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# CHARACTERISTICS OF THE MOTION AND DISTRIBUTION OF THE SOLID PHASE IN A JET DISCHARGING INTO A FLUIDIZED BED

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A model of the motion of the solid phase from the bed into a jet is proposed. A method for calculating the velocity field and solid-particle concentration field in the volume of the jet is developed.

The efficiency of technological equipment with a fluidized bed is often determined by processes occurring in jet flow, occurring in the bed during the operation of separate pieces of equipment (gas-distribution gratings, pneumatic nozzles, burners, etc.). In order to calculate and model these processes the characteristics of the motion and distribution of the solid particles in the volume of the jet, discharging into the fluidized bed, which have never been adequately studied, must be known. Existing studies of jet flows in a fluidized bed are concerned primarily with the analysis of the motion of the gas phase [1].

The characteristics of the motion and distribution of the solid phase in a jet discharging into a fluidized bed can be determined most completely based on the velocity and concentration fields. The calculation of these fields, however, is a complicated problem, which can be solved only with the use of approximate models for the real mechanism of transport of solid particles in the jet.

We shall base this model on the assumption that the transport of solid particles is determined completely by the motion of the gas. In the longitudinal direction it is determined by the convective component, while convection and turbulent diffusion are responsible for radial transport. We assume that solid particles do not affect the nature of the velocity field of the gas phase. This assumption is based on well-known experimental data [2, 3], which indicate that the volume concentration of the solid phase in the boundary layer of the jet is much lower than in the fluidized bed. These data also make it possible to neglect the interaction between the monodispersed particles. We assume that the gas phase of the jet

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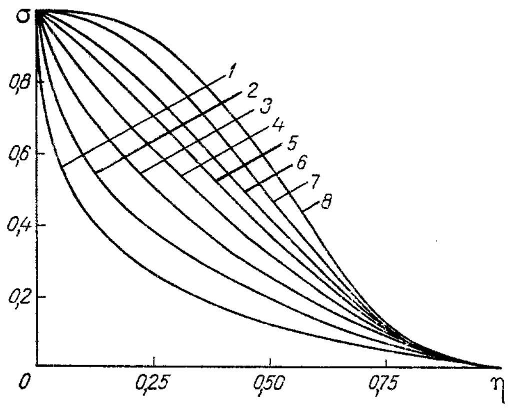

Fig. 1. Profiles of the concentrations of the solid phase in transverse sections of the jet: 1) $\beta$ = 0.01; 2) 0.1; 3) 0.2; 4) 0.3; 5) 0.4; 6) 0.5; 7) 0.7; 8) 1.0.

is an incompressible medium, whose properties are analogous to those of the gas which fluidizes the bed; this usually corresponds to the conditions which are realizable in practice. In order to simplify the problem we shall confine our analysis to the main section of an axisymmetric jet, and in addition, because of the curvilinear nature of the boundaries of a jet discharging into a fluidized bed [2] we assume that the pole of the jet is located in its initial section. We also neglect the nonuniformity of the velocity profile of the gas in the initial section of the jet, and we assume that the solid particles are spherical. We are interested in the case of efflux of a jet with quite high velocity (exceeding the terminal velocity of the particles), so that of all the forces acting on the solid particles in the gas flow we take into account only the inertial and drag forces.

These physical prerequisites and restrictions make it possible to formulate the problem mathematically using the equations of the boundary layer (equation of continuity and motion for the gas phase, diffusion equation for the solid phase), the equation of motion for one solid particle, and an integral realtion for the conservation of momentum over the length of the jet, written for the average parameters of motion of the phases

