HYDRODYNAMIC RESISTANCE OF A PSEUDO-FLUIDIZED BED CONTAINING PARTICLES OF MANY DIFFERENT SIZES

A. A. Akhundov and N. B. Kondukov

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The results of an investigation into the hydrodynamic resistance of a pseudo-fluidized bed containing irregularly-shaped particles of many different sizes are presented. An equation is derived for calculating the critical velocity of pseudo-fluidized behavior in highly dispersed mixtures of various building materials.

The resistance offered to a flow of gas by a layer of solid granular material when the latter passes from the stationary to the pseudo-fluidized state depends on the granulometric composition and shape of the particles forming the layer.

There have only been a limited number of hydrodynamic investigations into the behavior of a pseudo-fluidized bed with a wide distribution of particle sizes [1-10].

The calculated hydrodynamic relationships valid for a bed with a single particle size [11-15] cannot strictly be applied to one with a spread of particle sizes, owing to the lack of similarity between hydrodynamic phenomena in layers with one and many particle sizes on passing from simple filtration of the gas to completely fluidized conditions. For hydrodynamic similarity to exist in a layer of many particle sizes, it is essential that there should be similarity between the hydrodynamic conditions governing the motion of gas through the layer, that the ranges of existence of the heterogeneous system should be identical, and that the granulometric composition of the layer should exhibit similarity [4-7]. Following investigations into the physical characteristics of the gradual pseudo-fluidization of a mixture of many particle sizes consisting of spherical particles, a similarity criterion was established in [8] for the granulometric composition of a bed or layer, and the laws governing the changes taking place in the hydrodynamic drag coefficient of a bed of many particle sizes were established as a function of the modified Reynolds criterion.

It is quite clear that, for pseudo-fluidized beds containing irregular particles with a wide range of particle sizes, the drag coefficient will be higher than that corresponding to a bed of spherical particles for any specified value of the Reynolds criterion and any specified porosity. The reason for this lies in the well-known effect of particle shape, which at the present time is only capable of being estimated quantitatively by an experimental approach.

The effect of particle shape was accordingly studied in mixtures of natural and swollen perlites of various densities.

Perlite is the name given to igneous siliciferous rocks consisting of a volcanic water-containing glass, with inclusions of various kinds [16]. On heating the perlite directly in a high-temperature zone (800-1200°C) the particles swell, and a light, porous material is obtained [17, 18].

In order to carry out the experiments, crushed natural perlite with particle sizes from 0.1 to 3 mm and swollen perlite with particle sizes from 1.0 to 10 mm were carefully sieved into the original "narrow" fractions. From the resultant "narrow" fractions, multiple-size mixtures were prepared in prespecified proportions.

Sixty-four mixtures of natural and swollen perlite were brought into the pseudo-fluidized state.

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TABLE 1. Original and Calculated Characteristics of the Mixtures

