# FORCES ACTING ON A BODY IN A NONUNIFORM FLUIDIZED BED

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The resistive force acting on a fixed sphere in a nonuniform fluidized bed was measured and the force field around a rising gas bubble determined.

On bodies submerged in a fluidized bed (tubes, nozzle elements) there acts a vertical force associated with material motion and bursting of gas bubbles through the bed [1]. There is information about the average vertical component of this force acting on model bodies [1-4] and an empirical correlation for its evaluation was proposed [4]. At the same time, there has been little study of the instantaneous values of the resistive forces, which are of greatest interest for calculations. It is only known that they reach values considerably greater than the average values of resistive forces, but it is not clear how the magnitude of the force is linked with the motion of gas bubbles which gives rise to displacement of the solid phase.

Presented below are the results of an experimental study of the pattern of material motion near gas bubbles and of the resultant resistive forces acting on a body submerged in a fluidized bed.

In a rectangular column 24 × 3.5 cm in cross section with transparent walls, air was used to produce a fluidized bed of sand ($U_0$ = 6 cm/sec, d = 0.23 mm) or of silica gel ($U_0$ = 2 cm/sec, d = 0.19 mm). The initial height of the charge was kept the same and was 45 cm. A sensor-dynamometer, the operating principle of which was described in [5], was installed on the axis of the column 38 cm above the gas distribution grid. The sensor was a plastic sphere 5.5 mm in diameter mounted on a rigid metal spindle (2.5 cm long, 0.5 mm in

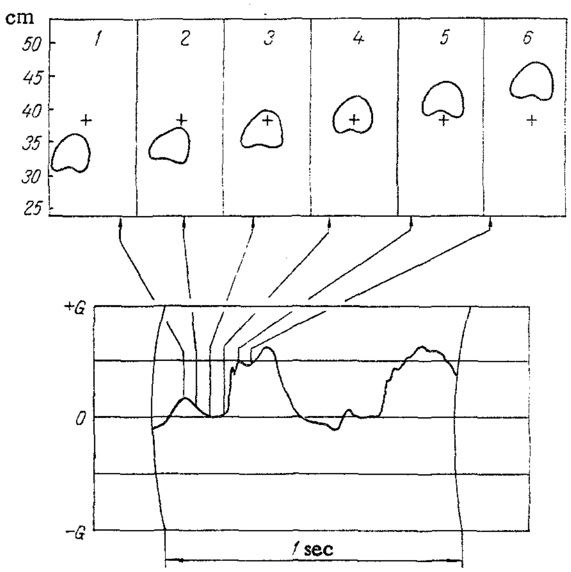


Fig. 1. Oscillogram of resistive force and film frames of gas-bubble motion in a fluidized bed. Sand, U = 17 cm/ sec.

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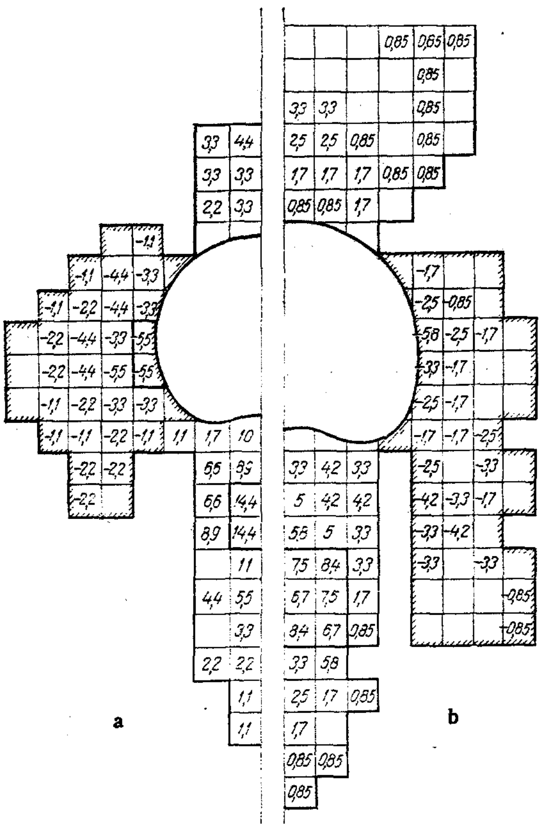