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{v}{y}=0; \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\varepsilon_k}{y}\frac{\partial}{\partial y}\left(y\frac{\partial u}{\partial y}\right); \tag{2}$$

$$U\frac{\partial \alpha}{\partial x}+V\frac{\partial \alpha}{\partial y}+\alpha\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{V}{y}\right)=\frac{\varepsilon_d}{y}\frac{\partial}{\partial y}\left(y\frac{\partial \alpha}{\partial y}\right); \tag{3}$$

$$2\pi\rho\int_0^b u(u-u_b)\,y\,dy+2\pi\rho_s\int_0^b(\alpha_b-\alpha)\,U(U-U_b)\,y\,dy=$$
$$=\rho u_0(u_0-u_b)\,\pi r_0^2; \tag{4}$$

$$\frac{dU}{d\tau}=\frac{3}{4}c\frac{\rho}{D_s\rho_s}(u-U)^2. \tag{5}$$

In view of the fact that in this problem we are interested only in the integral characteristics of the jet, while the characteristics of the turbulent transport are not analyzed, one of the well-known semiempirical theories of turbulence can be used to determine the relationship between the effective coefficient of turbulent viscosity and the average parameters of the flow [4].

We shall use the simplest "new" Prandtl theory of turbulence

$$\varepsilon_k=\varkappa b(u-u_b), \tag{6}$$

which was previously successfully used to describe jet flows in a fluidized bed [2, 5]. In this case, by analogy with free jets, we assume that $\varepsilon_k(y)$ = const, and we express the radius of the jet as

$$b=Kx. \tag{7}$$

To solve the problem we conditionally divide the jet in the longitudinal direction into sections of length $\Delta x$, which is short enough so that within each section it may be assumed that $u(x) = \text{const}$. In this case, the velocity of the gas phase can be assumed to very in a jumplike manner along the length of the jet at the boundaries of the sections.

We introduce the dimensionless variables

$$Z(\eta) = \frac{u - u_b}{u_m - u_b}; \quad f(\eta) = \frac{u}{u_m};$$
$$\sigma(\eta) = \frac{\alpha_b - \alpha}{\alpha_b - \alpha_m}; \quad \frac{y}{b} = \eta \tag{8}$$

and study any arbitrarily chosen section $\Delta x$. For this section, based on the continuity equation (1), after expressing the components of the average velocity of the gas phase in terms of the stream function $\varphi(\eta) = \int uydy$, substituting them into the equation of motion of the gas phase (2), and performing the corresponding transformations we obtain

$$-2u_m Z'(\eta) F(\eta) = \frac{\varepsilon_k}{K^2 x}[\eta Z'(\eta)]', \tag{9}$$

where $F(\eta) = \int f(\eta)d\eta$ is the dimensionless form of the stream function. We differentiate Eq. (9) and eliminate from it the dimensionless stream function $F(\eta)$. As a result we write the equation of motion of the gas phase

$$Z'''(\eta) Z'(\eta) + \frac{Z''(\eta) Z'(\eta)}{\eta} - [Z''(\eta)]^2 + \frac{2K}{\varkappa}[Z'(\eta)]^2 Z(\eta) + \frac{2Km}{\varkappa(1-m)}[Z'(\eta)]^2 = 0 \tag{10}$$

with the boundary conditions

$$\eta = 0; \quad Z(0) = 1; \quad Z'(0) = 0;$$
$$\eta = 1; \quad Z(1) = 0, \tag{11}$$

where

$$m = u_b/u_m. \tag{12}$$

The experimental studies of the velocity fields of the gas phase in a jet, discharging into a fluidized bed [2, 3, 6], indicate the similarity of the distributions of the velocities in the transverse sections of the jet, presented in the dimensionless form, and the possibility of approximating the profile obtained by the well-known Shlichting function

$$Z(\eta) = 1 - 2\eta^{3/2} + \eta^3. \tag{13}$$

Substituting the function (13) into Eq. (10) and integrating it with the boundary conditions (11), we obtain the dependence for determining the coefficient K relating, according to the expression (7), the radius of the jet and the longitudinal coordinate x:

$$K = \frac{81}{4}\varkappa\frac{1-m}{1+1{,}5m}. \tag{14}$$

In order to take into account the relative motion of the phases and to transform the diffusion equation for the solid phase (3) we introduce the concept of the coefficient of slipping, expressing it in terms of the longitudinal components of the velocities of the gas and solid phases:

$$\beta = U/u. \tag{15}$$

To a first approximation we shall assume that an analogous relationship also exists for the radial components of the velocities of the phases, and in addition we shall assume that the coefficients of slipping in both cases are equal and constant in the transverse cross sections of the jet, i.e, $\beta(y) = \text{const}$. Then Eq. (3), taking into account the equation of continuity (1), can be written in the form

$$\beta u\frac{\partial\alpha}{\partial x} + \beta v\frac{\partial\alpha}{\partial y} = \frac{\varepsilon_d}{y}\frac{\partial}{\partial y}\left(y\frac{\partial\alpha}{\partial y}\right). \tag{16}$$

Transforming to dimensionless variables in Eq. (16) and carrying out the corresponding transformations, we obtain

TABLE 1. Values of the Integrals $B_1$ and $B_2$

| $\beta$ | 0,001 | 0,1 | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,7 | 0,8 | 0,9 | 1,0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $B_1$ | 0,0154 | 0,0228 | 0,0298 | 0,0355 | 0,0399 | 0,0432 | 0,0457 | 0,0477 | 0,0493 | 0,0507 | 0,0518 |
| $B_2$ | 0,0232 | 0,0346 | 0,0454 | 0,0544 | 0,0614 | 0,0668 | 0,0710 | 0,0744 | 0,0772 | 0,0795 | 0,0815 |

$$-2u_m\sigma'(\eta)F(\eta)=\frac{\varepsilon_d}{\beta K^2 x}[\eta\sigma'(\eta)]'. \tag{17}$$

After dividing Eq. (17) by (9) we represent the diffusion equation of the solid phase in the form

$$\frac{[\eta\sigma'(\eta)]'}{\eta\sigma'(\eta)}=\beta \mathrm{Sc}_T\frac{[\eta Z'(\eta)]'}{\eta Z'(\eta)}, \tag{18}$$

where $\mathrm{Sc}_T = \varepsilon_k/\varepsilon_d$ is the turbulent Shmidt number. The boundary conditions of this equation have the form

$$\begin{aligned}&\eta=0;\quad \sigma(0)=1;\\&\eta=1;\quad \sigma(1)=0.\end{aligned} \tag{19}$$

After double integration we obtain the solution of Eq. (18) in the form of a dependence relating the concentration of the solid phase in the radial direction of the jet to the velocity of the gas phase:

$$\sigma(\eta)=1-\frac{\int\limits_0^\eta \frac{[\eta Z'(\eta)]^{\beta \mathrm{Sc}_T}}{\eta}d\eta}{\int\limits_0^1 \frac{[\eta Z'(\eta)]^{\beta \mathrm{Sc}_T}}{\eta}d\eta}. \tag{20}$$

To calculate the distribution of the solid phase in the transverse sections of the jet using the dpeendence (20) it is necessary to know the values of $\mathrm{Sc}_T$ and $\beta$.

At the present time there is no information about the turbulent Shmidt number for jets discharging into a fluidized bed. To estimate it we shall use the data obtained for a two-phase jet with an admixture of solid particles [7]. According to these data the tubulent Schmidt number varies slightly over the volume of the jet and to a first approximation can be assumed to equal $\mathrm{Sc}_T \approx 2$. We shall use this value in further calculations.

As an analysis of the dependence (20) shows, the concentration profile of the solid phase in the transverse sections, unlike the velocity profile, even with a constant value of the turbulent Schmidt number, varies along the length of the jet, which is a result of the variation in the coefficient $\beta$. It follows from Fig. 1 that the concentration profile of the solid phase transforms from a concave profile for small values of $\beta$ to a convex profile at large values of $\beta$.

