EXPERIMENTAL INVESTIGATION OF THE MOTION OF BODIES IN A FLUIDIZED BED

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UDC 532.546

Investigation of the resistance of bodies in a fluidized bed is of great practical interest. The factors influencing the motion of macroscopic bodies of different shapes in gas-fluidized free-flowing materials are examined in detail in [1-3] and a number of other works. Thus the methods and results of an experimental investigation of free fall of bodies in a fluidized bed are presented in [1]. The forces acting on a body submerged in a fluidized bed are estimated in [2]. In most works, however, the free fall of bodies with different shapes was studied, and in view of the limitation of the density of the material of the bodies this made it impossible to obtain high relative velocities. In addition, data on the resistance of solids under cramped conditions in the piston regime of fluidization of a free-flowing material are inadequate.

In the present paper we present experimentally determined characteristics of a gas-fluidized bed of sand with average grain size and height to diameter ratio of the bed equal to 4.5. We determine the dependence of the resistance of a cylindrical body in a fluidized free-flowing material on the fluidization regime and the conditions of flow around the cylindrical body with body-to-channel diameter ratio equal to 0.15, 0.225, and 0.3.

The investigation was conducted with the help of the experimental apparatus displayed schematically in Fig. 1. The apparatus consists of a 0.2 m in diameter and 1.1 m high cylindrical channel 4 and the bottom 1 to which is attached a combined-type gas-dispensing apparatus 8 with a useful cross section of 0.61%. A connecting rod with a plate 10 for positioning removable weights 9 and a dielectric measuring rod with ferrite markers 6, which served simultaneously as a controlling rod, was attached to the experimental body 5. The free-flowing material 3 consisted of quartz sand with characteristic grain size of 0.4 mm and initial porosity of 0.42. The fluidization regime was formed by the gas-supply system 2. In order to record the velocity of the body the graduated rod with the ferrite markers was passed through a measuring inductance coil 7, which is connected in the electric circuit of an ID-2I indicator and an N145 light-beam oscillograph. The average velocity was determined from the time interval between passage of the coil through two neighboring markers.

The variable parameters in the investigation of the resistance force acting on the body were as follows: the motive force N, the porosity ε of the fluidized bed, and the diameter d and the length ℓ of the body. The output parameter was the velocity of the body w. The motive force was determined by the removable weights. The ranges of the geometric parameters were d = 0.03-0.06 m and ℓ = 0.1-0.2 m.

In order to determine the resistance force F_ψ acting on the body in the fluidized bed and the resistance coefficient ψ we studied the parameters of only an established regime of flow around the body. In practice, the steady-state regime is achieved when the body sinks under gravity to 1-2 of its diameter from the free surface of the fluidized bed and remains up to a distance of 2-3 diameters from the bottom of the apparatus. The quite long measuring section ensured stability of the data obtained.

The results of the experimental determination of the hydraulic characteristics of a 0.9 m high fluidized bed of a free-flowing material are presented in Table 1. It follows from analysis that for beds with $H_0/D > 1$ the structure of the beds changes sharply and becomes nonuniform already for small degrees of expansion. In the process there arise pulsations of the pressure and concentration of free-flowing material, and these pulsations lead to a change in the vertical force acting on the body. Thus, according to [2], the vertical force can be 7-15 times greater than the time-averaged value.

St. Petersburg. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 4, pp. 99-103, July-August, 1993. Original article submitted February 19, 1992; revision submitted August 7, 1992.

 0021-8944/93/3404-0538$12.50

TABLE 1

w_f, m/sec*	Visible height, m	Degree of expansion $\lambda = H/H_0$	Behavior of the bed
0,080	0,900	1,000	Appearance of separate eddies on the surface of the bed
0,153	0,905	1,006	Start of boiling
0,239	0,980	1,090	Bubble-boiling regime
0,308	1,040	1,160	Appearance of the piston effect
0,380	1,100	1,220	The final height of the bed is difficult to measure, piston effect intensifies

*The velocity of the fluidizing gas is calculated from the data of [7].

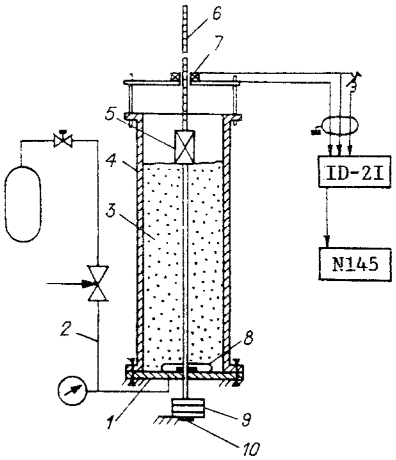

Fig. 1

In practice the determination of the porosity of the fluidized bed is a quite complicated problem. According to [4-6], the particle concentration in the bed varies exponentially along the axis, and it was established that it is nonuniform in the radial direction. For degree of expansion of the bed $\lambda < 2$, however, the porosity of the bed can be assumed to be constant over the height and can be determined from the equation [5]

$$\varepsilon = 1 - (1 - \varepsilon_0)/\lambda \tag{1}$$

where $\lambda = H/H_0$ is the degree of expansion of the fluidized bed.

