SCREENING OF A SURFACE BY REFLECTED PARTICLES

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A model is proposed for the process of screening of a surface by expelled and reflected particles in a dust flow together with a method for evaluating the screening effect in the vicinity of the body's critical point.

When a dust flow occurs over a body reflected particles and particles of body material eroded from the surface may collide with other particles moving toward the surface. A portion of their kinetic energy is then absorbed and changes the direction of particle motion changes, producing the so-called screening effect, which leads to a decrease in intensity of material removal as compared to its value in the absence of particle collisions.

The phenomenon almost always occurs to some degree when a flow holding solid particles acts on a body. For example, formation of a screening layer is possible in dusty flows in various energy generation devices which use solid fuel, in gas supply equipment channels, in air- gas-dynamic tubes carrying two-phase flows, in incidence of a two-phase jet on an obstacle, in motion of a body in a dusty atmosphere [1-3], etc.

The screening effect affects the service life of components in various pieces of equipment, so that its study is a problem of practical importance.

This question was examined some time ago in experimental studies [1-3] and theoretical investigations [4, 5]. However those studies offered no concrete recommendations for quantitative evaluation of the changes in intensity of material removal G when the screening effect is considered. Such estimates are possible on the basis of the model of this process proposed by the present author in [6].

It should be noted that consideration of the effect of body surface screening by reflected particles on erosion removal of material in the general case is a remarkable complex multiparameter problem. Therefore, in developing a mathematical model it is desirable to limit consideration to the most significant parameters in the vicinity of the body's critical point. Other limitations and assumptions will be noted in the course of developing the model.

We will consider Fig. 1a, which schematically depicts a model of the screening layer. Here x_i is the mean radius of some i-th annular section of the surface with width Δ; x_n is the radius of the circle on the surface of the body for which the intensity of G is calculated with consideration of screening.

Upon collision with the body the dust particles rebound from the surface with some velocity v_2, and remaining within the confines of a layer of thickness h, are set in motion by the gas and removed from the surface with a velocity w_p, together with fragments of abraded surface material. Since in the vicinity of the critical point (above the body surface) within the limits of the layer $w_p \ll v_p$, it is obvious that accumulation of particles is possible here, with increase in particle concentration, as follows from the equation of conservation of particle flow

$$2\pi\Delta(\rho_v v_p+\rho_w u_w)\sum_{i=0}^{n} x_i=2\pi n\Delta\frac{\pi}{6}\, d_p^3\sum_{i=0}^{n}\lambda_i\rho_c\sum_{i=0}^{n} w_{pni}, \quad (1)$$

where ρ_m is the density of the mechanical mixture of particles, assuming (arbitrarily) along the surface of the continuous layer; $n = x_n/\Delta$ is the number of divisions of the radius x_n into segments of width Δ; λ is the number of particle centers ($1/m^2$) in the screening layer (of thickness h) in a projection on a plane perpendicular to the velocity vector v_p.

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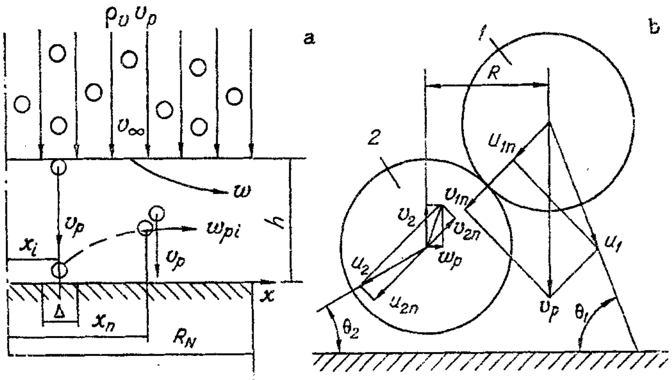

Fig. 1. Diagram of particle motion in screening layer: a) flowover model; b) collision model.