We shall determine the coefficient of slipping of the phases from the solution of the equation of motion (5) of a single solid particle. For this, after expressing the velocity of the particle in terms of the time derivative of the longitudinal coordinate, we write Eq. (5) in the form

$$U\frac{dU}{dx}=\frac{3}{4}c\frac{\rho}{D_s\rho_s}(u-U)^2. \tag{21}$$

In this case the drag of the solid particle in the gas flow can be determined from the known laws [8], but taking into account the fact that in practice comparatively large particles and substantial efflux velocities of the jet, ensuring a developed turbulent state, are used in the fluidized bed, we shall adopt Newton's law, i.e., C = 0.44. Then Eq. (21), substituting (15), assumes the form

$$\frac{d\beta}{dx}=\psi\left(\frac{1}{\beta}+\beta-2\right), \tag{22}$$

where $\psi = 0.33\rho/D_s\rho_s$.

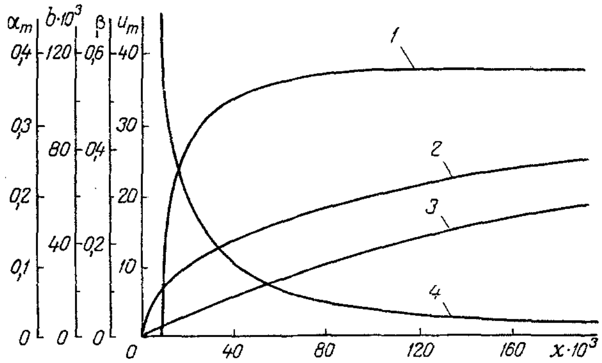


Fig. 2. Variation of the main parameters along the length of the jet: 1) $\alpha_m(x)$; 2) $\beta(x)$; 3) $b(x)$; 4) $u_m(x)$. $u_m$, msec; b, x, m.

Studying the motion of the particle on the section Δx, we write the boundary conditions for Eq. (22)

$$x = x_{n-1}, \quad \beta = \beta_{n-1}; \qquad x = x_n; \quad \beta = \beta_n, \tag{23}$$

where n is the number of the section. Integrating Eq. (22) on the section Δx with the boundary conditions (23), we obtain

$$x_n = x_{n-1} + \frac{1}{\psi}\left(\frac{1}{1-\beta_n} - \frac{1}{1-\beta_{n-1}} + \ln\left|\frac{1-\beta_n}{1-\beta_{n-1}}\right|\right). \tag{24}$$

We shall determine the distribution of the solid phase along the axis of the jet from the integral momentum relation (4). Transforming to dimensionless variables and substituting (15), we write this equation in the following form:

$$2\rho u_m^2 b^2 \int_0^1 f(\eta)[f(\eta) - m]\,\eta d\eta + 2\rho_\text{т}\beta^2(\alpha_b - \alpha_m) u_m^2 b^2 \int_0^1 \sigma(\eta) f(\eta)[f(\eta) - m]\,\eta d\eta = \rho u_0 (u_0 - u_b) r_0^2. \tag{25}$$

Having established a relationship between the functions f(η) and Z(η) with the help of the second relation of (8) and the dependence (13), and carrying out the corresponding transformations, we obtain

$$\alpha_m = \alpha_b - \frac{\rho}{\rho_\text{т}\beta^2}\left[\frac{(1-m_0) r_0^2}{2m_0^2 b^2 Q_2} - \frac{Q_1}{Q_2}\right], \tag{26}$$

where $m_0 = u_b/u_0$:

$$Q_1 = \frac{243}{3640}\left(\frac{1-m}{m}\right)^2 + \frac{9}{70}\left(\frac{1-m}{m}\right); \qquad Q_2 = B_1\left(\frac{1-m}{m}\right)^2 + B_2\left(\frac{1-m}{m}\right); \tag{27}$$

$$B_1 = \int_0^1 \sigma(\eta)[Z(\eta)]^2\,\eta d\eta; \quad B_2 = \int_0^1 \sigma(\eta) Z(\eta)\,\eta d\eta. \tag{28}$$

The integrals $B_1$ and $B_2$ here are determined by the numerical integration with fixed values of β (the results of the calculations are presented in Table 1).