The motion of the body in the fluidized bed is associated with breakdown in the structure of the bed in the vicinity of the moving body, namely, in the stern region. Here particles of the free-flowing material which are not supported by the flow precipitate onto the surface of the body. A stagnant zone consisting of particles which are pressed against the body and move with the velocity of the body also forms in front of the body, where the compressive stresses are highest.

In the general case the equation of motion of the body in a fluidized bed has the form

$$\frac{m dw}{dt} = N + G - F_\psi - F_B - F_{fr} - \frac{\alpha\, dw}{dt}. \tag{2}$$

Here w is the velocity of the body (in m/sec); G is the weight of the experimental body (in N); F_ψ is the resistance force acting on the body (in N); $F_B = \rho V g$ is the buoyancy force (in N); V is the volume of the body (in m³); g is the acceleration of gravity (in m/sec²); F_{fr} is the friction force in the mobile sites of the apparatus (in N); and, α is the apparent-mass coefficient.

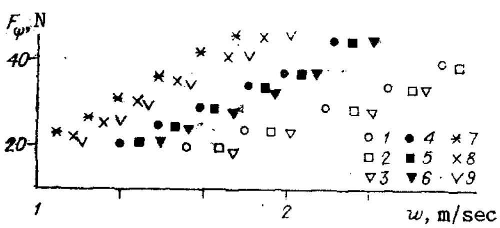

Fig. 2

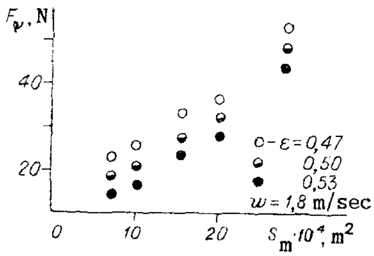

Fig. 3

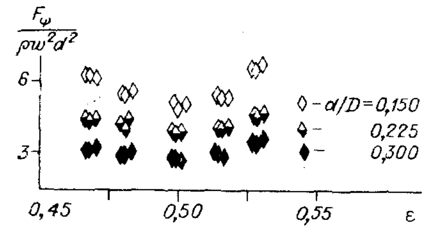

Fig. 4

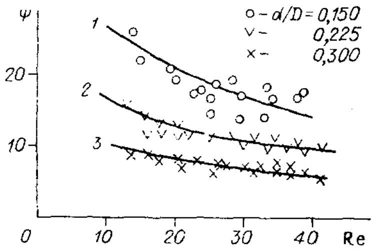

Fig. 5

Under conditions of steady motion of the body Eq. (2) assumes the form

$$F_{\psi} = N + G - F_{B} - F_{fr}. \tag{3}$$

The density of the fluidized bed is determined from the equation

$$\rho = \rho_s(1-\varepsilon) + \rho_f\varepsilon,$$

where ρ_s is the density of the crystal lattice of the free-flowing material (in kg/m^3) and ρ_f is the density of the fluidizing gas (in kg/m^3).

Since the degree of expansion of the bed did not exceed 1.22, it was assumed that the porosity is constant on the measuring section of the bed, and the numerical value of the porosity was determined from Eq. (1).

The experimentally measured resistance force acting on the body in the fluidized free-flowing material versus the velocity of the body is displayed in Fig. 2, where the points 1-3 correspond to ε = 0.47, 0.50, and 0.53 with d = 0.03 m; 4-6 to ε = 0.47, 0.50, and 0.53 with d = 0.045 m; and, 7-9 to ε = 0.47, 0.50, and 0.53 with d = 0.06 m. Analysis of the data obtained shows that for $w < 2$ m/sec the resistance force is virtually a linear function of the velocity. This agrees with the results of [1]. For higher velocities this relation becomes nonlinear.

Figure 3 displays the experimental data on the resistance force versus the area of the maximum midsection of an experimental body moving with fixed velocity. It is evident that the resistance force is a nonlinear function of the cross section of the fluidization channel covered by the body. As the cross section of the body increases, the resistance force increases. This indicates that the constriction affects the resistance for d/D = 0.15.