According to the rule of mixtures, for ρ_m we find the expression

$$\rho_c = \rho_p \left(\frac{G+1}{G\rho_p/\rho_w + 1} \right), \tag{2}$$

where $G = (\rho_w u_w)/\rho_v v_p$. Then from Eq. (1), using Eq. (2), we have

$$\lambda = \frac{6}{\pi} \frac{\rho_v v_p (G\rho_p/\rho_w + 1) R_N}{\rho_p v_\infty d_p^3 n} \sum_{i=0}^{n} \frac{\bar{x}_i}{\bar{w}_{pni}}, \tag{3}$$

where

$$\bar{w}_{pni} = \frac{w_{pni}}{v_\infty}; \quad \lambda = \sum_{i=0}^{n} \lambda_i; \quad \bar{x}_i = \frac{\Delta}{R_N}\left(\frac{1}{2} + i\right), \quad i = 0, 1, 2, \ldots, n$$

(at i = 0, $\bar{x}_i$ corresponds to the mean relative radius of a circle, and at i = 1, 2, ..., n, to a ring).

Equation (3) will allow us to evaluate the effect of various parameters on the increase in density of the layer above the surface by reflected and abraded particles.

In view of the possiblity of intercollision of particles upon their approach to the surface the intensity of mass removal G must be considered in a probability formulation as the sum

$$G = G_0 p_0 + G_{\Sigma 1} p_1 + \cdots + G_{\Sigma m} p_m, \tag{4}$$

where G_0, p_0 are the intensity of mass removal and the probability of its existence for free (collisionless) particle flight; $G_{\Sigma m}$ p_m is the mathematical expectancy of the intensity and its corresponding probability for repeated collisions. Then, for example,

$$G_{\Sigma 1} = G_1 + G_2, \tag{5}$$

which indicates the sum of the intensities of removal created by primary (unperturbed) particles G_1 and secondary particles G_2 which have experienced collision with primary particles.

To calculate the probabilities p_0, p_1, ..., p_m we use Poisson's law

$$p_m = \frac{a^m}{m!} \exp(-a), \tag{6}$$

where m = 0, 1, 2, ... are possible values of events; $a = \pi R^2 \lambda$ is the mathematical expectancy of the number of particle centers within the limits of some elementary circular area of radius R (see Fig. 1b), incidence into which can lead to collision of particles.

To determine p_m with Eq. (6) it is necessary to know the value of $\sum_{i=0}^{n} \bar{x}_i/\bar{w}_{pni}$ in Eq. (3), which can be obtained by solution of the equation of particle motion in the screening layer, which we write in the following form:

$$\frac{d\bar{w}_p^2}{d\bar{x}} = A[(\bar{w} - \bar{w}_p) + 0{,}167\,\mathrm{Re}_\infty^{0{,}67} (\bar{w} - \bar{w}_p)^{1{,}67}], \tag{7}$$

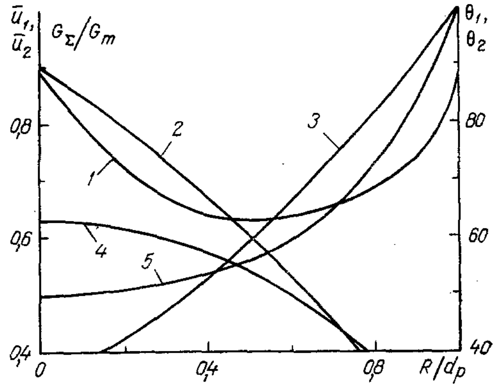

Fig. 2. Particle collision and removal parameters: 1, 2) collision angles θ_1, θ_2 for primary and secondary particles with surface; 3, 4) collision velocities for primary and secondary particles $\bar{u}_1$ and $\bar{u}_2$ with surface; 5) current relative net intensity.

where

$$A = \frac{36 R_N \rho_0'}{d_p \rho_p \mathrm{Re}_\infty}; \quad \mathrm{Re}_\infty = \frac{v_\infty d_p \rho_0'}{\mu_0'};$$

$\bar{w} = \beta\bar{x}$, according to [7], $\beta = d\bar{w}/d\bar{x} = 4/3\pi\sqrt{\bar{\rho}(2-\bar{\rho})}$, $\bar{\rho} \approx \rho_\infty/\rho_0'$.