Number of mixture	Equivalent diameter, mm	Density of material, kg /m³	Critical velocity, m/sec	ξ	Re	Re_{ε}	ξ_{ε}	$\left(\frac{d_{max}}{d_e}\right)^{0,6}$	$\xi_{\varepsilon}\left(\frac{d_{max}}{d_e}\right)^{0,6}$
1	0,125	1900	0,046	700	0,37	0,62	630	1,0	630
2	0,134	1900	0,054	610	0,465	0,77	55	1,22	665
3	0,148	1900	0,064	460	0,605	1,01	415	1,16	470
4	0,179	1900	0,0745	370	0,855	1,38	420	1,0	420
5	0,208	1900	0,082	386	0,96	1,66	309	1,18	380
6	0,224	1900	0,086	396	1,23	2,18	298	1,06	316
7	0,25	1900	0,106	290	1,70	3,0	222	1,0	222
8	0,27	1900	0,137	185	2,36	3,96	167	1,12	187
9	0,294	1900	0,155	162	2,92	5,0	136	1,12	149
10	0,354	1900	0,155	202	3,54	6,4	151	1,0	151
11	0,405	1900	0,234	101	5,98	10,3	30,5	1,37	41,8
12	0,553	1900	0,27	87	8,0	14,0	87,0	1,275	110
13	0,555	1900	0,32	62,5	11,9	18,9	67,0	1,14	76
14	0,69	2100	0,47	42	21,4	33	48	1,53	73,2
15	0,73	2100	0,5	37,4	23,4	35,8	45,5	1,5	68
16	0,78	2100	0,52	37,6	25,7	40,0	45,5	1,48	66
17	0,79	2100	0,56	32,6	28,4	43,6	39,4	1,4	55
18	0,805	2100	0,617	26	31,8	48,0	33,2	1,4	46,5
19	0,86	2100	0,675	24,0	37,2	58,0	27,4	1,30	35,6
20	0,99	2100	0,75	22,4	47,5	74,5	25,5	1,215	31,2
21	0,917	2340	0,664	30,6	37,0	64,4	27,7	1,42	41,5
22	0,693	2100	0,6	28,3	26,5	33,5	45,2	1,6	45,2
23	1,215	2340	0,59	54,8	44,5	75	47,6	1,0	47,6
24	1,16	2100	0,79	23,6	59,0	92	27,0	1,12	30,1
25	0,919	3240	0,92	16,9	57,0	91	17,9	1,405	25,1
26	1,168	2340	0,955	18,9	66,0	103	21,8	1,26	27,4
27	1,542	2340	0,85	32,5	81	132	31,9	1,07	34,2
28	2,231	2340	1,05	30,3	142	229	30,7	1,00	30,7
29	2,466	2340	1,25	24,0	198	310	27,2	1,062	29,0
30	2,116	2340	1,17	15,8	149,0	237	16,8	1,21	20,3
31	1,682	2340	1,19	17,8	120	189	19,4	1,34	26,0
32	1,093	2340	1,13	11,9	74	114	14,45	1,73	25,0
33	1,726	2340	0,855	36,5	92	151	34,4	1,0	34,4
34	1,426	2340	0,92	23,0	87,5	136	26,8	1,12	30
35	1,095	2340	0,77	25	56,3	88	28,3	1,31	37,0
36	1,31	2340	0,77	30,3	67,0	105	34,3	1,17	40,1
37	0,35	1980	0,15	25,0	3,36	6,0	130	1,0	130
38	0,40	1980	0,23	115	5,9	10,9	72	1,4	102
39	0,462	2000	0,34	42,3	10,5	16,7	61,0	1,27	75
40	0,462	1935	0,25	105	7,45	14,0	63,0	1,275	80
41	0,69	1970	0,34	92	14,8	28,4	58	1,0	58
42	1,39	2340	0,848	22,8	75,3	118	25,8	1,0	25,8
43	0,47	2400	0,354	61,0	10,6	13,1	59,5	1,23	63,5
44	0,77	2400	0,57	33,3	30,5	49,0	34,4	1,58	54,5
45	2,231	2400	1,18	25,5	74	296	21,5	1,0	21,5
46	1,11	2440	0,832	25,9	67,5	113,5	22,6	1,26	28,4
47	1,215	830	0,4	45,2	32,3	52	46,3	1,0	46,3
48	2,231	830	0,685	29,3	97,0	161	27,0	1,0	27,0
49	1,726	830	0,615	26	88,2	103	35,4	1,0	35,4
50	2,735	825	0,698	26,2	23	192	30,0	1,0	30,0
51	2,466	830	0,79	22,0	24	200	22,2	1,062	23,5
52	1,682	830	0,73	16,2	81	122,3	21,3	1,34	28,4
53	1,426	830	0,57	26,0	53,6	83,6	30	1,12	33,6
54	1,542	830	0,608	23,9	62,5	97,4	27,5	1,07	29,4
55	3,44	825	1,06	16,0	228	358	17,7	1,0	17,7
56	8,3	870	1,47	19,8	775	1190	23,9	1,0	23,9

TABLE 1. (Continued)

Number of mixture	Equivalent diameter, mm	Density of material, kg/mm	Critical velocity, m/sec	ξ	Re	Re_ε	ξ_ε	$\left(\frac{d_{max}}{d_e}\right)^{0,6}$	$\xi_\varepsilon\left(\frac{d_{max}}{d_e}\right)^{0,6}$
57	6,4	950	1,45	16,8	595	900	22,3	1,17	25,4
58	6,9	760	1,37	21,2	640	1010	19,2	1,12	22,8
59	5,9	675	1,0	34,6	378	670	25,4	1,0	25,4
60	4,6	840	1,23	16,3	354	560	19,7	1,21	23,0
61	3,8	1080	1,17	18,7	292	445	24	1,0	24,0
62	5,2	830	1,26	16,7	420	670	17,8	1,08	19,9
63	4,2	930	1,25	15,7	336	525	17,8	1,21	21,6
64	4,4	910	1,31	15,4	370	565	18,5	1,47	27,2

