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DETERMINATION OF FLOW VELOCITIES CAUSING BLOWING AND MOVEMENT OF SOLID PARTICLES

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In pneumatic transport and also in air cleaning of various surfaces it is often necessary to move, blow off, wash off, different solid particles of granular materials, soils, sands, icicles, and other loose materials.

Under actual conditions solid particles at a surface with flow over it change their condition depending on the velocity of the running flow. There are numerous experimental data for determination of critical velocities, but there is no single procedure. Authors record the process of blowing away (washing off) in different ways on the basis of visual observation of the condition of particles under the action of a flow [1].

We call critical those values of velocity for undisturbed flow outside the boundary layer of a surface with flow around it under whose influence the condition of solid particles changes. We designate in terms of u_1^* the velocity when particles are in a limiting equilibrium condition, i.e., they may complete oscillatory-translational motion by a distance not more than their diameter without separating from the surface, m/sec; u_2^* when separating (washing away) of individual particles is observed, m/sec; u_3^*, when there is mass blowing way (washing away) of solid particles, i.e., erosion starts to develop. Corresponding to these velocities, values of Reynolds's number for average particle diameter are designated in terms of $Re_1^* = u_1^*d/\nu$, $Re_2^* = u_2^*d/\nu$, $Re_3^* = u_3^*d/\nu$.

Existing methods for determining these critical velocities reflect insufficiently the change in condition of solid particles under the action of flow. Also there has been little study of the intensity of the wear of solid particles under the action of a given (critical) flow velocity.

A semiempirical method is provided here for determining critical flow velocities under whose action these states set in for solid particles of a certain size and density. For this purpose experiments were carried out in aerodynamic units at the M. T. Urazbaev Institute of Mechanics and Seismic Stability of Structures, Academy of Sciences of the UzbSSR. An aerodynmic tube of the open type of rectangular cross section in the operating section at the outlet of the nozzle 0.2 × 0.3 m operated on a forced air stream. Use of a GM (generator–motor) electric circuit made it possible to control the running flow velocity from 0 to 40 m/sec. An experimental plate with sharp edges 0.6 m long was set up at a height of 0.07 m from the lower wall of the working section so that the wind stream flowed smoothly over the plane surface. A groove 0.06 m wide and 0.006 m deep was made at a distance of 0.3 m from

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TABLE 1

i	$10^4 d$, m	$10^6 \sigma$, m	a_{ji}	b_{ji}	a_{ji}	b_{ji}	a_{ji}	b_{ji}
			j					
			1		2		3	
1	1.95	±5.5	0.87	−1.4295	12.2	−20.96	436	−806.04
2	2.82	±3.2	0.87	−1.5575	12.2	−23.15	436	−890.52
3	4.07	±9.2	0.87	−1.7540	12.2	−26.19	436	−987.22
4	5.65	±6.5	0.87	−1.9375	12.2	−28.38	436	−1068.92
5	12.5	±250	0.87	−2.3305	12.2	−33.6	436	−1263.34

the start of the plate in order to set up carriers with specimens of solid particles so that their surface was flush with the surface of the plate. The intensity of wear was determined for rolling particles of meadow sandy loam with a particle size from $1.4 \cdot 10^{-4}$ to $1.5 \cdot 10^{-3}$ m and a density of $\rho_s = 2720$ kg/m^3 at air stream velocities from 3.0 to 12 m/sec (with an interval of 0.3 m/sec). Size fraction analysis was carried out by dry sieving (by the Savvinov method), and the square deviation of sizes σ from the average size is shown in Table 1. Wind flow velocity was determined by a pneumatic method over specimens for the boundary layer of the plate, and the intensity of blowing away and wear was determined by a gravimetric method using analytical balances VLA-200g-M. The duration of blowing was 120 sec and it was selected from calculation that the process of blowing away occurred in a steady-state regime.