The dependences obtained permit calculating the velocity field and the concentration field of the solid phase in a jet discharging into a fluidized bed. The starting data for this calculation are $u_b$, $\alpha_b$, $\rho_s$, ρ, $D_s$, $r_0$. In addition, it is also necessary to know the value of the test coefficient of the jet ϰ and the velocity distribution of the gas phase along the axis of the jet $u_m(x)$, which is determined experimentally or calculated using well-known models [2, 5, 9]. The calculation is carried out in the following order.

1. Choosing values of the coefficient of slipping from $\beta_0$ to $\beta_k$ (n = 1, 2, 3, ..., k), we partition the jet in the longitudinal direction into sections Δx.

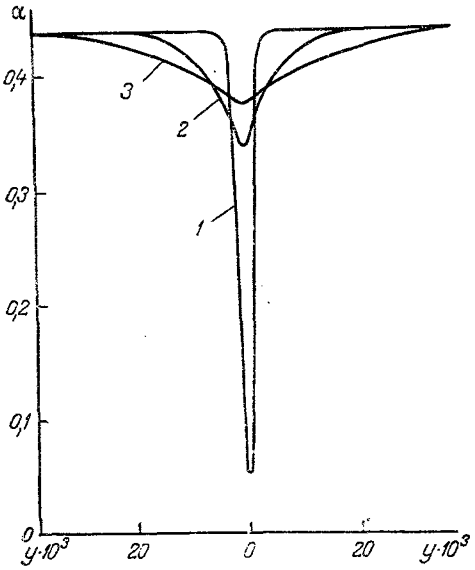


Fig. 3. Distribution of the solid phase in the jet: 1) $x = 8.3 \cdot 10^{-3}$ m; 2) $38.5 \cdot 10^{-3}$; 3) $103.2 \cdot 10^{-3}$. y, m.

2. We calculate the longitudinal coordinate of the boundaries of the sections $x_n$ from the dependence (24), under the assumption that in the starting section of the jet $x_0 = 0$, $\beta_0 = 0$.

3. For each section successively, starting with n = 1, we determine the parameters which vary along the jet: the function $\sigma(\eta)$, the integrals $B_1$ and $B_2$, the relative velocity of the gas phase on the axis of the jet m, the quantities $Q_1$ and $Q_2$, the coefficient K, the radius of the jet b, and the concentration of the solid phase on the jet axis $\alpha_m$, using for this the dependences (20), (28), (12), (27), (14), (7), and (26). The calculations are performed taking into account the fact that the axial velocity of the gas phase is constant in a section $\Delta x_n$ and corresponds to the velocity determined from the given dependence $u_m(x)$ at $x_n$.

4. With the help of the dependences (8), (15), (13), and (20) we calculate the velocity of the gas and solid phases as well as the concentration of the solid phase in the sections of the jet.

Such a calculation was carried out for a jet discharging into a fluidized bed under the following conditions: $u_0 = 50$ m/sec; $r_0 = 2.0 \cdot 10^{-3}$ m; $D_T = 0.5 \cdot 10^{-3}$ m; $\rho_s = 1100$ kg/m³; $\rho = 1.16$ kg/m³. The velocity of the gas and the concentration of the solid particles on the boundary of the jet were assumed to equal the working velocity of the gas in the apparatus and the average concentration of the gas phase in the fluidized bed with W = 5. The distribution of the velocity of the gas phase along the axis of the jet was determined using the well-known formula of G. A. Minaev [1, 9] (Fig. 2, curve 4).

