MODEL OF PARTICLE DEPOSITION FROM TURBULENT GAS-SOLID FLOW IN CHANNELS WITH ABSORBENT WALLS

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A nonlocal model of particle deposition is developed without resorting to empirical information on the fluctuating motion of the particles. The effects of particle inertia are described by a system of differential equations for the moments of the dispersed phase velocity. The model is tested on examples of flows in channels with smooth walls and with "grassy" roughness.

Despite the considerable interest in the problem, a theory that consistently describes the process of particle deposition in channels has not yet been constructed. The first models for calculating the deposition rate [1, 2] were based on the "free path" principle. In these studies it was assumed that in the flow core up to some conventional boundary the particles were transported as a result of turbulent diffusion, and that in the concluding stage there is an inertial run to the wall powered by the energy previously communicated by the turbulent eddies of the carrier phase. The further development of the theory was based on the modification of the coefficients and parameters of the Friedlander—Johnstone model [3, 4], the introduction of the elements of a stochastic approach [5, 6], and the more accurate taking into account of the structure of the turbulence near the wall [7].

The main shortcoming of these studies is the large number of empirical constants and the possibility of using the approaches proposed only over relatively narrow ranges of variation of the particle dimensions. For these reasons the use of diffusion models in combination with the rather artificial method of displacing the boundary conditions by the length of the "free path" is not entirely satisfactory. A number of authors [8, 9] have recently carried out direct numerical modeling of the deposition processes. An analysis of the results of these investigations indicates that the characteristics of the dispersed phase in the wall zone cannot be obtained on the basis of a local equilibrium approach.

1. It is proposed to consider the steady stabilized flow of a gas—particle medium in plane-parallel ($\alpha = 0$) and axisymmetric ($\alpha = 1$) channels with absorbent walls. The mass and, in particular, the volume concentration of the particles are assumed to be small, which makes it possible to neglect their collisions and their reaction on the carrier medium. The dynamic properties of the particles are characterized by the relaxation time τ and the Brownian diffusion coefficient D. Assuming a Gaussian random turbulent gas velocity fluctuation field, the equation for the particle probability density distribution P in the phase space of the coordinates x_k and velocities V_k has the following form [1]:

$$\frac{\partial P}{\partial t}+V_k\frac{\partial P}{\partial x_k}+\frac{\partial}{\partial V_k}\left(\frac{U_k-V_k}{\tau}+F_k\right)P=g\langle u_i'u_k'\rangle\frac{\partial^2 p}{\partial x_i\,\partial V_k}+\left(\frac{f}{\tau}\langle u_i'u_k'\rangle+\frac{D}{\tau^2}\delta_{ik}\right)\frac{\partial^2 P}{\partial V_i\,\partial V_k}. \quad (1.1)$$

Here, U_k and u_k' are the average and fluctuating components of the gas velocity; $\langle u_i'u_k'\rangle$ are the second one-point moments of the fluctuations; and F_k is the acceleration caused by the external body force.

The coefficients of entrainment of the particles in the fluctuating motion of the gas

$$f=\frac{1}{\tau}\int_0^\infty \psi(s)\exp\left(-\frac{s}{\tau}\right)ds,\qquad g=\frac{1}{\tau}\int_0^\infty \psi(s)\left(1-\exp\left(-\frac{s}{\tau}\right)\right)ds$$
$$\psi(s)=\langle u_i'(t)u_j'(t+s)\rangle/\langle u_i'(t)u_j'(t)\rangle \quad (1.2)$$

are determined by the two-time correlation function of the gas velocity fluctuation $\psi(s)$ taken along the particle trajectory.

We will derive the equation for the moments from (1.1). The correlations containing an angular velocity component (when $\alpha = 1$) are determined from the condition of elimination of divergence on the channel axis. The equation for the mass balance of the solid phase C is obtained by integrating (1.1) over velocity space:

$$\frac{1}{r^\alpha}\frac{\partial}{\partial r}r^\alpha\langle V_r\rangle C+\frac{\partial}{\partial x}\langle V_x\rangle C=0,\quad \langle V_r^aV_x^b\rangle=\frac{1}{C}\int PV_r^aV_x^b\,d\mathbf{V},\quad C=\int P\,d\mathbf{V} \quad (1.3)$$

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where x and r are measured in the longitudinal and transverse directions from the channel axis (plane of symmetry).

