THE RESISTANCE OF A DENSE MOVING LAYER THROUGH WHICH A GAS STREAM IS INJECTED FROM BELOW

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For a tall and narrow vessel with an opening in the bottom – through which granular material is discharged under conditions of a gas countercurrent – we have experimentally confirmed the equality of the resistance factors for a moving and a nonmoving layer. We have established the practical equality for the porosity of a dense layer – at the threshold of fluidization – and the porosity of a moving bed.

The resistance of a moving bed differs (given the same gas flow rate) from the resistance of a fixed bed [1-7]. However, in practical terms, all of the above-cited references describe the change in the resistance of a moving bed relative to that of a fixed bed by means of empirical formulas. An exception is the work by Happel [1], in which an attempt is made to determine the resistance coefficient for a moving bed. The data from that reference can be used for the laminar regime of motion in the case of materials that are approximately spherical in shape. In a turbulent regime of motion, the author makes no provision for the change in the function of porosity with a change in the Reynolds number, thus making unlikely the use of the derived results for conditions different from those under which the experiments were carried out.

In this paper we determine the effect of material motion on the resistance coefficient for a turbulent filtration regime.

The resistance of a fixed bed in a vessel of constant cross section can be determined from the Leva equation [8]

$$\Delta p = \lambda \frac{h}{d} \frac{w_0^2}{2g} \gamma_g \frac{[(1-\varepsilon)\varphi]^{3-n}}{\varepsilon^3}. \tag{1}$$

We can also use this equation to determine the resistance of a moving bed, assuming that $\varepsilon = \varepsilon_m$, $w_0 = w + u$, since the sum of the forces acting on the particles and governing the resistance to the passage of the gas is no different for a bed in uniform motion than for a fixed bed. However, we can expect changes in the resistance coefficient as a result of changes in the positions of the particles during the motion. The resistance of the bed in the tube whose bottom has been fitted out with a diaphragm (Fig. 1) differs from the resistance of a column of a material of equal cross section and can be determined in the form

$$\Sigma\Delta p = \Delta p_1 + \Delta p_2, \tag{2}$$

where Δp_1 is the resistance of a bed of height h_1 and, according to (1), is defined as

$$\Delta p_1 = \lambda_1 \frac{h_1}{d} \frac{w_1^2}{2g} \gamma_g \frac{[(1-\varepsilon_1)\varphi]^{3-n_1}}{\varepsilon_1^3}. \tag{3}$$

The resistance of the bed in the segment h_2 is determined from a similar relationship in the following manner:

$$\Delta p_2 = \frac{1}{h_2} \int_0^{h_2} \lambda \frac{h}{d} \frac{w^2}{2g} \frac{[(1-\varepsilon)\varphi]^{3-n}}{\varepsilon^3} dh. \tag{4}$$

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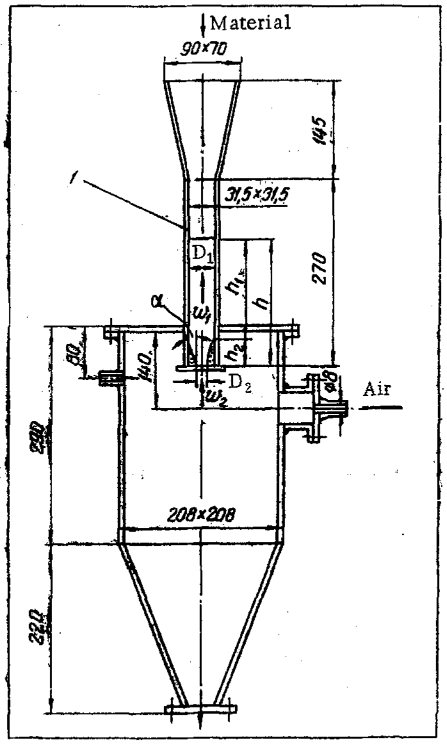

