A METHOD OF STUDYING THE MOTION OF BODIES IN A FLUIDIZATION BED

R. B. Rozenbaum, O. M. Todes, and L. N. Fainshtein

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A method is proposed for measuring both the average and the instantaneous velocity of bodies in a fluidization bed.

On a body immersed in a fluidization bed there act complex oscillations of bed particles. As a result, the body does not fall at a constant velocity but, instead, also oscillates in a mode which depends on the state of fluidization as well as on the dimensions, the shape, and the density of bed particles and of that body.

Daniels [1, 2] has proposed a method for measuring the ~~average motion of~~ a solid body in an opaque fluidization bed. These authors have subsequently perfected this method [3], built a special test apparatus for measuring the average relative velocity of slowly moving balls or bodies with other shapes in a fluidization bed, and then estimated the effective viscosity of such a bed.

For a thorough study of the motion of bodies by continuous observation and tracking the parameters of this motion, the authors have now modified that method so that measurements are possible over a wider range of the fall velocity.

The test apparatus is shown schematically in Fig. 1. Above the column in which a fluidization bed is produced we have a dc motor and generator set with a coupling which aligns their shafts.

On the motor shaft we have mounted a pulley with a nylon thread around the groove. A test body is attached to the end of this thread. The body, while falling, pulls the thread and sets the entire system into rotation.

The external forces acting on a body (its nominal "weight") can be varied by applying a voltage to the motor and thus producing a torque opposite to the torque produced by the falling body; in this way, it is possible to vary the average fall or even lift velocity of a body.

The resulting generator voltage, proportional to the rotor rpm and thus also to the velocity of the body, is applied to a scaling dc amplifier U which consists of an operational amplifier in an integrating circuit and a two-stage power amplifier.

The power amplifier makes it possible to load the system with a recording instrument whose time constant is small and whose internal resistance is 5 Ω. The operational amplifier ensures the necessary gain over a wide test range. The input–output characteristic of the amplifier is linear over the operating range. The slope of this characteristic (the scale) is adjustable and can be selected to match the generator voltage. The amplifier input resistance, equal to tens of ohms, does not affect the level of the generator output signal. The signal from the amplifier is transmitted to a recording instrument with a pen deflection proportional to the control voltage $U^-(t)$ and $U^+(t)$ or the velocity of the body up (v^-) and down (v^+), respectively.

During our experiment we had sand particles in the 0.28-0.60 mm size range in a column 0.08 m in diameter fluidized with air coming from a compressor through the distributor grid at the bottom of the column.

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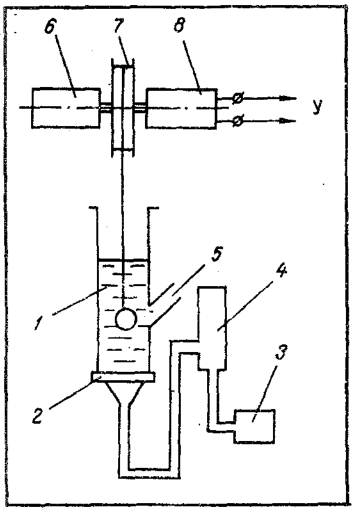

Fig. 1. Schematic diagram of the apparatus for studying the motion of bodies in a fluidization bed: 1) column; 2) grid; 3) compressor; 4) rheometer; 5) tap for manometer connection; 6) motor; 7) pulley; 8) generator.

A fluidization bed is characterized by random oscillations of individual particles or of particle clusters, and by slipping bubbles [4]. As a result of interaction between an immersed body and bed particles or air bubbles, the velocity of the body varies not only in magnitude but also in direction.

The curves in Fig. 2 represent the fall velocity (curve a) and the slow lift velocity (curve b) of a steel ball (diameter $d = 6.35$ mm) in a fluidization bed, as a function of time, at a mean-over-the-bed velocity of the fluidizing stream $u \approx 0.116$ m/sec.

The abscissas represent time in seconds and the ordinates represent the voltage in volts proportional to the velocity of the body. The dashed line indicates the average velocity $\bar{v}$, which has been determined as follows: the alternating control (output) voltage from amplifier U was applied through semiconductor diodes to two integrators in parallel, the diodes having been connected in such a way that one passed only a positive voltage $U^+(t)$ and the other passed only a negative voltage $U^-(t)$. Each diode passed the voltage to its respective integrating circuit consisting of a modulator MDM, a dc amplifier UPT, and a power amplifier UM.