Given in Fig. 1 is the dependence of dimensionless values of solid consumed $\varphi = 10^8 q/(\rho_s \sqrt{\rho^* g d})$ on $\mathrm{Re} = ud/\nu$ for different flow velocities and average diameter $d = 1.95 \cdot 10^{-4}$, $2.82 \cdot 10^{-4}$, $4.07 \cdot 10^{-4}$, $5.65 \cdot 10^{-4}$, and $1.25 \cdot 10^{-3}$ m (points 4-8). Here q is mass consumption of particles per unit time from a unit of surface, kg/(m^2, sec); $\rho^* = (\rho_s - \rho)/\rho$ is the ratio of the force of gravity for a solid particle (after deduction of Archimedes force) to Archimedes force. Complex ρ^* characterizes the behavior of foreign particles in a liquid medium [2], with $\rho_s < \rho$ a particle floats in the stream, with $\rho_s > \rho$ it precipitates (it sinks). Subsequently, in the case being considered $(\rho_s - \rho)/\rho > 0$; $\sqrt{\rho^* g d} = u_0$ is the scale of velocity proportional to fall diameter (fall velocity) for particles [1] $\omega_0 = (1/C_d)\sqrt{2\rho^* g d K_2/K_1}$; $\rho_s u_0$ is a typical value for solid consumption; g is free fall acceleration, m/sec^2; ν is kinematic viscosity coefficient for the supporting flow, m^2/sec; u is undisturbed flow velocity, m/sec; ρ and ρ_s are density of the flow and of a solid particle, kg/m^3; C_d is pressure loss coefficient; K_1 and K_2 are particle shape coefficients (for a sphere $K_1 = \pi/4$, $K_2 = \pi/6$).

As can be seen from Fig. 1c, for particles of a certain average diameter and density the relationship $\varphi = f(\log \mathrm{Re})$ is described by intersecting lines 1-3, i.e., by three regimes:

1) the initial regime (straight line 1 in Fig. 1b, increasing along the ordinate by two orders of magnitude) corresponds to a particle condition when under the influence of flow individual particles lose their stability and they may roll over without separating (blowing away) from the surface.

2) A transitional regime (straight line 2 in Fig. 1a, increasing along the ordinate by an order of magnitude) corresponding to a particle condition when there is rolling, blowing away, and wear of individual particles under the action of the flow.

3) A stable regime (straight line 3 in Fig. 1c) corresponding to the condition of mass blowing away of particles, i.e., developed erosion.

Thus, with different flow velocities for a given particle diameter of the particles being considered the nature of change in φ in relation to Re is described by three relations.

It is easy to obtain from Fig. 1 a value of the dimensionless solid consumption for each regime individually:

$$\varphi_{ji} = a_{ji} \lg \mathrm{Re} + b_{ji}. \quad (1)$$

Here j characterizes the change in φ in relation to regime and correspondingly it takes values of 1, 2, and 3; i indicates the change in φ in relation to average particle diameter d.

For the values of flow velocity and average size fraction of specimens considered a change in experimental constants a_{ji} and b_{ji} in the regimes indicated (j = 1, 2, 3) is given