We note that in composing Eq. (7) as a particle resistance law use was made of Klyachko's expression [8]

$$C_D = \frac{24}{\mathrm{Re}}(1 - 0{,}167\,\mathrm{Re}^{0,67}).$$

Equation (7) was solved with the following boundary conditions: at $\bar{x} = \bar{x}_i$, $\bar{w}_p = 0$, $\bar{w} = \beta\bar{x}_i$ at $\bar{x}_i = \bar{x}_n$, $\bar{w}_{pi} = \bar{w}_{pni}$, $\bar{w} = \beta\bar{x}_n$. Moreover, the usual assumptions were made as to sphericity of particles, boundary layer thickness was assumed negligibly small, surface curvature in the vicinity of the critical point was neglected, and it was assumed that upon rebounding particles had negligibly small velocity ($v_2 \approx 0$, $w_p \approx 0$), did not rotate or break up, and had no effect on the gas flow, that the original particles rebounding from the surface and the particles of eroded material had the same size d_p; collisions of particles during motion along the surface were not considered.

We will not turn to determination of the quantity $G_{\Sigma m}$ in Eq. (4).

The intensity of material removal G_0 in the vicinity of the body's critical point for free particle flight without mutual collisions will be considered known, and can be found, for example, from relationships presented in [9, 10]. In particular, we can write the following general expression

$$G_0 = \frac{v_p^2}{2H_{er}} f(\theta) f(T, v_p, \rho_p) \simeq C v_p^s f(\theta), \tag{8}$$

where H_{er} is the enthalpy of erosion destruction of the material; C is some constant of erosion destruction; the exponent s is assumed constant for a given material over some v_p interval at constant temperature; $f(\theta) = G(\theta)/G_m$ is the ratio of material removal intensity as a function of the angle of particle collision with the surface θ to the intensity at the angle of maximum removal.

Data on f(θ) are presented for some materials in [12]. For a typical plastic $f(\theta) \approx \sin^{1,3}\theta$.

Determination of the quantity $G_{\Sigma m}$ proves to be more complex, since even finding $G_{\Sigma 1}$ with Eq. (5) requires detailed consideration of the particle collision process shown schematically in Fig. 1b.

On the basis of equations describing oblique central collision of two bodies moving in translation [11], one can write a system of equations for determining the basic parameters of motion of particles after collision in the form

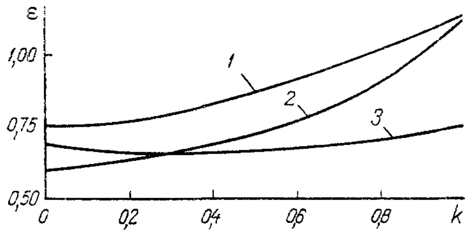

Fig. 3. Mathematical expectancy of change in relative net intensity: 1) steel, s = 2.5; 2) aluminum, s = 3.6; 3) plastic, s = 2; $v_p \leq 500$ m/sec.

$$\bar{u}_1 = \left[\bar{R}^2 + \frac{(1-k)^2}{4}(1-\bar{R}^2)\right]^{1/2}, \quad \bar{u}_2 = \frac{1+k}{2}\sqrt{1-\bar{R}^2},$$
$$\theta_1 = 90 - \theta_2 + \varphi, \quad \theta_2 = \arccos \bar{R}, \tag{9}$$
$$\varphi = \arcsin\left(\frac{1-k}{2}\sqrt{1-\bar{R}^2}/u_1\right), \quad k = \frac{u_{2n} - u_{1n}}{v_{1n} - v_{2n}},$$

where K is the recovery coefficient, equal to the ratio of the absolute velocities of the bodies before and after collision, and is dependent solely on the elastic properties of the colliding particles. We note that at k = 1 the collision is completely elastic, while for 0 < K < 1 the collision is incompletely elastic.

The meaning of the other quantities in system (9) should be clear from the diagram shown in Fig. 1b.

As an example the variation in collision parameters with relative distance between particle centers $\bar{R} = R/d_p$ (without averaging over the arc $\pi\bar{R}^2$) for a typical plastic at k = 0.25 is shown in Fig. 2.

It follows from the figure that in the interval $0 \leq \bar{R} \leq 0.8$ the current net intensity of material removal decreases by a factor of approximately two as compared to the intensity of removal for free particle flight.

Estimates show that for significant flow enthalpy a significant thermal flux may travel toward the eroding surface, which can be described approximately by the expression

$$q_w \approx \alpha(T_0 - T_w) + \gamma\rho_v v_p \frac{v_p^2}{2},$$

where γ is a coefficient, equal to 0.3 and 0.7 for brittle and plastic materials, respectively [13].