Multiplying (1.1) by V_r and integrating with respect to V, we obtain the balance equation for the transverse component of the momentum of the solid phase:

$$\frac{\partial}{\partial r}\langle V_r^2\rangle C+\frac{\partial}{\partial x}\langle V_rV_x\rangle C=\left(-\frac{\langle V_r\rangle}{\tau}+F_r\right)C-g\langle u_r'^2\rangle\frac{\partial C}{\partial r}-\left\{g\langle u_r'u_x'\rangle\frac{\partial C}{\partial x}\right\} \quad (1.4)$$

The components of the particle momentum flux density entering into expression (1.4) include both the turbulent stresses in the solid phase and the direct transfer of momentum by the average motion.

From (1.4) we obtain the equation for the radial component of the particle flux

$$j=C\langle V_r\rangle=-\tau(\langle V_r^2\rangle+g\langle u_r'^2\rangle)\frac{\partial C}{\partial r}-\tau C\frac{\partial\langle V_r^2\rangle}{\partial r}+\tau F_rC-\tau\left(\frac{\partial}{\partial x}\langle V_rV_x\rangle C+g\langle u_r'u_x'\rangle\frac{\partial C}{\partial x}\right)$$

in accordance with which the motion of the solid phase in the direction of the channel wall is mainly determined by the turbulent diffusion with a diffusion coefficient $D_T = \tau[\langle V_r^2\rangle + g\langle u_r'^2\rangle]$ that depends on the particle velocity fluctuation level, the turbulent migration under the influence of the particle turbulent energy gradient, and the effect of the body force.

The equation for the moment $\langle V_r^2\rangle$ takes the form:

$$\frac{\partial}{\partial r}\langle V_r^3\rangle C+\frac{\partial}{\partial x}\langle V_r^2V_x\rangle C=2\langle V_r\rangle CF_r-$$
$$2g\left[\langle u_r'^2\rangle\frac{\partial}{\partial r}\langle V_r\rangle C+\langle u_r'u_x'\rangle\frac{\partial}{\partial x}\langle V_r\rangle C\right]+\frac{2C}{\tau}\left(\chi\langle u_r'^2\rangle+\frac{D}{\tau}\langle V_r^2\rangle\right) \quad (1.5)$$

From (1.5), assuming that the transfer terms are small, we can derive the following expression for the particle energy corresponding to the transverse degree of freedom:

$${}^1/_2\langle V_r^2\rangle={}^1/_2(f\langle u_r'^2\rangle+D/\tau) \quad (1.6)$$

The local-equilibrium approximation based on (1.6), is well satisfied in the turbulent core of the flow; however, it may be upset in the wall zone, where all the variables have large gradients. Nonlocal effects can be taken into account on the basis of the solution of Eq. (1.5). For determining $\langle V_r^3\rangle$ we assume a quasi-Gaussian distribution of the particles with respect to the transverse velocity component, analogous to Millionshchikov's hypothesis in the theory of single-phase turbulent flows, $\langle V_r^4\rangle = 3\langle V_r^2\rangle^2$. In this case from the equation for the third moments in the boundary layer approximation, which makes it possible to omit the derivatives with respect to x from the equations for the higher moments, we have [11]

$$\langle V_r^3\rangle=-D_T\frac{d\langle V_r^2\rangle}{dr}+\langle V_r\rangle\left[\langle V_r^2\rangle+2\left(f\langle u_r'^2\rangle+\frac{D}{\tau}\right)\right] \quad (1.7)$$

Thus, the total third moment describes the diffusion transport of particle energy $\langle V_r^2\rangle/2$ and the convective transfer to the disturbance of the symmetry in the distribution P with respect to V_r.