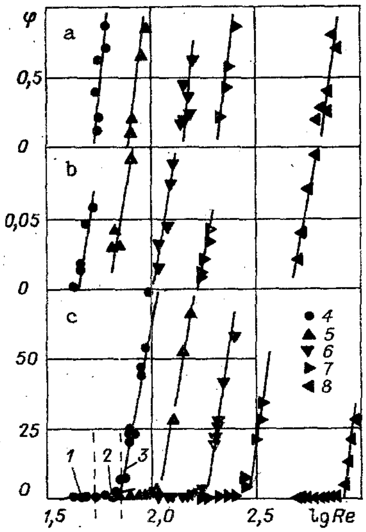

Fig. 1

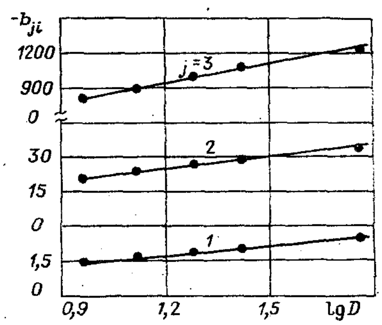

Fig. 2

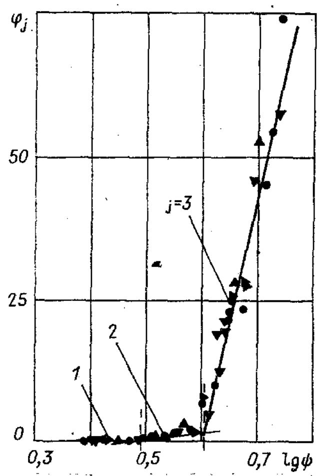

Fig. 3

TABLE 2

j	n_j	A_j	B_j	r_j	$\sigma_{\varphi j}$	$\sigma_{\psi j}$	$\langle\varphi_j\rangle$	$\langle\psi_j\rangle$	ψ_j^*	ψ_j
1	19	0.87	−0.34	0.90	0.029	0,030	0,034	0.430	2.460	2.460—3,070
2	24	12.2	−5.86	0.88	0.360	0.026	0.546	0.526	3.070	3.070—4.043
3	28	436	−263	0.93	21.100	0.045	24.70	0.660	4.043	⩾4.043

in Table 1, whence it can be seen that values of a_{ji} depend weakly on particle size fraction and they change with a transition from one regime to another, i.e., they characterize the quantitative change in solid consumption in relation to flow velocity, but values of b_{ji} depend strongly on the regime, and also on particle size. If the dependence on the logarithm of dimensionless diameter D is plotted (Fig. 2), it is easy to obtain analytical expressions describing the dependence on b_{ji} on log D in the flow regimes being considered for any average diameter:

$$-b_{1i} = 1{,}134 \lg D + 0{,}34; \tag{2}$$

$$-b_{2i} = 15{,}90 \lg D + 5{,}86; \tag{3}$$

$$-b_{3i} = 568 \lg D + 263 \tag{4}$$

[$D = (\rho^* g/\nu^2)^{1/3} d = \mathrm{Ar}^{1/3}$ is Archimedes number]. By substituting in Eq. (1) corresponding values of a_{ji} from Table 1 and b_{ji} from relationships (2)-(4), we find expressions for determining φ:

$$\varphi_1 = 0{,}87(\lg \mathrm{Re} - 1{,}303 \lg D) - 0{,}34; \tag{5}$$

$$\varphi_2 = 12{,}20(\lg \mathrm{Re} - 1{,}303 \lg D) - 5{,}86; \tag{6}$$

$$\varphi_3 = 436(\lg \mathrm{Re} - 1{,}303 \lg D) - 263. \tag{7}$$

By designating $\log\psi = \log \mathrm{Re} - 1.303 \log D = \log(\mathrm{Re}/D^{1.303})$, we obtain a general expression for φ:

$$\varphi_j = A_j \lg \psi + B_j, \tag{8}$$

where ψ means mobility coefficient [1].

The mobility coefficient used in the hydrodynamics of channeled flows may be converted into the form $u/u_0 = u/\sqrt{\lambda^* g d} = (ud/\nu)/(\nu\sqrt{\pi^* g d^3}) = \mathrm{Re}/D^{1/5}$. This means that $\psi = \mathrm{Re}/D^{1.303}$ also corresponds to u/u_0.

Indicated by lines in Fig. 3 is the change in φ in relation to ψ (8), and test data for solid particles of different average diameter are plotted by points (see Fig. 1 for their values). It can be seen that independent of the average particle diameter d the change in $\varphi_j = f(\psi)$ is described by a single broken line, and a change in the nature of the development is observed with a transition from one regime to another. Given in Table 2 is the change in coefficients for Eq. (8) and their statistical evaluation (coefficient of paired linear correlation r, mean square deviation σ_ψ and σ_φ, and also average values $\langle\varphi\rangle$ and $\langle\psi\rangle$ for n number of tests) for each regime obtained using the least squares method [3].

Thus, the curve $\varphi_j = f(\psi)$ on the whole (Fig. 3) with certain values of ψ undergoes breaks which correspond to the start of the following regime. Whence it is possible to find critical values $\psi = \psi_j^*$ relating to the start of each regime.