Fig. 1

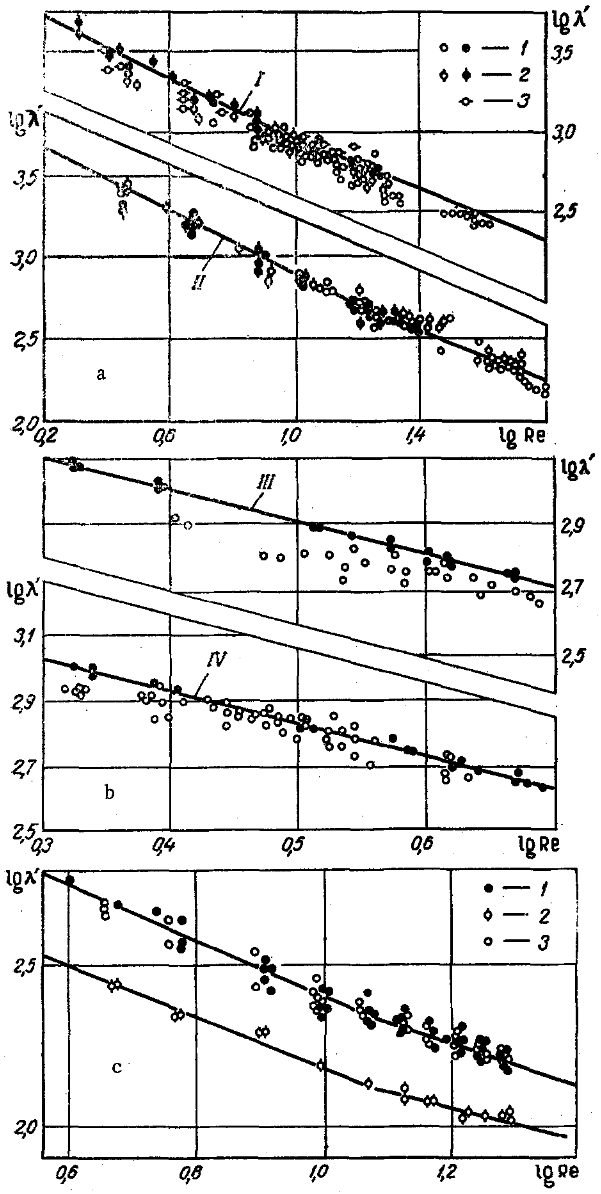

Fig. 2

Fig. 1. Working section of the model ($D_2 = a \times b$; 17.8 × 17.8; 14.5 × 14.5; 12.5 × 12.5; 8.5 × 8.5).

Fig. 2. Dependence of $\lambda' = f(\mathrm{Re})$ for limestone $d_{av} = 1.025$ mm (I) and $d_{av} = 1.426$ mm (II) (a), quartzites (III) and for fireclay (IV) (orifice 12.5 × 12.5 mm) (b), and for limestone d = 1.025 mm (c): a – 1) orifice 17.8 × 17.8 for all heights; 2) 14.5 × 14.5; 3) 12.5 × 12.5; c: 1) orifice diameter 14.1 mm (roughness ≈0, all heights); 2) the same (roughness ≈0.205 m); 3) triangular orifice (area 156 mm^2, all heights). For a and b the filled symbols indicate the fixed bed and the open symbols denote the moving bed.

where

$$w = w_2\left[\frac{D_2}{D_2 + 2h\,\mathrm{tg}\,\alpha}\right]. \tag{5}$$

Under practical conditions, when we know the overall height h of the bed and the velocity w_1 of gas motion, determination of the resistance in the form of

$$\Delta p = \lambda_1 \frac{h}{d} \frac{w_1^2}{2g} \gamma_g \frac{[(1-\varepsilon_1)\varphi]^{3-n_1}}{\varepsilon_1^3} \tag{6}$$

TABLE 1. Characteristics of the Materials Being Tested

Material	Fraction, mm	Average diameter, mm	Density, kg/m^3	Porosity
Limestone	0,45—0,8	0,625	2520	0,464
" "	0,8 —1,25	1,025	2500	0,453
" "	1,25—1,6	1,425	2540	0,476
Fireclay	0,45—0,8	0,625	1825	0,482
Quartzites	0,45—0,8	0,625	2850	0,500
Millet	2,025	2,025	1350	0,428

leads to an error whose relative magnitude is

$$\frac{\Delta p}{\Sigma \Delta p} = \left(\lambda_1 \frac{h}{d} \frac{w_1^2}{2g} \gamma_g \frac{[(1-\varepsilon)\varphi]^{3-n_1}}{\varepsilon_1^3}\right)$$

$$\times \left(\lambda_1 \frac{h_1}{d} \frac{w_1^2}{2g} \gamma_g \frac{[(1-\varepsilon_1)\varphi]^{3-n_1}}{\varepsilon_1^3} + \frac{1}{h_2} \int_0^{h_2} \lambda \frac{h}{d} \frac{w^2}{2g} \gamma_g \frac{[(1-\varepsilon)\varphi]^{3-n}}{\varepsilon^3} dh\right)^{-1} \tag{7}$$

To impart a final form to (7) we determine the value of Δp_2 from (1) by substituting into the latter the average integral velocity

$$w_{av} = \frac{1}{h_2} \int_0^{h_2} w_2 \frac{D_2}{D_2 + 2h \operatorname{tg} \alpha} dh = w_2 \frac{D_2}{2h \operatorname{tg} \alpha} \left[\frac{1}{D_2} - \frac{1}{D_1}\right]. \tag{8}$$

