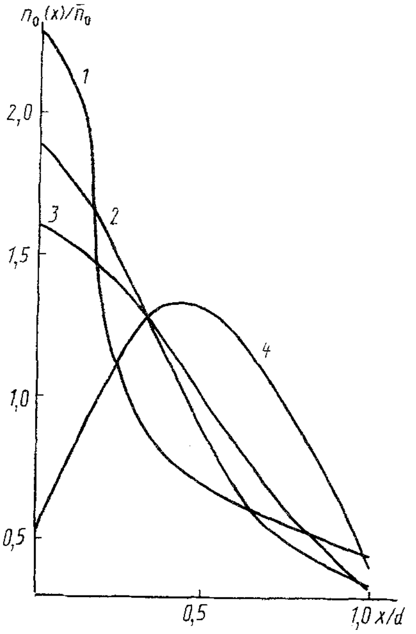

Fig. 3

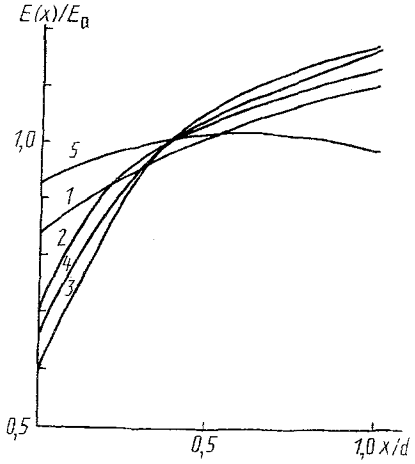

Fig. 4

Fig. 3. Distribution of the relative particle concentration over the interelectrode gap $n(x)/\bar{n}_0$ for values of the parameter $q_{max}E_0/mg$: 1) 2; 2) 5; 3) 10; 4) 100.

Fig. 4. Electric field intensity in the interelectrode gap for values of the parameter $q_{max}E_0/mg$: 1) 1.5; 2) 2; 3) 5; 4) 10; 5) 100.

At the beginning of the calculation for each value of n_b it is assumed that $n_m = 0$, and $n_d + n_s = n_b$ with the normalization (10). Therefore the system of equations is solved by tracing the process of the particle distribution and by forming the distribution function by layers. The convergence of the iteration is monitored, not only by the quadratic norm of (9), which is usual in such cases, but also by estimating the proximity of the current density by layers:

$$J_m = n_m \sum_i q_i V_{m,i} f_{m,i}. \tag{11}$$

Figure 1 shows the concentrations of the fluidized phase and the solid phase of the EDF system as functions of the bulk concentration for $q_{max}E_0/mg = 2$ when $Q_{max} = q(E_0)$. For small values of n_b there is no precipitation layer. As the bulk concentration grows, the number of fluidized particles saturates. This is accompanied by the appearance and growth of the concentration of the solid phase in proportion to the bulk concentration. The concentration $n_{0,max}$ is the maximum possible concentration of the fluidized phase. Figure 2 shows $n_{0,max}$ as a function of $q_{max}E_0/mg$. It can be seen that this function has three characteristic regions. For small values of $q_{max}E_0/mg = 1$-3, the EDF system is very nonuniform. Most of the particles are directly next to the electrode (Fig. 3). In this case, the nonuniformity grows as $q_{max}E_0/mg$ grows (Fig. 4). Figure 5 shows the particle distribution function vs. charge in the layer next to the precipitation surface layer. For $q_{max}E_0/mg =$ 1-3, the fluidized phase basically contains particles whose charge is determined by the self-consistency of the field in the surface layer. The maximum concentration in this case is determined by the strength of this field, for which $q_{max,s}E_{s,1} \simeq mg$. A further increase in n_0 leads to an increase in the charge density in the lower layer and a decrease in $q_{max,s}$ and $E_{s,1}$ such that increasing the number of particles becomes impossible. At values $q_{max}E_0/mg = 3$-10, a transition occurs from the field mechanism for limiting the concentration of the fluidized particles to a recombination mechanism. For $q_{max}E_0/mg > 10^2$, n_0 is limited almost completely by the formation of a weakly charged EDF system [4]. However, in this case, both the field and the concentration are nonuniform, due to a known effect which occurs in systems which contain cross flows of differently charged recombining particles. Here a symmetric longitudinal particle-concentration nonuniformity arises with charges of various signs, which leads to nonuniformities in the charge density and, correspondingly,

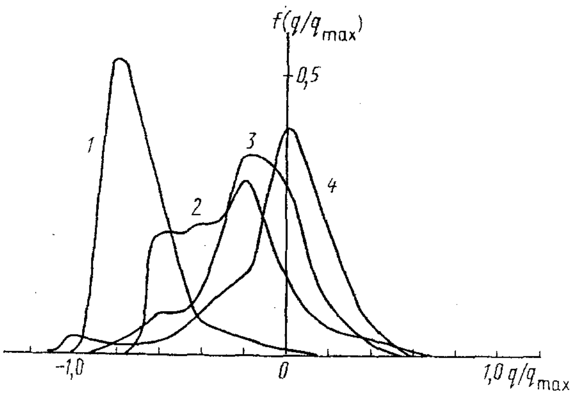

Fig. 5. Distribution function by charge for the lower layer of fluidized particles for values of the parameter $q_{max}E_0/mg$: 1) 2; 2) 5; 3) 10; 4) 100. q/q_{max}, rel.units.

in the electric field strength. This effect has been observed in EDF processes [2, 7], although the estimates are not reliable. As can be seen from Figs. 3 and 4, this mechanism has a rather small effect on E(x), although it does lead to a marked nonuniformity in the concentration. The distribution function in this case, by becoming asymmetric in each layer, becomes symmetric relative to the layers equidistant from the center in the interelectrode gap. Thus, if the lower layer contains particles with charge $-q_{max}$ and almost no particles with charge $+q_{max}$, then the reverse is true in the upper layer. Overall, however, just as in [4], the EDF system basically contains weakly charged particles. When the parameter $q_{max}E_0/mg$ exceeds 10^2, the quantity $n_{0,max}/n_{in} \simeq 4$, which agrees with results [4] obtained with the assumption of a uniform EDF system.