With $\psi = \psi_1^*$ particles are in a limiting equilibrium condition, i.e., at the threshold of the initial regime. Values of ψ_1^* are found from the relationship $\varphi_1 = 0$ or $0.87 \log\psi_1^* - 0.34 = 0$. Whence

$$\psi_1^* = 2.46 \text{ or} \quad \mathrm{Re}_1^* = 2.46\,D^{1.303}. \tag{9}$$

At the start of the transitional regime, i.e., with $\psi = \psi_2^*$, there is separation of individual particles from the surface with flow over it. The critical value ψ_2^* at the threshold of the transitional regime is determined from the condition $\varphi_1 = \varphi_2$, i.e., $0.87 \log\psi_2^* - 0.34 = 12.20 \log\psi_2^* - 5.86$. Whence

$$\psi_2^* = 3.07 \text{ or} \quad \mathrm{Re}_2^* = 3.07\,D^{1.303}. \tag{10}$$

With $\psi = \psi_3^*$ soil particles are at the boundary of mass blowing away, i.e., at the start of a stable regime or developed erosion. Critical value ψ_3^*, i.e., corresponding to the point of the change from a transitional regime to a stable regime, is found from the condition $\varphi_2 = \varphi_3$ or $12.2 \log\psi_3^* - 5.86 = 436 \log\psi_3^* - 263$. Whence

$$\psi_3^* = 4.043 \text{ or} \quad \mathrm{Re}_3^* = 4.043\,D^{1.303}. \tag{11}$$

In Fig. 4 lines 1-3 indicate the change in Re_1^*, Re_2^*, and Re_3^* with D according to (9)-(11). Here points 4 give data for wind erosion of dry sand ($d = 5\cdot10^{-5}$-$2.1\cdot10^{-3}$ m, $\rho_S = 2650$ kg/m³, $\rho = 1.21$ kg/m³) [4]; 5, 6 for sand and soil ($d = 5\cdot10^{-5}$-$1.75\cdot10^{-3}$ m, $\rho_S = 2650$ kg/m³, $\rho = 1.21$ kg/m³) [5]; 7 for sand ($\rho_S = 2650$ kg/m³, $\rho = 1.21$ kg/m³) [6]; 8 for wave erosion of quartz particles ($d = 3.4\cdot10^{-4}$-$3.4\cdot10^{-2}$ m, $\rho_S = 2650$ kg/m³, $\rho = 997.3$ kg/m³) [7]; 9 for blowing snow ($d = 2\cdot10^{-4}$-$7\cdot10^{-4}$ m, $\rho_S = 920$ kg/m³, $\rho = 1.39$ kg/m³) [8]; 10-12 for blowing away of solid bodies ($d = 6.1\cdot10^{-4}$-$7\cdot10^{-3}$ m) of different specific gravity, respectively (γ = 9613, 14,715, 26,874 N/m³) [9]; 13 are data for Reynold's number relating to average limiting velocities during pneumatic transport of cleaned wheat grains ($d = 2.59\cdot10^{-3}$, $3\cdot10^{-3}$ m, $\rho_S = 1320$ kg/m³), 14 is the same for sand ($d = 3.42\cdot10^{-4}$, $7.15\cdot10^{-4}$, $9\cdot10^{-4}$ m, $\rho_S = 2650$ kg/m³), 15 is the same for peas ($d = 5.76\cdot10^{-3}$ m, $\rho_S = 2770$ kg/m³), 16 is the same for coal ($d = 6.25\cdot10^{-4}$, $1.275\cdot10^{-3}$ m, $\rho_S = 1500$ kg/m³) [10]; 17 is for erosion velocities of bonded soils ($d = 3.7\cdot10^{-4}$, $1.5\cdot10^{-3}$, $4\cdot10^{-3}$ m, $\rho_S = 2650$ kg/m³, $\rho = 997.3$ kg/m³) [11]. These data were brought to the conditions of our experiment taking account of the change in densities for flow and the materials being blown away. As can be seen from Fig. 4, the experimental results of many authors obtained under different conditions and media for a different material of solid particles and flow are in quite good agreement with our results, and they are described by critical Eqs. (9)-(11).