We also present the equations for the moments $\langle V_x\rangle$ and $\langle V_rV_x\rangle$ obtained from (1.1)

$$\frac{1}{r^\alpha}\frac{\partial}{\partial r}r^\alpha\langle V_rV_x\rangle C+\frac{\partial}{\partial x}\langle V_x\rangle^2C=\left(\frac{\langle U_x\rangle-\langle V_x\rangle}{\tau}+F_x\right)C-$$
$$g\langle u_r'u_x'\rangle\frac{\partial C}{\partial r}-\left\{g\langle u_x'^2\rangle\frac{\partial C}{\partial x}-\frac{\partial}{\partial x}\langle V_x'^2\rangle C\right\} \quad (1.8)$$

$$\frac{\partial}{\partial r}\langle V_r^2V_x\rangle C+\frac{\partial}{\partial x}\langle V_rV_x^2\rangle C=C\left[\langle V_r\rangle\left(\frac{\langle U_x\rangle}{\tau}+F_x\right)+\right.$$
$$\left.\langle V_x\rangle F_r\right]-g\left[\langle u_r'^2\rangle\frac{\partial}{\partial r}\langle V_x\rangle C+\langle u_r'u_x'\rangle\left(\frac{\partial}{\partial x}\langle V_x\rangle C+\right.\right.$$
$$\left.\left.\frac{\partial}{\partial r}\langle V_r\rangle C\right)+\langle u_x'^2\rangle\frac{\partial}{\partial x}\langle V_r\rangle C\right]+\frac{2C}{\tau}(f\langle u_r'u_x'\rangle-\langle V_rV_x\rangle) \quad (1.9)$$

In the boundary layer approximation, supplemented by the condition $\langle V_r^2\rangle >> \langle V_r^2V_x'\rangle$ from (1.9) and (1.4) we have

$$\langle V_r V_x\rangle = f\langle u_r' u_x'\rangle + \frac{\tau}{2}\left[\langle V_r\rangle\left(\frac{\langle V_x\rangle+\langle U_x\rangle}{\tau} + F_x\right) - D_r\frac{d}{dr}\langle V_x\rangle\right] \tag{1.10}$$

In accordance with expression (1.10), the moment $\langle V_r V_x\rangle$ is generated by the entrainment of the particles into the turbulent motion of the gas described by the local-equilibrium term $f\langle u_r' u_x'\rangle$, convection and diffusion.

By virtue of the formulation of the problem none of the characteristics of the dispersed phase, except for the concentration C, varies along the x axis, and the C distributions in different sections of the channel are similar. In this case from (1.3) there follows

$$\frac{\partial C}{\partial x} = -CR^{\alpha}(C\langle V_r\rangle)\big|_{r=R}\left(\int_0^R r^{\alpha}C\langle V_x\rangle dr\right)^{-1} \tag{1.11}$$

where R is the radius (half-width of the channel).

Moreover, since $\langle V_x\rangle >> \langle V_r\rangle$, the terms in braces in Eqs. (1.4) and (1.8) can be neglected.

The system of nonlinear differential equations (1.3)—(1.5), (1.8) together with the closing relations (1.7), (1.10), (1.11), provide the basis for modeling turbulent particle transport in channels.

2. The boundary conditions for the equations obtained are determined by the interaction of the particles and the channel walls. We introduce the coefficient of restitution of the longitudinal velocity component ζ and the probability χ of particle rebound from the boundary after impact. Then the probability density of particle transition in phase space upon collision with the wall takes the form:

$$P(V_-|V_+) = \chi\delta(V_{r-}+V_{r+})\delta(V_{x-}-\zeta V_{x+}),\quad V_{r+}>0 \tag{2.1}$$

where the plus and minus subscripts denote the parameters before and after impact.

We assume a Gaussian distribution of the dispersed phase with respect to V_{r+} at the wall:

$$P(V_{r+}) \sim \exp\left(-\frac{V_{r+}^2}{2\langle V_r^2\rangle}\right)$$

Then the velocity moments are related as follows [11]:

$$\langle V_r\rangle = \sqrt{\frac{2}{\pi}}\frac{1-\chi}{1+\chi}\langle V_r^2\rangle^{1/2},\qquad \langle V_r^3\rangle = \sqrt{\frac{8}{\pi}}\frac{1-\chi}{1+\chi}\langle V_r^2\rangle^{3/2} \tag{2.2}$$