Fig. 2. Resistive force field near a gas bubble [a) silica gel, R ≈ 2.5 cm, force in units of $2 \cdot 10^{-3}$ N, U = 11 cm/sec; b) sand, R ≈ 3 cm, force in units of $10^{-2}$ N, U = 17 cm/sec].

diameter) the end of which was fastened to an elastic bar (phosphor-bronze plate). The other end of the bar was rigidly fastened to a fixed support. The resistive force acting on the sphere was measured with two strain gauges (base 5 mm, resistance 100 Ω) fastened on each side of the elastic bar and connected to a TA-5 strain-gauge recording station. The output signal from the recording station was recorded on a strip chart by an H-327/1 high-speed recorder. The measuring system made it possible to record the resistive force acting on the sensor in the fluidized bed to better than 7% in the frequency range up to 50 Hz. The normal frequency of the sensor was 150 Hz, which made it possible to record reliably the resistive forces in a fluidized bed, since the frequencies of the forces did not exceed 30-50 Hz.

The sensor was installed in the bed so that the vertical component of the resistive force was recorded. At the same time, a picture of the motion of the gas bubbles in the fluidized bed was taken. Motion pictures were taken on 16-mm film at a speed of 24 frames per second. In order to synchronize the film frames and the strip chart on which the resistive force of the sensor was recorded, a special circuit was used which consisted of a pulse generator operating at a frequency of 0.3 Hz and a control unit. An electric lamp set up in the field of view of the motion-picture-camera objective was turned on by means of control pulses and a mark was made on the strip chart of the recorder simultaneously. Because of this synchronization, there was no difficulty in determining the correspondence between film frames and chart sections to an accuracy of 1/24 sec.

TABLE 1. Characteristics of Dispersed Material

| No. | Material | $U_*$, cm/sec | ρ, g/cm³ | d, mm |
|---|---|---|---|---|
| 1 | Sand | 6 | 2,6 | 0,23 |
| 2 | Sand | 28 | 2,6 | 0,63 |
| 3 | Silica gel | 2 | 1,1 | 0,19 |
| 4 | Silica gel | 14 | 1,5 | 0,76 |
| 5 | Aluminosilicate | 80 | 1,3 | 2,0 |

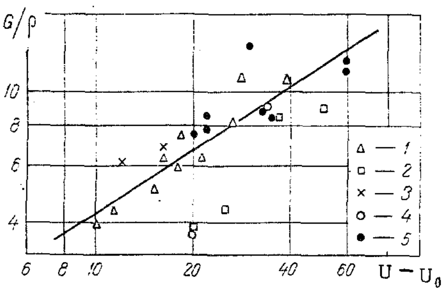


Fig. 3. Dependence of maximum forces in a fluidized bed on excess gas filtration rate. 1, 2, 3, 4, 5 are material numbers as shown in Table 1. $G/\rho$, $cm^4/sec^2$; $U-U_0$, cm/sec.

A sample of the oscillogram obtained is shown in Fig. 1. The experiments with sand were performed at an air filtration rate of 17 cm/sec. The upper portion of the figure shows a view of the film frames representing the pattern of gas-bubble motion in the fluidized bed. The position of the sensor-dynamometer is denoted by the cross in the figure. The scale on the left is plotted in centimeters. When a gas bubble approaches the sensor (frame 1), a relatively small signal appears which gradually decreases (frame 2). The resistive force acting on the sensor becomes zero inside the gas bubble (frames 3 and 4). When the lower boundary of the gas bubble intersects the sensor (frame 5), the force increases abruptly and subsequently continues to increase (frame 6). Reuter [1] also noted a similar interaction between a gas bubble in a fluidized bed and a disk (6 cm in diameter). In the region behind the bubble, the vertical component of the resistive force was approximately 2-3 times greater than its value in the frontal region ahead of the gas bubble.

Figure 2 shows the resistive force field (projection on the vertical) in the neighborhood of a gas bubble. It was constructed in the following manner. The resistive force was determined from the recordings on the strip chart. For the same times, the position of the probe relative to the bubble was determined from the film frames. For this purpose, the frames were projected on a screen, the field of which was divided into squares corresponding to an actual size of 1 × 1 cm. Analysis was made of more than 150 frames of similarly sized gas bubbles penetrating the sensor region. The average value of the instantaneous magnitude of the resistive force for each of the squares is denoted by the numbers in the figure. These numbers were obtained from three to four values for which the maximum deviation from the average was 35%. The portions of the squares where measurements were inadequate were left unfilled. The region of positive forces is outlined with a solid line and the region of negative forces (directed downwards) is denoted by hatching. The forces perceived by the sensor in the remaining space were almost zero.