The qualitative conformity of the results of the tests of many authors makes it possible to assume that expressions (9)-(11) may be used in order to determine critical flow velocities under whose effect particles are in one or another condition.

The amount of wear with flow velocities equal to the critical value $u = u_j^*$ is of particular interest for theoretical studies. Presented in Fig. 5 is the change in φ with flow velocities corresponding to threshold values in different transfer regimes. With critical flow velocities Eqs. (8), describing the change in φ_j in relation to ψ in different transfer regimes, take the form

$$\varphi_1^* = 0, \qquad q_1^* = 0; \tag{12}$$

$$\varphi_2^* = 0{,}084, \quad q_2^* = 0{,}084\cdot10^{-8}\rho_s\,\sqrt{\rho^* g d}; \tag{13}$$

$$\varphi_3^* = 1{,}542, \quad q_3^* = 1{,}542\cdot10^{-8}\rho_s\,\sqrt{\rho^* g d}. \tag{14}$$

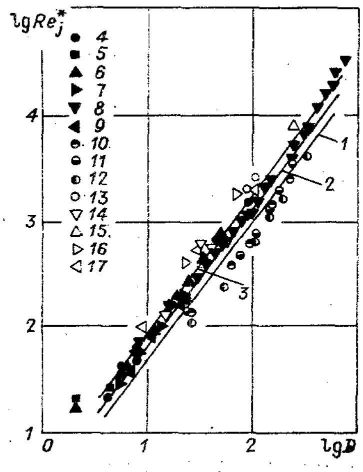

Fig. 4

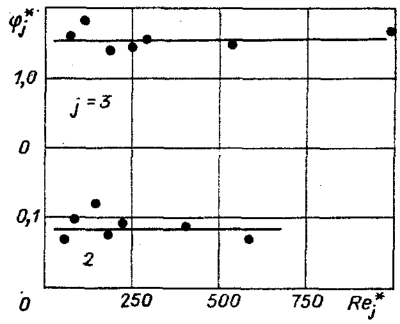

Fig. 5

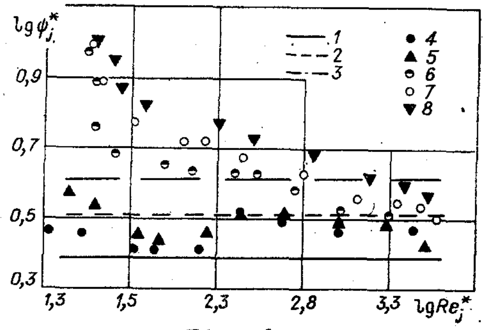

Fig. 6

As can be seen from Fig. 5 and expressions (12)-(14), the value of φ_j with critical velocities independent of average diameter remains constant. This situation may be used as a boundary condition during theoretical study in the region of solid particle movement from a smooth surface with different flows.

From Table 2 it can be seen that with a change in ψ from 2.46 to 3.07 there is an initial regime (particle rolling), in the transitional regime (particle rolling and separation) ψ changes from 3.07 to 4.043, and in the region of massive blowing away of particles (stabilized) $\psi \geq 4.043$.

Shown in Fig. 6 is the change in critical value ψ_j^* in relation to Re_j^*, lines 1-3 correspond to numbers with which initial, transitional, and stabilized regimes set in for different particle sizes on a smooth surface. For particles with diameter $d > 1 \cdot 10^{-4}$ m ($Re_1^* = 18.12$, $Re_2^* = 22.62$, $Re_3^* = 29.8$) ψ does not depend on flow viscosity. Given by points 4-8 are the results of tests [12] for blowing away of solid particles of different size from surfaces with uniformly distributed sand roughness (height of elements $K = 1 \cdot 10^{-5}$, $1 \cdot 10^{-3}$, $2 \cdot 10^{-3}$, $3 \cdot 10^{-3}$, and $4 \cdot 10^{-3}$ m, respectively). As can be seen from Fig. 6, data for $K = 1 \cdot 10^{-5}$ and $K = 1 \cdot 10^{-3}$ agree with our data. This is connected with the fact that height $K \leq 1 \cdot 10^{-3}$ m has a weak effect on the mobility of solid particles. Starting from $K = 2 \cdot 10^{-3}$ m or more the effect of roughness is marked with $\log Re_j^* < 2.0$. It is possible that this explains the divergence of results of A. Shields, V. S. Knoroz, and others.