The main reasons for $\langle V_r V_x\rangle$ deviating from the local-equilibrium value at the wall are the loss of momentum when the particles interact with the wall and deposition. We represent the moment $\langle V_r V_x\rangle$ as a sum of equilibrium and nonequilibrium terms: $\langle V_r V_x\rangle = f\langle u_r' u_x'\rangle + \Delta\langle V_r V_x\rangle$. We determine $\Delta\langle V_r V_x\rangle$ from the condition of statistical independence of the distribution P with respect to V_r and V_x in the incident and reflected particle fractions. From (2.1) we find

$$\langle V_r\rangle = \frac{\langle V_r\rangle_+ C_+ + \langle V_r\rangle_- C_-}{C_+ + C_-} = \langle V_r\rangle_+\frac{1-\chi}{1+\chi},\quad \langle V_x\rangle = \langle V_x\rangle_+\frac{1+\zeta\chi}{1+\chi},\quad \Delta\langle V_x V_r\rangle = \langle V_x\rangle_+\langle V_r\rangle_+\frac{1-\zeta\chi}{1+\chi}$$

Thus, using (2.2) we obtain

$$\Delta\langle V_r V_x\rangle = \sqrt{\frac{2}{\pi}}\frac{1-\chi\zeta}{1+\chi\zeta}\langle V_r^2\rangle^{1/2}\langle V_x\rangle$$

An analogous expression for the mixed moment of the velocity of large particles was obtained in [12] on the basis of the small parameter method. Finally, we obtain

$$\langle V_r V_x\rangle = f\langle u_r' u_x'\rangle + \sqrt{\frac{2}{\pi}}\frac{1-\chi\zeta}{1+\chi\zeta}\langle V_r^2\rangle^{1/2}\langle V_x\rangle \tag{2.3}$$

The boundary conditions (2.2), (2.3), supplemented by the conditions of symmetry on the channel axis, close the system of transport equations.

3. The system of differential equations (1.3)—(1.5), (1.8) was solved numerically for the case of total absorption of the particles on the walls ($\chi = 0$).

For calculating the gas velocity distribution we used the approximate expression for the turbulent viscosity coefficient

$$\nu_{t+} = \frac{1}{6}\left[\sqrt{1+4\left[1-\exp\left(-\frac{R_+-r_+}{A}\right)^2\varkappa^2(R_+-r_+)^2\right]}-1\right]\left(1+\frac{r_+}{R_+}\right)\left(\frac{1}{2}+\left(\frac{r_+}{R_+}\right)^2\right) \tag{3.1}$$