Figure 4 illustrates the dimensionless resistance force versus the porosity. This dependence reflects the degree of expansion or the regime of fluidization of the bed of free-flowing material. The dimensionless resistance force is lowest for numerical porosity 0.49-0.50. This dependence is explained by the manifestation of two opposing factors. Expansion of the bed leads to a general reduction of the particle concentration of the free-flowing material, improving the conditions of particle flow around the body. As the flow velocity of the fluidizing gas increases, however, the structure of the fluidized bed becomes significantly nonuniform, and this leads to a jump-like change in the particle concentration, as is characteristic for the piston regime of fluidization. The instantaneous value of the resistance force changes in a jumplike manner analogously, and the average value increases with the volume-averaged porosity of the bed.

Thus it is evident that for fluidization channels with $H_0/D = 4.5$ the dimensionless resistance $F\psi/\rho w^2 d^2$, of the body decreases as the fluidization number increases from 1 to 2.18, and as the fluidization number increases further, the resistance increases.

The resistance coefficient is determined from the well-known expression

$$\psi = 2F_\psi/(\rho(w+w_s)^2 S_m),$$

where w_s is the velocity of the particles of the free-flowing material, as determined from [2]; $F\psi$ is found from Eq. (3); and, S_m is the area of the maximum midsection of the experimental body (in m^2).

It should be noted that in order to determine a relation of the form $\psi = \psi(\text{Re})$ it is necessary to define the concept of viscosity for a fluidized bed of free-flowing material, as it appears in the Reynolds number. At the present time there exist different approaches to finding the viscosity. These approaches are examined in detail in [1]. The application of different approaches and the conditions under which the investigations were performed gave significantly different numerical values of the viscosity. We adopted the approach recommended in [1], where the concept of an effective viscosity of a fluidized bed of a free-flowing material was employed.

Figure 5 displays the experimental data on ψ as a function of Re for cylindrical experimental bodies. It was established that the length of the body in the range $\ell = 0.1$-0.2 m has virtually no effect on the value of ψ. This is due to the fact that the lateral friction force of the body and the medium makes an insignificant contribution to the resistance force; this contribution did not exceed 10% in magnitude. Least-squares analysis of the experimental data gave the following relations:

$$\psi = 53{,}5\text{Re}^{-0{,}33} \quad (d/D = 0{,}15); \tag{4}$$

$$\psi = 17{,}2\text{Re}^{-0{,}20} \quad (d/D = 0{,}225); \tag{5}$$

$$\psi = 16{,}5\text{Re}^{-0{,}26} \quad (d/D = 0{,}30). \tag{6}$$

The curves 1-3 in Fig. 5 were constructed according to Eqs. (4)-(6), respectively. We conjecture that the difference in the values of the coefficients and exponents is due to the influence of the degree of constriction.

Thus the relations obtained make it possible to determine the resistance force acting on a cylindrical body in a fluidized bed of free-flowing material as well as the optimal regime of fluidization, in which the resistance is minimized for the range of variable parameters presented in this work. Thus the maximum rms deviation of the dimensionless resistance force $F\psi/(\rho w^2 d^2)$ for the experimental bodies was equal to 0.48; similar results were also obtained in [1].

According to [8], the behavior of a fluidized bed depends mainly on the variation in the particle size, the particle density, the height of the layer, the velocity of the gas, and the construction of the gas-dispensing apparatus. On this basis it can be concluded that extrapolation of the results to apparatus with different scales is approximate, and as the scale changes, more accurate data must be obtained using apparatus with closer or equal scale.

As far as the empirical relation $\psi = \psi(\text{Re})$ is concerned, the validity of the results depends mainly on how accurately the effective viscosity μ^* of the fluidized bed is determined for large beds with larger particles in the free-flowing medium.

LITERATURE CITED

1. O. M. Todes and R. B. Rozenbaum, Motion of a Body in a Fluidized Bed [in Russian], Izd. Lenin. Gos. Univ., Leningrad (1981).
2. B. A. Michkovskii and A. P. Baskakov, "Dynamical forces acting on a body submerged in a fluidized bed," Tr. UPI, No. 227 (1974).
3. Yu. P. Gupalo, "Motion of a body in a fluidized bed," Inzh. Fiz. Zh., 5, No. 2 (1962).
4. N. I. Syromyatnikov, "Structure of a suspended layer," Tr. UPI, No. 61 (1956).
5. V. S. Al'tshuler and G. P. Sechenov, Processes in a Fluidized Bed under Pressure [in Russian], Izd. Akad. Nauk SSSR, Moscow (1963).

6. J. F. Davidson and D. Harrison (eds.), Fluidization, Academic Press, NY (1971).
7. Fand, Kim, Lam, and Fan, "Hydraulic resistance in the motion of a liquid in porous media consisting of spheres with disordered packing," in: Transactions of the American Society of Mechanical Engineers. Theoretical Foundations of Engineering Calculations, No. 3 (1987).
8. Collection of Articles on the Hydrodynamics and Mass Transfer in a Fluidized Bed [in Russian], Atomizdat, Moscow (1964).