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GENERAL ARRANGEMENT OF REGIMES FOR SPATIAL LOCAL FLOWS

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Different local features at the surface of a body are breaks or sharp changes in boundary conditions, separation or joining of a flow, irregularities, etc., and they may have a marked effect on local and global characteristics of flow over it [1]. This situation stimulates continued interest towards to flow in local regions, which apart from considerable practical importance, often exhibit considerable theoretical novelty (see, e.g., [2-6], where a systematic study was carried out of planar local regions of flow). However, the majority of local regions are spatial, and whereas in studying flat regions considerable success have been achieved, for spatial regions only individual solutions have been obtained, often using considerable simplifications [7-19]. In addition, due to the absence of systematic studies it is difficult to determine the boundaries for existence of different flow regimes in local spatial regions, and limiting transitions which make it possible to changeover from one flow regime to another. In this work systematic studies are carried out for flow regimes in local spatial regions for each of the boundary problems formulated, the main properties of their solution are studied, and a general classification for the arrangement of flow regimes is built up.

1. Consideration is given to flow over a flat semi-infinite plate by a uniform subsonic or supersonic flow of viscous gas with Mach numbers $(M_\infty^2 - 1) \sim O(1)$ or more, but for precritical Reynold's numbers. Let there be in the surface of the plate at a certain distance ℓ from its leading edge a small spatial protuberance or hollow (Fig. 1). A steady-state solution of the Navier–Stokes equations is constructed for a spatial region of disturbed laminar flow with $Re_\infty = \rho_\infty u_\infty l/\mu_\infty = \varepsilon^{-2}$ tending towards infinity. Here ρ_∞, u_∞, and μ_∞ are values of density, velocity, and dynamic viscosity coefficient in an undisturbed uniform running flow. Subsequently we shall use only dimensionless values, and for this all linear dimensions are related to ℓ, pressure p is related to $\rho_\infty u_\infty^2$, enthalpy h is related to u_∞^2, and the rest of the flow functions are related to their values in an undisturbed uniform running flow.

Considering the dimensions of a small irregularity, it is assumed that its typical thickness a in order of magnitude is less or equal to the typical width of an undisturbed boundary layer on a plate in this area, i.e., $a \lesssim \delta \sim O(\varepsilon)$, and its typical extent b in order of value is greater or equal to a and less than or equal to unity, i.e., $a \leqslant b \leqslant 1$. The nature of the irregularity width c in order of magnitude may be greater or equal to a, i.e., $c \geqslant a$. With a > b or a > c flow may have the same features as that with a ~ b or a ~ c, and only the longitudinal or transverse dimensions of the disturbed flow region will be determined by the value of a. It is evident that a, b, c > ε^2 (for flow regions in which one of the characteristic dimensions is commensurate in order of value to the typical length of free flow of a gas molecule ~$O(\varepsilon^2)$, Navier–Stokes equations will not be valid), i.e., characteristic thickness a, extent b, and width c of an irregularity are satisfied by the relationships

$$\varepsilon^2 < a \leqslant \varepsilon, \; a \leqslant b \leqslant 1, \; a \leqslant c. \tag{1.1}$$

This means that the test region for measurement of values of a, b, and c is limited by boundaries of truncated pyramid ABCDEFGH (Fig. 2). Among irregularities with characteristic dimensions (1.1) consideration is only given to those which initiate considerable local pressure gradients $\partial p/\partial x > 1$ or $\partial p/\partial Z > 1$ or for which in the disturbed flow regions convective

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