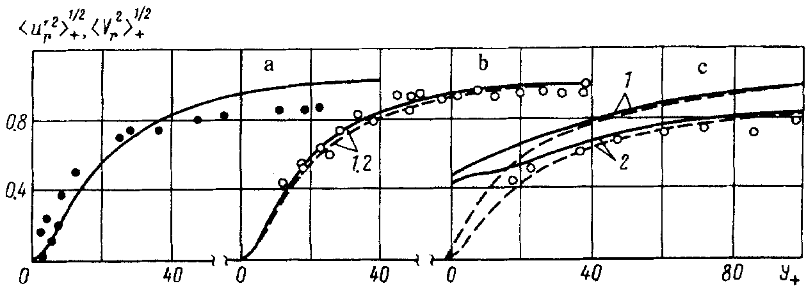

Fig 1

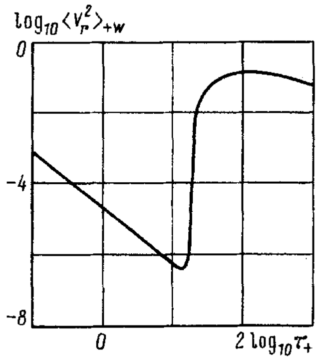

Fig 2

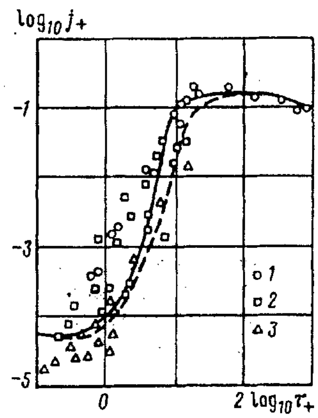

Fig 3

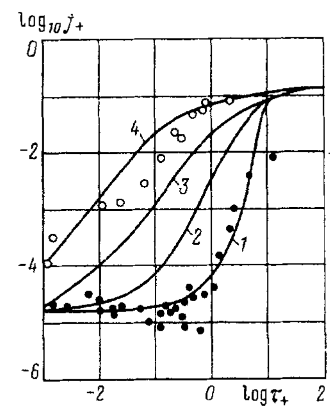

Fig 4

which at points distant from the wall goes over into the Reichardt formula and in the vicinity of the wall into the Van Driest relation [13] ($\varkappa = 1.4$, $A = 26$). The plus subscript denotes that all the quantities have been nondimensionalized by dividing by the friction velocity u_* and the kinematic viscosity ν.

In accordance with (1.2), the entrainment coefficients f and g depend on the parameter $\Omega = T/\tau$, where T is the time scale of the energy-bearing fluctuations. The time scale of the turbulence is related to the Prandtl—Nikuradze mixing length l [14]:

$$T_+=\sqrt{l_+^{2}+100}, \qquad l=R\left(0.14-0.08\left(\frac{r}{R}\right)^2-0.06\left(\frac{r}{R}\right)^4\right) \tag{3.2}$$

The intensity of the turbulent fluctuations of the gas in the transverse direction is calculated from the expression

$$\langle u_r'^2\rangle=\nu_t/T\,\mathrm{Sc}_t \tag{3.3}$$

In Fig. 1a we compare calculations made with (3.3), using (3.1), (3.2), with $\mathrm{Sc}_t = 0.9$ and the experimental data presented in [15]. There is satisfactory agreement between (3.3) and the experimental results in the wall zone ($y = R - r$).

The distribution of the particle fluctuation energy is shown in Figs. 1b and 1c. The broken and continuous curves correspond to the calculation results obtained without and with allowance for the Saffman force which acts in the transverse direction and develops in shear flow when the velocities of the carrier and solid phases are mismatched [16]. The Saffman force causes acceleration:

$$F_r=\frac{9.6}{\pi}\frac{\rho_f}{\rho_p}\frac{U_x-\langle V_x\rangle}{d}\frac{dU_x}{dr}\left(\frac{\nu}{-dU_x/dr}\right)^{1/2}$$

where ρ_χ and ρ_p are the densities of the gas and the material of a particle with diameter d, respectively.

The important influence of the Saffman force on particle transport in a viscous sublayer and deposition processes was first noted in [17].

For the approximation of the two-time correlation function $\psi(s)$ the following expressions are most frequently used: the step [18] and exponential [19] relations

$$\psi(s)=(1-H(s-T)), \quad \psi(s)=\exp(-s/T)$$

(H is the Heaviside function), which give different values for the entrainment coefficients.

For small dynamic relaxation times ($\tau_+ = 1.1$) the particles are strongly entrained into the fluctuating motion of the gas and the two approximations of $\psi(s)$ (the step 1 and exponential 2 approximations) lead to similar values of the fluctuation energy (Fig. 1b) in the wall zone of a plane channel. The experimental data of Goren and Erhart, presented in [9], are in good agreement with the calculations. In Fig. 1c, using the same notation as in Fig. 1b, we have plotted the distribution of the fluctuation energy of particles with greater inertia ($\tau_+ = 1.43$). The increase in particle size leads to a fall in the intensity level of the turbulent particle velocity fluctuations with a simultaneous flattening of the fluctuation profile. Comparison with the experimental data suggests the choice of an exponential approximation of the correlation function $\psi(s)$.

The fluctuation energy of the large particles in the wall zone may exceed the value of the turbulent energy of the gas, in which case the intensity of the fluctuations at the wall will be nonzero. It should be noted that this effect can be obtained only on the basis of a nonlocal simulation of the turbulence in the solid phase and is determined by the diffusion and convective mechanisms of fluctuation transfer by the inertial particles.