Thus, the effect of this mechanism on the maximum concentration of fluidized particles can be considered insignificant under the assumed conditions. Figure 2 also shows estimates of the quantity $n_{0,max}$ obtained in [4, 5]. In the first case, for $q_{max}E_0/mg \gg 1$, the estimate is $n_{0,max} \simeq 2n_{in}$ and does not depend on $q_{max}E_0/mg$. As can be seen from our calculations, and also in [4], this estimate gives low values of $n_{0,max}$ by almost a factor of two. Therefore, for engineering calculations one can assume $n_{0,max} \simeq 4n_{in}$ for $q_{max}E_0/mg \gg 1$. In the second case, the effect of the force of gravity is considered in the calculation: $n_{0,max} = n_{in}\ln(q_{max}E_0/mg)/\ln 2$. This estimate gives high values of $n_{0,max}$, again by roughly a factor of two for $q_{max}E_0/mg = 1$-3 using the field mechanism and almost agrees with the function for $n_{0,max}$ for $q_{max}E_0/mg = 5$-10, when the recombination mechanism starts to limit the concentration. Accordingly, for engineering calculation we can take $n_{0,max} = n_{in}\ln(q_{max}E_0/mg)/(2\cdot\ln 2)$ for $q_{max}E_0/mg = 1$-3.

In conclusion, we must examine the problem of applying this calculation to situations where the initial assumptions are not fulfilled. This can occur, for example, for relatively large particles in low-viscosity media. In this case, the charged particles do not "drift" due to their large translation velocity. However, as was shown above for the field mechanism for limiting the concentration, a rough equality occurs between the force of gravity and the force acting on the particle from the self-consistent electric field; therefore the particle velocities are small. In the reverse case of the recombination for limiting the concentration, the low translation velocity of the particle is caused by the formation of a weakly charged EDF system.

Thus, a low particle velocity at the maximum concentration gives the basis to assume that the qualitative dependence of $n_{0,max}$ on the parameter $q_{max}E_0/mg$ is preserved even for wider assumptions on the nature of the particle motion.

NOTATION

r, particle radius; m, particle mass; d, interelectrode distance; U, potential difference; s, resistance of the medium per unit velocity; $\beta = 4\pi r^2$, scattering cross section; $n_{in} = 1/(\beta d)$, initial concentration.

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MODELLING THE COMBUSTION OF HIGH-ASH CONTENT SOLID FUEL IN CIRCULATING SYSTEMS

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UDC 662.61

We analyze the complete combustion of high-ash content fuel in circulating systems, based on the solution of the equation for the probability density distribution of particles by size and carbon content.

The concept of the creation of ecologically clean methods of processing solid fuels has forced a reconsideration of the merits of traditional torch and bed methods of combustion. It has brought about the first plan for a system with multiple cycling of fuel and ash through external cyclones: furnaces with circulating fluidized or air-charged beds [1-4]. However, despite the significant practical achievements in creating furnaces with circulating fluidized (or air-charged) beds, methods for calculating such devices have only just begun to be developed [5-11]. Naturally, therefore, further progress in realizing circulating systems of solid fuel combustion is linked to the development of methods to mathematically model the relevant processes in these systems. In this work, we analyze certain models of the complete combustion of high-ash content fuel as applied to furnaces with external loop circulation of solid material.

1. To develop the theory for calculating circulating combustion systems, it is necessary to determine the character of the behavior of the ash in the process of complete fuel combustion. Depending on this character, one of the models of carbon particle structure is adopted. In the simplest case, it is assumed that there is complete separation of the ash from the solid carbon in fuel processing devices, which is called the "external ash" model. In this model, the ash has virtually no effect on coke combustion, and calculation of the fractional state of the fuel, number of circulation repetitions and other characteristics of the circulating system reduce to solving the equation for the density distribution by size of the carbon particles and the ash [10]. The "segregated ash" model which circulates in the literature essentially leads to the same computational scheme as that for the carbon particles. Within the framework of this model, it is assumed that the ash is separated and falls out of the particles in the process of combustion. As a rule, this model is valid for low-ash content fuels. For calculating the combustion of high-ash content fuels, the "contracting fuel nucleus" ("progressive ash sheath") and the "volumetric reaction" models have gained wide currency. When using the first of these, it is assumed that diffusion resistance to the transport of oxidizer inside the unburned nucleus is infinitely large, and the heterogeneous chemical reaction takes place at the boundary between the constant-density nucleus and the ash sheath. The "contracting fuel nucleus" model is applied to low-porosity coal with ash which is capable of forming a stable shell. In the "volume reaction" model, it is assumed that combustion takes place throughout the entire volume of the particle (in which case its dimension remains unchanged). As a result, the volumetric concentration of carbon and the density of the particle are decreasing. This model is valid for coals with large amounts of volatiles: after their release, a highly porous structure is formed. In the general case, the outer radius of the particle R, the radius of the fuel nucleus r (the thick-

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