The equivalent diameter of the particles in the mixtures was calculated from the equation

$$d_e = 1 \Big/ \sum_{i=1}^{i=m} \frac{g_i}{d_i}, \qquad (1)$$

where g_i is the gravimetric proportion of the class; $d_i = \sqrt[3]{2d_1^2 d_2^2/(d_1 + d_2)}$ is the nominal diameter of the particles in the fraction, determined from the aperture sizes of the passing and nonpassing meshes (d_1 and d_2, respectively).

The experiments were carried out in specially constructed model installations, in which the diameters of the devices for creating the pseudo-fluidized bed were 100 and 200 mm.

In carrying out the experiments and analyzing the results, we were guided by the initial requirements applicable to the hydrodynamic resistance (drag) of multiple-size beds containing spherical particles [4-8].

The results of the experiments relating to the critical pseudo-fluidized state (see Table 1) were analyzed in the form of a relation between the product of the equivalent hydrodynamic drag coefficient times the similarity criterion of the granulometric composition of the bed and the modified Reynolds criterion (Fig. 1, curve 3). This curve indicates a tendency for the equivalent drag coefficient to vary in accordance with the ordinary laws applicable to a granular bed, which may be expressed in general form in the following manner:

$$\xi \frac{\varepsilon^2}{1-\varepsilon}\left(\frac{d_{max}}{d_e}\right)^{0,6} = \frac{A}{Re_\varepsilon^n}. \qquad (2)$$

The values of A and n were determined by approximating the experimental results in the form of three separate sections or ranges, each with a constant n, using the method of least squares.

The analysis yielded the following values of A and n:

Section I for $0{,}5 < Re_\varepsilon < 20 \quad A = 500, \quad n = 0.68,$

Section II for $20 < Re_\varepsilon < 80 \quad A = 480, \quad n = 0.58,$

Section III for $80 < Re_\varepsilon < 1200 \quad A = 57, \quad n = 0.14.$

Allowing for the physical characteristics of the gradual approach of a mixture of many particle sizes to the pseudo-fluidized state, it was earlier proposed [4-7] that the critical velocity of pseudo-fluidization should be calculated by equating the resistances (drag factors) at the end of the transient mode and the beginning of the pseudo-fluidized mode, which are respectively described by the following equations:

$$\Delta P = \xi \frac{H}{d_e} \rho \frac{w^2}{2}, \qquad (3)$$

$$\Delta P_{cr} = Hg(\rho_s - \rho_g)(1-\varepsilon). \qquad (4)$$

For the critical state of pseudo-fluidization we obtain the following relationship after solving Eqs. (3) and (4) simultaneously and taking account of Eq. (2):

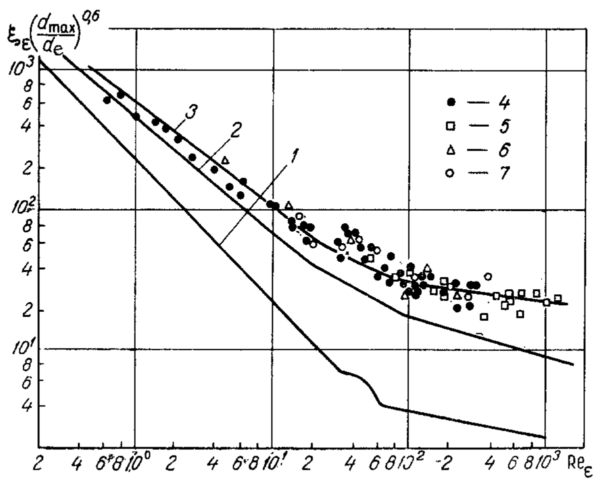

Fig. 1. Relation between the product of the equivalent hydrodynamic drag coefficient and the similarity criterion of the granulometric composition ($\xi_{\varepsilon,d}$), on the one hand, and the modified Reynolds criterion (Re_ε) on the other: 1) layer with a single particle size; 2) multiple-size layer containing spherical particles; 3) the same containing irregular particles; 4) natural perlite; 5) swollen perlite; 6) clay; 7) limestone.