A characteristic feature of the dependence of the intensity of the solid-phase transverse velocity fluctuations at the wall on the inertia parameter τ_+ is the presence of a maximum at $\tau_+ \approx 100$ (Fig. 2). The increase in $\langle V_r^2\rangle_W$ is attributable to the enhanced role of the diffusion and convective mechanisms of particle energy transfer from the flow core to the wall with increase in the inertia of the particles. The fall in $\langle V_r^2\rangle_W$ beyond the maximum is associated with the decreased intensity of the turbulent energy of the particles in the flow core as their inertia increases, since at points away from the wall $\langle V_r^2\rangle = f\langle u_r'^2\rangle$. Brownian motion has an important influence on the fluctuation level of the small particles; in this case the fall in $\langle V_r^2\rangle_W$ with increase in the inertia of the Brownian particles is associated with the decrease in the Brownian diffusion coefficient D.

The behavior of the turbulent energy of the dispersed phase is reflected in the dependence of the dimensionless flux at the wall, given by the expression [3]

$$j_+ = -\frac{1}{u_* R^\alpha}\int_0^R r^\alpha U_x\,dr\,\frac{\partial \ln C}{\partial x}$$

on the inertia parameter τ_+. Figure 3 gives the results of calculating j_+ for a circular channel when Re = 50 000, $\rho_p/\rho_f = 770$. The continuous and broken curves correspond to calculations made with and without allowance for the effect of the Saffman force. An analysis of the results obtained indicates that the entire range of variation of τ_+ can be conventionally divided into three intervals: the deposition of small ($\tau_+ \leqslant 1$), medium ($1 \leqslant \tau_+ \leqslant 100$), and large ($\tau_+ \geqslant 100$) particles. The principal mechanisms determining the deposition of small particles are turbulent and Brownian diffusion.

The fall in the deposition rate with increase in τ_+ is associated with the decrease in the Brownian diffusion coefficient as the particle size increases. The principal mechanisms determining the desposition of medium particles are turbulent diffusion and turbulent migration resulting from the nonuniform distributions of particle concentration and turbulent carrier-phase velocity fluctuation intensity and also the Saffman force; the contribution of Brownian diffusion to deposition is now insignificant. The increase in deposition velocity with increase in τ_+ is attributable to the increased role of the migration transport mechanism. The deposition velocity is mainly determined by the value of the particle fluctuation energy at the wall. Therefore the fall in the deposition coefficient (beyond the maximum at $\tau_+ \approx 100$) as the inertia of the large particles increases is associated with the decrease in the intensity of the turbulent transverse velocity fluctuations (Fig. 2). The results of the calculations are consistent with the experimental data on the deposition coefficients obtained by various authors ([3] — 1, [1] — 2, [20] — 3).

A promising means of intensifying deposition on the channel walls is to use "grassy" roughness. On the particle size interval $10^{-3} < \tau_+ < 10$ the deposition velocity has been found to increase by several orders [20]. The authors of these publications, in particular [21], associate the effect with the increased efficiency of particle capture and assume that in this case deposition is determined by other mechanisms — inertial flow over the fibers in the transverse direction. However, on smooth walls the use of coatings that ensure almost total absorption of the dispersed phase did not increase the deposition rate.

The anomalously high deposition can be explained if it is borne in mind that a "grassy" coating does not lead to significant distortion of the structure of the turbulent flow [20]. At the same time, the actual absorption surface is displaced a distance h equal to the fiber dimension into the flow. The proposed deposition model gives correct results in the this case also without it being necessary to change the physical premises. In fact, for particles with $d = 0.65$ μm and $\rho_p/\rho_f = 1000$ calculations for turbulent flow in a channel with $h = 100$ μm led to results in good agreement with the experimental data [22]. In Fig. 4 curves 1—4 correspond to the roughness scales 0, 10, 30, and 100 μm, respectively. A "grassy" coating has no effect on particles with $\tau_+ > 100$.

These data throw some light on the causes of the considerable scatter of the experimental data for deposition on smooth surfaces: the presence of even minor roughness leads to a sharp increase in the deposition rate.

Thus, the model proposed describes the transport and deposition processes over a broad range of variation of the particle inertia in relation to both smooth surfaces and surfaces with "grassy" roughness.

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