After integration, both integrals

$$\int_0^t U^+(t)\,dt \sim \int_0^t v^+(t)\,dt \sim S^+,$$

with S^+ denoting the distance traveled by a body moving down and

$$\int_0^t U^-(t)\,dt \sim \int_0^t v^-(t)\,dt \sim S^-,$$

with S^- denoting the distance traveled by a body moving up were measured on a voltmeter whose scale had been calibrated in units of distance.

With the speed of the recorder chart and with the travel time of a body known, it is easy to determine the average velocity of a body moving through a fluidization bed.

On a ball moving through a fluidization bed there act the force of its weight $P = mg$, the opposing force F_{op} produced by the motor, the friction force F_{fr} between thread and pulley, determined by measurement, and the force F_{fb} which the bed exerts on the immersed body.

The force of the bed F_{fb} can approximately and fictitiously be resolved into two components. On the one hand, according to Archimedes' principle, a fluidization bed with a high density ρ_{fb} should produce a buoyancy force $F_{buoy} = (\pi d^3/6)\rho_{fb} g$; on the other hand, a body which moves through a bed in a certain direction and transfers momentum to the bed particles should be subject to a net resistance force F_{res} in the direction opposite to the velocity vector. Such a resolution of the bed force is fictitious, inasmuch as the impacts on the body are not regular and the bed is not homogeneous. For this reason, both F_{res} and F_{buoy} must be regarded as some average quantities and ρ_{fb} in the expression for F_{buoy} must be treated as the mean bed density. The imprecision of this concept is compounded by the fact that a body

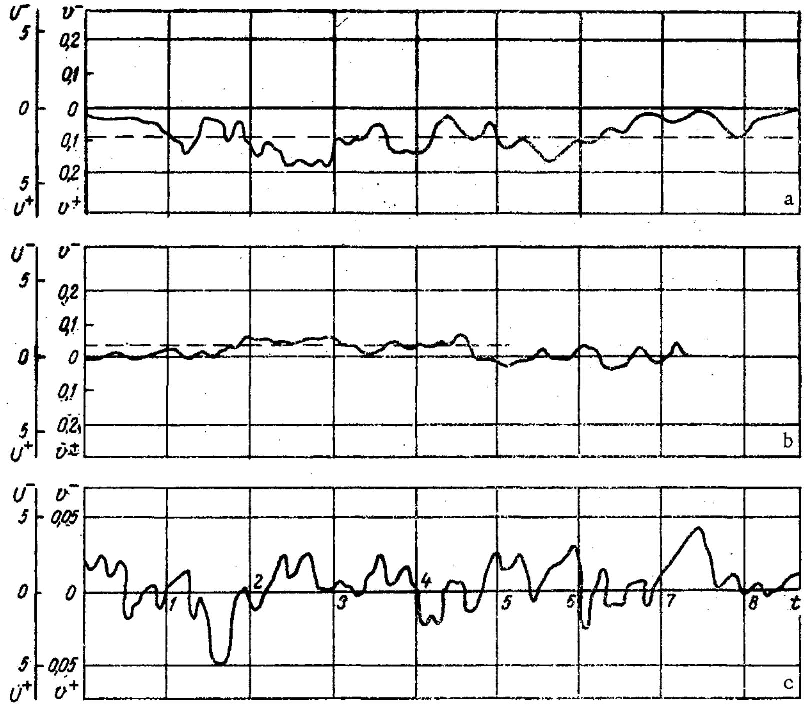

Fig. 2. Recorded velocity of a body in a fluidization bed, as a function of time: a) fall; b) lift; c) suspension at mid-height; voltages U^+, U^-, V; velocities v^+, v^-, m/sec; time t, sec.

immersed in a fluidization bed distorts the local bed structure [5]. With the motion of such a body systematically oriented (fall or lift), nevertheless, this resolution of force F_{fb} into the said components seems entirely justified as far as the practical application of these concepts is concerned.

Finally, one must remember that, when a body moves through a fluidization bed, then, owing to the velocity fluctuations, the steady motion of such a body at some average velocity becomes a fictitious concept too. When instantaneous accelerations occur in the total balance of forces, then, according to d'Alembert's principle, one should also take into account inertia forces. An estimate of accelerations on the basis of Fig. 2 indicates that these do not exceed 5% of the acceleration due to gravity so that, therefore, the inertia forces may be disregarded and the motion of bodies under the given conditions here may be regarded as almost steady.