Also using the data of [13] for determination of α, it can be shown that even for a flow density $\rho_v v_p$, where isolated collisions are most probable, a significant heating of the surface is sometimes possible, especially if it is metallic. This fact indicates that at high values of q_w it is necessary to consider the corresponding change in the quantity G_0 with temperature [10], and the problem of G determination must be solved in composite formulation with consideration of heat exchange.

For multiple collisions the pattern of particle behavior becomes so complicated that computation of collision parameters becomes practically impossible, so that one must use data obtained experimentally. To do this it will be convenient to represent Eq. (4) with consideration of Eq. (6) in the following form:

$$G = G_0 p_0 + G_\Sigma p_1' = G_0[(1-\varepsilon)\exp(-a) + \varepsilon], \tag{10}$$

where $p'_1 = 1 - p_0$ is the probability of not less than one particle collsiion; ε is the mathematical expectancy of the quantity G_Σ/G_0 with consideration of uniform particle distribution within a circle of radius $\bar{R} = 1$ which for multiple collisions is regarded as a parameter of the process and determined experimentally, or can be computed for a limited number of collisions.

Thus, in particular, when only single collisions are considered, which is sufficient for the majority of practical cases, the quantity ε can be determined in accordance with Eq. (5)

$$\varepsilon = \frac{2G_m}{G_0} \int_{\frac{s}{2}}^{1} [f(\theta_1)\overline{u}_1^s + f(\theta_2)\overline{u}_2^s] \overline{R} d\overline{R}.$$

Results of ε(K) calculations for a single collision for some materials using data from [8, 15] are presented in Fig. 3. It is evident that ε depends significantly on the recovery coefficient k, and as $k \to 1$ even indicates the possibility of increasing removal intensity in the presence of some screening layer. Data available in the literature [12] on results of experimental studies confirm this.

At significant collision velocities, where $v_p \geq 150\text{-}200$ m/sec, the recovery coefficient lies in the range $0 \leq k \leq 0.5$, so that $\varepsilon < 1$ always, and can be determined approximately from calculation results (Fig. 3) or calculated using data on f(θ) for concrete materials.

The discussions of the behavior of the quantity ε presented above refer to conditions where the particle flow has an enthalpy significantly less than the enthalpy of the particle material mixture, i.e.,

$$C_pT + v_p^2/2 \ll H_f,$$

where C_p is the specific heat of the particle material.

For thermally stressed dusty flow action conditions it is possible that

$$C_pT + v_p^2/2 \geqslant H_f.$$

Then the additional energy liberated upon particle collision may become so high that the particles melt, lose stability, and break up. It is then possible, for example, in the case of plastics for the so-called thermal destruction mechanism [14] to occur, in which case (for plastics) $\varepsilon \approx 0.05\text{-}0.2$. This means that at significant mass flow densities, as follows from Eq. (10), as $\exp(-a) \to 0$, $G \to G_0\varepsilon$, i.e., in the limit mass removal is a multiple of ε.

Results of material tests obtained under such conditions obviously do not reflect true resistance to erosion action. It is evident from analysis of Eq. (10) that for reliable results tests of erosion resistance of materials should be carried out at relatively low mass flow densities, i.e., at $\exp(-a) \to 1$, where the effect of particle collisions can be neglected. The influence of the screening effect obviously must be considered in comparing results of material tests obtained with different values of flow parameters, especially in testing models of different forms and sizes.

As $\exp(-a) \to 1$ Eq. (10) takes on the simpler form

$$G \simeq G_0 \exp(-a).$$

For convenience in representing results and performing calculations of the screening effect, with the aid of Eq. (3) Eq. (10) can be written in the following form:

$$\left[\frac{G - G_0\varepsilon}{G_0(1-\varepsilon)}\right]^{\varkappa} = \exp\left(-\frac{1}{n}\sum_{i=0}^{n}\frac{\overline{x}_i}{\overline{w}_{pni}}\right), \tag{11}$$

where

$$\varkappa = \frac{d_p\rho_p v_\infty}{6R_N\rho_v v_p(G\rho_p/\rho_w + 1)}.$$

Equation (11) was solved together with Eq. (7) by a computer with parameters varied over the range $0.2 \leq \beta \lesssim 0.8$; $1 \leq Re_\infty \leq 10^4$; $10^{-4} \leq A \leq 10$, which essentially covers all cases of practical interest.