Here the quantities λ and h are taken with respect to the same velocity. With consideration of the assumption, the relative change in the resistance of the bed amounts to

$$\frac{\Delta p}{\Sigma \Delta p} = \frac{h}{\left\{h_1 + \frac{\lambda_2}{\lambda_1} h_2 \left(\frac{D_2}{D_1}\right)^2 \frac{D_2}{2h_2 \operatorname{tg} \alpha} \left(\frac{1}{D_2} - \frac{1}{D_1}\right) [1-\varepsilon]^{n_1 - n_2}\right\}}. \tag{9}$$

Consequently, in calculating the resistance coefficient with the usual formula

$$\lambda = \frac{\Delta p}{\frac{h}{d} \frac{w_1^2}{2g} \gamma_g \frac{[(1-\varepsilon_1)\varphi]^{3-n_1}}{\varepsilon_1^3}} \tag{10}$$

we can note a dependence of the resistance coefficient on the height of the dense layer and on the geometric dimensions of the installation.

For the case of material motion, relationship (9) remains valid; however, a further change in the resistance coefficient is possible because of a change in the porosity in segments 1 and 2.

The resistance of a moving bed was studied on a plastic model (Fig. 1). The main part of the model is a rectangular tube with dimensions 31.5 × 31.5 mm, with a plate containing a variety of orifices attached to the end of the tube. Air was used as the counterflow agent. The characteristics of the materials used in the tests are given in the table. The resistance of the moving bed was determined for various heights of the bed in the tube (145, 205, and 270 mm) by the following method. For the selected air flow rate the feeder provided for an influx of material such that the bed was kept at the required height in the tube. The resistance of the moving bed, the air flow rate, and the flow rate of the material were measured as soon as a steady-state discharge regime was established.

We determined the resistance of the fixed bed on the same model, with the same orifices at the bottom of the tube; these orifices were covered with a brass grid whose cells had dimensions of 0.2 × 0.2 mm. The sequence of the experiment was the following: the test material was poured into tube 1 of the model to the required height. The bed was brought to a state of fluidization.

Since the porosity of the moving bed was not measured, we assumed that

$$\lambda' = \lambda f(\varepsilon) = \lambda \frac{[(1-\varepsilon_1)\varphi]^{3-n_1}}{\varepsilon_1^3}$$

represented the resistance coefficient for both the moving and the nonmoving beds. For the resistance of the bed we assumed a quantity equal to the difference between the measured magnitude of the resistance in the case of a bed and the resistance of the tube without a bed, given the identical air flow rate.

Typical experimental data in the coordinates $\log \lambda' - \log Re$ are given in Fig. 2a-c. The solid lines have been drawn from the experimental data for a dense layer.

As follows from (9), the relative change in the resistance of the dense layer depends on the geometric dimensions of the installation (D_1 and D_2), on the height h of the dense layer, and on the angle α. However, in the experiments the change in the resistance coefficients for all of the materials and orifice dimensions does not exceed the error of the experiment, which on the average is equal to 5%, thus indicating that it has little effect on the resistance of the segment h_2. From the results of the tests the angle $\alpha = 60°$ and more.

The experimental data on the resistance coefficient for the moving bed are plotted on the same curves (Fig. 2). In practical terms, they coincide with the data for the fixed bed over the entire range of variations in the velocity of the granular material. The slight deviation toward a reduction for limestone d = 1.025 and for the quartzites can be explained by the slight (1-2% for the limestone and 4% for the quartites) change in porosity during motion. Happel [1] suggests a change in porosity within limits of 1%.

Other authors also found that the resistance coefficients for the fixed and moving beds were equal. The Happel [1] experimental data converted for the laminar regime yield agreement for 15-20% of the coefficients of the moving and fixed beds (without consideration of the form factor). With consideration of the form factor the convergence is improved. The equality of the resistance coefficients is confirmed by the Durnov [6] and Chukin [5] data, which have also been converted. The authors of [7] also state that the resistance coefficients are equal.

The geometric dimensions of the orifice have virtually no effect on the resistance coefficient of a moving bed (Fig. 2c), since the h_2 zone is small for the conditions of the test. A change in the roughness of the vessel walls, leading to a change in porosity, has a marked effect on λ' and, in all probability, will not affect the magnitude of the resistance coefficient.

NOTATION

Δp is the resistance of the bed, N/m^2;
d is the average diameter of the granular material, m;
g is the free-fall acceleration, m/sec^2;
γ_g is the specific weight of the gas, N/m^3;
φ is the form factor;
n is the exponent in (1);
w is the gas velocity, m/sec;
u is the material velocity, m/sec;
h is the overall height of the dense layer, m;
h_1 is the height of the dense layer in a tube of identical diameter, m;
h_2 is the height of the dense layer, of variable cross section, m.

Subscripts

1 and 2 respectively, pertain to the quantities determined in segments h_1 and h_2.

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