In this case, the resistance force is during downward motion

$$F_{res} = mg - F_{buoy} - F_{op} - F_{fr},$$

and during upward motion

$$F_{res} = F_{op} + F_{buoy} - mg - F_{fr}.$$

The opposing force is proportional to the motor voltage V

$$F_{op} = \alpha g V,$$

with the coefficient α determined experimentally (in our apparatus V = 1 V with a body weighing $1.54 \cdot 9.81 \cdot 10^{-3}$ N).

Thus, during the fall of a ball

$$F_{res} = \left(m - \frac{\pi d^3}{6}\rho_{fb} - \alpha V\right) g - F_{fr}$$

and during the lift of a ball

$$F_{res} = \left(\alpha V + \frac{\pi d^3}{6}\rho_{fb} - m\right) g - F_{fr}.$$

For the ball in our experiment $F_{res} = 7.80 \cdot 10^{-3}$ N, $\bar{v} = 9.0 \cdot 10^{-2}$ m/sec during the fall test (Fig. 2a) and $F_{res} = 2.67 \cdot 10^{-3}$ N, $\bar{v} = 3.49 \cdot 10^{-2}$ m/sec during the lift test. Assuming that the Stokes equation [3]:

$$F_{res} = 3\pi\mu^* d\bar{v},$$

applies to the motion of a ball at such velocities, we can then estimate the effective viscosity of the bed

$$\mu^* = \frac{F_{res}}{3\pi d\bar{v}} \approx 1.31 \text{ N} \cdot \text{sec/m}^2.$$

The Reynolds number for the pseudofluid would then be

$$Re = \frac{\bar{v} d \rho_{fb}}{\mu^*} \approx 0.57,$$

i.e., at a stream velocity of the fluidizing agent $u \approx 0.116$ m/sec the bed behaved like viscous oil and the ball moved in a quasilaminar mode.

According to Fig. 2a, the frequency of velocity fluctuations was ≈2 Hz and thus equal to the frequency of density fluctuations in the fluidization bed: the frequency of velocity fluctuations is measured as half the number of intersections between the $v^+(t)$ curve and the straight line which represents the average velocity, the frequency of density fluctuations is measured by other methods [4].

The density of a fluidization bed is not really uniform over the height [4]. The density is lower at the top and the effect of the lift force acting on an immersed body is weaker here than in layers underneath. As a result, a body slowly emerging from the bed remains almost in suspension; such a state of a body is indicated in Fig. 2b with sufficient clarity by the periodic velocity variations of the oscillating body.

This case is shown in Fig. 2c with even more clarity: the opposing force on the ball was here such that, under the given fluidization conditions, the ball was suspended at mid-height like a "turbulimeter" and subjected to impact from the bed until it began to follow the bed oscillations [6]. The examples cited in Fig. 2 correspond to conditions prevailing in gravity-flotation treatment of useful mineral ores for concentration, with the bed acting as the heavy phase [7, 8, 9].

Lumps of the concentrate (e.g., barren rock) whose density is higher than the mean density of the fluidization bed sink in the latter (Fig. 2a).

Lumps (e.g., of coal) whose density is lower than the mean bed density ρ_{fb} buoy (Fig. 2b). Finally, lumps whose density is close to ρ_{fb} remain immersed in the pseudofluid, moving alternately up and down (Fig. 2c).

The motion of a body in a fluidization bed has not been studied in great detail so far, and only a few reports on radioactive [10] or purely visual [11] methods are available. Our method described here makes it feasible to study the motion of bodies of various sizes, masses, and shapes in a fluidization bed. By varying the bed parameters over wide ranges, it is possible to explore thoroughly enough the laws which govern the motion of immersed bodies as well as that of the bed particles.

NOTATION

U^+, U^- are the voltages at the output of the scaling amplifier;
v^+, v^- are the velocities of a body down and up, respectively;
t is the travel time of a body;
S^+, S^- are the distances traveled by a body down and up, respectively;
$\bar{v}$ is the average velocity of a body;
u is the mean velocity of the fluidizing stream;
d is the ball diameter;
ρ_{fb} is the density of the fluidization bed;
μ^* is the effective dynamic viscosity of the fluidization bed;
Re is the Reynolds number;
F_{res} is the resistance force;
F_{buoy} is the buoyancy (lift) force;
F_{op} is the opposing force;
F_{fr} is the friction force between thread and pulley;

P is the weight of a body;
m is the mass of a body;
g is the acceleration due to gravity;
F_{fb} is the force of the fluidization bed acting on an immersed body in motion;
V is the voltage at the motor terminals;
α is a proportionality factor.

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