In the calculations the vicinity of the critical point was defined by the limits $\overline{x}_n \leq 0.2$, $n = 5$ (at $n > 5$ evaluations showed that G/G_0 varied little).

We will note that a solution of Eq. (7) can be obtained numerically by any of the known methods, however, for example, when the Euler method or the improved broken line method of [17] is used, solutions can be obtained easily with programmable calculators.

The results of the calculations performed can be approximated with the expression

$$\frac{G - G_0\varepsilon}{G_0(1-\varepsilon)} = \exp\left\{\frac{1}{\varkappa}(27{,}2\lg Re_\infty - 140)[1 + 3{,}28(0{,}96 - \beta)^{2{,}85}]\ \exp[-(4{,}1 + \lg A)^{1{,}17}] - \frac{1}{2\beta\varkappa}\right\} \tag{12}$$

with the error of the approximation not exceeding 20%.

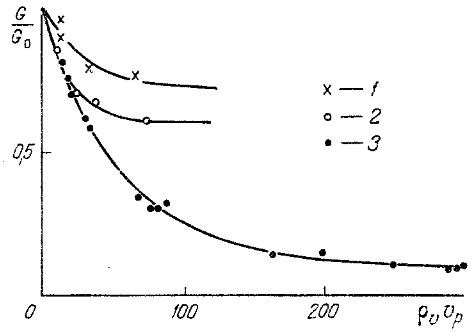

Fig. 4. Calculation of change in relative intensity with consideration of screening and comparison with experimental data: 1) alumina; 2, 3) plastic. $\rho_v v_p$, kg/m²·sec.

When it is necessary to consider the effect on screening of particles of removed material, G can be calculated by the method of successive approximations. In those cases where G is small, the intensity can be found directly from Eq. (12), taking G = 0 in the expression for $\varkappa$ G = 0.

If the particles of the erosive medium and the removed material move in the vicinity of the critical point with almost no delay relative to the gas, determination of G becomes even simpler, using the equation

$$\frac{G - G_0\varepsilon}{G_0(1-\varepsilon)} \approx \exp\left(-\frac{1}{2\beta\varkappa}\right), \tag{13}$$

which can be obtained from Eqs. (11), (12), as $A \to \infty$. Equation (13) can be used for approximate estimates and permits determination of the minimum possible values of the screening effect.

As an illustration of the possibilities of the proposed method for evaluating the screening effect, Fig. 4 presents results of calculations of the change in relative intensity G/G_0 for materials tested in [16] and for more thermally stressed regimes as a function of particle mass flow density. In the cases considered the calculation results agree satisfactorily with experiment.

NOTATION

G, intensity of erosion material removal; w, w_p, gas and particle velocities along body surface; $\rho_v v_p$, particle mass flow density; ρ_v, particle mass per unit volume; x, coordinate with origin at critical point; R_N, body radius; Δ, width of annular segment; v_p, primary particle velocity; d_p, mean diameter of erosive medium particles adn particles removed from surface; ρ_w, density of material surface; ρ_c, density of particle mixture; ρ_p, density of particle material; u_w, linear removal velocity; p, probability; a, mathematical expectancy; R, radius of circular collision area; ρ_0', gas density at the critical point; β, dimensionless velocity gradient; μ_0', gas dynamic viscosity coefficient at braking temperature; Re, Reynolds number; H_{er}, enthalpy of erosion distribution; θ, particle-body surface collision angle; $f(\theta)$, angular intensity function; k, velocity recovery coefficient; ε, mathematical expectancy of change in relative net intensity; α, heat liberation coefficient; q_w, thermal flux to surface; γ, energy accomodation coefficient; T_0, T_w, gas braking and surface temperatures; c_p, specific heat of particle material; H_f, melt enthalpy; A, parameter; $\varkappa$, parameter; s, exponent. Subscripts: p, particle; w, surface; 1, primary particle; 2, secondary particle; 0, critical point, initial value, absence of screening; c, mixture; er, erosion; f, liquid; n, limiting; ∞, removed from layer; v, flow.

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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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