The coefficient of the jet $\varkappa$ was evaluated approximately, starting from the presence of a potential core in the jet [1], indicating that the solid particles, entering the jet from the fluidized bed, reach the axis of the jet at a definite distance from the ends of the initial section. There are no solid particles at this distance on the axis of the jet, i.e., $\alpha_m = 0$. this is also confirmed by an analysis of the dependence (26), according to which the calculation of the concentration of the solid phase on the axis of the jet is physically meaningful only for values of the longitudinal coordinate x (which affects the concentration through β, b, $Q_1$ and $Q_2$), exceeding a definite value. If it is assumed that the solid particles reach the axis of the jet on its transitional section, whose length can be determined from empirical dependences presented in [9], the, substituting the values $x = x_{trans}$, $\alpha_m = 0$ into the dependence (26) and transforming it, we obtain

$$\varkappa = \frac{4r_0(1+1.5m_{trans})}{81(1-m_{trans})x_{trans}m_0}\sqrt{\frac{(1-m_0)\rho}{2(\alpha_b\rho_s\beta^2_{trans}Q_{2trans}+\rho Q_{1trans})}}.$$

Here the parameters $m_{trans}$, $\beta_{trans}$, $Q_{1trans}$, $Q_{2trans}$ correspond to $x_{trans}$. The coefficient of the jet determined in this manner for the conditions indicated above equals 0.022.

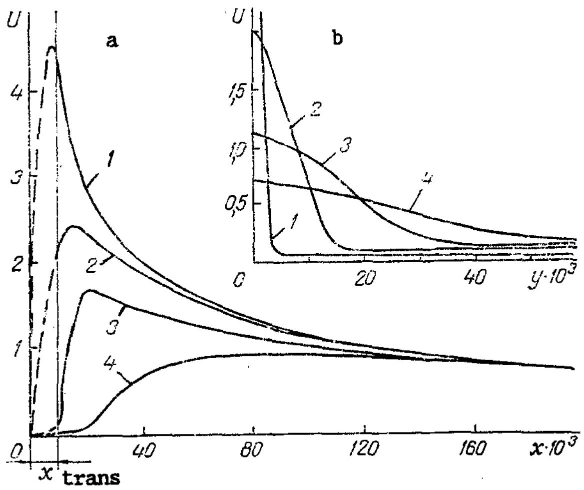


Fig. 4. Variation of the velocity of the solid phase: a) in the longitudinal direction (1) $y = 0.0 \cdot 10^{-3}$ m; 2) $2.0 \cdot 10^{-3}$; 3) $5.0 \cdot 10^{-3}$; 4) $10.0 \cdot 10^{-3}$); b) in the radial direction (1) $x = 8.3 \cdot 10^{-3}$ m; 2) $38.5 \cdot 10^{-3}$; 3) $103.5 \cdot 10^{-3}$; 4) $223.8 \cdot 10^{-3}$). U, m/sec.

Analysis of the computational results shows that the particle concentration along the jet (Fig. 2, curve 1) increases from zero in the zone near the attachement to a value approaching the concentration in the layer. In addition, the main increase in the concentration (up to 90%) occurs near the transitional section of the jet. The concentration of solid particles varies analogously also in the transverse sections of the jet (Fig. 3), assuming values from the minimum value on the axis of the jet to the concentration at the boundary of the jet. From the curve showing the variation of the radius of the jet along the length of the jet (Fig. 2, curve 3) it is evident that the jet, discharging into the fluidized bed, has boundaries which expand at an angle of 20-25°. As the distance from the attachment increases, the magnitude of the expansion of the jet decreases. The dependence of the coefficient of slipping on the longitudinal coordinate (see Fig. 2, curve 2) is characterized by the fact that near the attachment it grows rapidly, and away from it it grows slowly. This can be explained by the characteristics of the motion of the phases in the jet. The velocity of the gas phase is highest near the attachment, while the longitudinal component of the velocity of the solid phase is negligibly small. As a result, in the initial section $\beta \to 0$ and the phases have a high dynamic nonuniformity. Away from the attachment the particles are accelerated by the flow and the dynamic nonuniformity decreases. Two sections can be separated in the curves showing the variation of the velocity of the solid particles along the jet (Fig. 4a): the acceleration section, in which the velocity of the solid particles increases to a maximum value, and a deceleration section, where the velocity of the particles decreases monotonically as a result of the deceleration of the gas flow. On the axis of the jet the length of the acceleration section is comparable to the length of the transitional section of the jet. For particles located at a distance form the axis of the jet (curves 2, 3, 4 in Fig. 4a), the length of the acceleration section increases. In the transverse sections of the jet the velocity of the solid particles varies from the maximum value on the axis of the jet to the velocity of the particles in the fluidized bed (Fig. 4b). Thus the velocity field of the solid phase in a jet discharging into a fluidized bed is characterized by a significant nonuniformity.