There are two regions in the neighborhood of a moving gas bubble: a region of negative forces to the side and a region of positive forces above and below the bubble. The maximum negative forces were observed laterally at the boundary of the bubble and the greatest positive forces were produced in the wake of the bubble. The magnitudes of the positive forces exceeded the values of the negative forces. Their ratios were approximately 1.5 and 2.5, respectively, in fluidized beds of sand and silica gel. Resistive force depended significantly on the density of the disperse material. Thus, in a fluidized bed of silica gel ($\rho$ = 1.1 g/cm$^3$), the maximum resistive force was almost 2.5 times less than in a fluidized bed of sand ($\rho$ = 2.6 g/cm$^3$).

In the frontal region of the bubble at distances up to two diameters of the spherical probe from the bubble boundary, one should expect the values of the recorded signal to be somewhat reduced because of collapse of the bubble dome by the sensor.

The diagrams shown make it very clear that there is a zone of influence around a moving bubble which is roughly equal to the radius of the bubble in the forward and lateral directions and which extends approximately two bubble diameters behind the bubble. In the region behind the bubble, the dispersed material follows the bubble; to the side of the bubble, the material falls downward. It is natural that the resistive force resulted from the rate of flow of the solid phase over the fixed sensor submerged in the fluidized bed.

The maximum forces created in a fluidized bed are associated with the motion of gas bubbles and specifically depend on the properties of the dispersed material. To reveal the effect of the characteristics of the dispersed material on resistive force, experiments were performed with various materials (Table 1) in the same column with the sensor at its previous position. The greatest forces acting on the sensor-dynamometer were recorded during the experiments. The experimental results are shown in Fig. 3 on a logarithmic scale. The choice of coordinates was based on the assumption that there is a linear dependence of resistive forces on material density, which was noted for the average values of the forces [4]. It was further assumed that fluctuations of the forces produced by displacement of the solid phase during motion of gas bubbles is determined by the filtration of an excess amount of gas above that needed to maintain the material in a suspended state. In the assumed coordinate system, the experimental points obtained at various air filtration rates for five different materials are grouped around a straight line described by the relation

$$\frac{G}{\rho} = (U - U_0)^{0.66}.$$

The greatest deviation of experimental points from the approximating relation does not exceed 70%, which must be considered satisfactory for so unstable a system as a fluidized bed. It must be pointed out that this relation also extends to experiments with large particles where the resultant gas bubbles become commensurate with the cross section of the column and plunger displacement of the material in the bed is observed.

The relation obtained demonstrates the effect of material characteristics and of gas filtration rate on maximum forces in a bed, but it does not reflect the effect of the geometric parameters of the system.

## NOTATION

d, particle diameter; G, force acting on a body in a fluidized bed; $U_0$, rate for initiation of fluidization; U, gas filtration rate; $\rho$, material density; R, bubble radius.

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# FRAMEWORK CONDUCTION IN A GRANULAR SYSTEM


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Equations are derived for the effective transport coefficients in a system of contacting spherical particles immersed in a nonconducting medium.


A substantial contribution can come from the contacting-particle framework to the transport processes in a high-concentration granular medium; for instance, this framework component can have a marked effect on the total heat flux in a granular medium if the thermal conductivity of the particles is much higher than that of the continuous phase (see [1, 2] for a survey of the experimental data). In particular, the theory of thermal conductivity for granular materials [3] for $\lambda_1 \gg \lambda_0$ always gives results for the effective thermal conductivity systematically lower than those from experiment if the transfer by contact between the particles is neglected, whereas theory agrees extremely well with experiment if $\lambda_1 \leqslant \lambda_0$.

Under certain extreme conditions, this component of the flux may be the dominant one. For instance, it has been found [4] that this occurs for uranium and zirconium powders in various gases at pressures below $10^{-2}$–$10^{-1}$ mm Hg.


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