The results obtained, in spite of the simplifying assumptions made, are qualitiatively well confirmed by the experimental data presented in [10].

## NOTATION

b, radius of the jet; c, drag of the particles; $D_s$, diameter of the solid particles; $r_0$, initial radius of the jet; $\tau$, time; u, $u_0$, $u_m$, $u_b$, instantaneous value, the initial value, the value on the axis of the jet, and the value on the boundary of the jet of the velocity of the gas phase; U and $U_b$, instantaneous value of the longitudinal component of the velocity of the solid particle and the value at the boundary of the jet; v and V, instantaneous value of the transverse component of the velocity of the gas phase and of the solid particle, respectively; W, fluidization number; x, longitudinal coordinate; y, transverse coordinate; $\alpha$, $\alpha_m$, $\alpha_b$, instantaneous value of the volume concentration of the solid phase and the volume concentration of the solid phase on the axis of the jet and on the boundary of the jet; $\varepsilon_k$, $\varepsilon_d$, kinematic coefficient of turbulent viscosity of the gas phase and the coefficient of turbulent diffusion of the solid phase; $\varkappa$, jet coefficient; and $\rho$ and $\rho_s$, density of the gas and of the solid particles.

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# HEAT TRANSFER IN A VIBRATING-ROTATING BED OF DISPERSED MATERIAL


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The results of studies of heat transfer between a surface and a bed are presented. The experimental results are compared with calculations based on a two-temperature model. It is shown that the computational results are in satisfactory agreement with the experiments.


In heat-treatment of dispersed materials (heating, drying, thermal decomposition, baking, cooling) it is often not desirable to blow through the bed because of the high hydraulic resistance of the bed, removal of particles of the material, etc. For this reason, apparatus with mixers are used increasingly more often [1-3]. They have the significant drawback that their heat-transfer coefficients and the mixing rates of the components are relatively low. In order to intensify the heating and mixing of the dispersed materials, a new method for moving the dispersed materials was proposed: a vibrating-rotating dispersed bed [4]. A vibrating-rotating bed differs from a vibrating-fluidized bed, which is similar, in that there are no vibrating structures, which greatly complicate the technological equipment when the large sizes which, as a rule, are preferable in practice, are used.

A vibrating-rotating bed is created in the apparatus with the help of an activator, placed at the bottom of the bed. As the activator rotates it turns the blade fastened on its top surface, and the blade is continuously sweeping particles and raises up part of the bed. As a result of the interaction of the activator with the dispersed material the particles begin to rotate relative to the axis of the chamber and oscillate in the vertical plane [5]. Structures of this type are distinguished by their structural simplicity and high operating reliability.

Both large (2-5 mm) and fine (0.01 mm) particles of their mixtures in any ratio can be equally well heat-treated in such an apparatus. The moisture content of the loaded material has virtually no effect on the motion of the particles, and in spite of the intensive mixing even the finely dispersed materials create virtually no dust, which makes cumbersome dust extractors and filters unnecessary. When dispersed materials are dried in a vibrating-rotating


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