$$\mathrm{Re} = \left[C\,\mathrm{Ar} \left(\frac{d_{max}}{d_e} \right)^{0,6} \right]^m. \tag{5}$$

Using the specific values of A and n, we obtain the following values for C and m in Eq. (5):

Section I for $0.5 < \mathrm{Re}_\varepsilon < 20$ $C = 0.002$, $m = 0{,}76$,
Section II for $20 < \mathrm{Re}_\varepsilon < 80$ $C = 0{,}0021$, $m = 0{,}7$,
Section III for $80 < \mathrm{Re}_\varepsilon < 1200$ $C = 0{,}014$, $m = 0.54$.

The mean deviation of the experimental data from the calculated values based on Eq. (5) is no greater than ±15%.

The results of analogous experiments carried out with crushed clay materials, keramzite (clay filler), and siliciferous rocks are also shown in Fig. 1 in relation to curve 3. Analysis shows that the relationship established is also valid for these materials.

Equation (5) with specific values of C and m may therefore be recommended for calculating the critical velocity of pseudo-fluidization in mixtures containing irregular particles of many sizes, consisting of clay, volcanic, and siliciferous rocks, over the corresponding ranges of Re_ε.

We see from an analysis of curves 2 and 3 in Fig. 1 that for spherical particles the $\xi_{\varepsilon,d} = f(Re_\varepsilon)$ relationship does not vary in the same way as the corresponding relationship for irregular particle shapes. Hence the hydrodynamic form factor of multiple-size mixtures consisting of irregularly shaped particles cannot be determined by any universal method, simply by comparing with a standard curve based on one experimental value of the drag coefficient for an arbitrary value [19] of the Reynolds criterion. The form factor is dependent upon the value of the Reynolds criterion.

Figure 2 shows the dependence of the hydrodynamic form factor of the particles on the modified Reynolds criterion for perlite.

The hydrodynamic form factor of the particles is calculated by dividing the equivalent hydrodynamic drag coefficients relating to multiple-size beds, comprising particles of irregular shape (curve 3, Fig. 1), by those relating to spherical particles (curve 2, Fig. 1) for the same value of the modified Reynolds criterion.

We see from Figs. 1 and 2 that, with increasing Reynolds criterion, the form factor also increases, while with diminishing Reynolds criterion the difference between the drag coefficient relating to beds with regular and irregular particle shapes degenerates. This is already obvious from the experiments of Leva [11] but has never been pointed out in the literature.

On analyzing the results of Fig. 2 by the method of least squares for the materials in question, we obtain the following relationship between the particle form factor and the Reynolds criterion:

$$\varphi = 1.14\,\mathrm{Re}_\varepsilon^{0.06}. \tag{6}$$

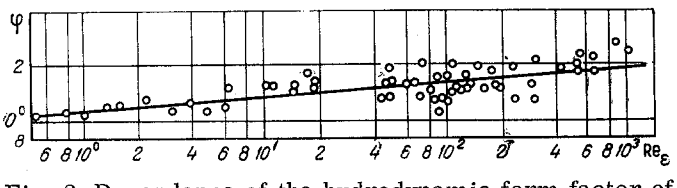

Fig. 2. Dependence of the hydrodynamic form factor of the particles (φ) on the modified Reynolds criterion (Re_ε).

Figure 1 also shows the relation between the drag coefficient and the Reynolds criterion (curve 1) obtained for beds containing spherical particles of a single size stacked in a regular manner [19]. The form factor may naturally also be obtained by comparing curves 1 and 3.

NOTATION

$Re = wd_e/\nu$	is the Reynolds criterion;
w	is the gas velocity, m/sec;
d_e	is the equivalent particle size, m;
ν	is the kinematic viscosity of the gases, m^2/sec;
$Ar = (gd_e^3/\nu^2)$	
$(\rho_s - \rho_g)/\rho_g$	is the Archimedes criterion;
ρ_s, ρ_g	are the density of solid particles and gas, respectively, kg/m^3;
g	is the free-fall acceleration, m/sec^2;
ξ	is the hydrodynamic drag coefficient;
ε	is the porosity of bed;
d_{max}	is the maximum particle diameter, m;
ΔP	is the pressure drop of the gases in the layer, N/m^2;
H	is the height of the layer, m;
$\xi(\varepsilon^2/(1-\varepsilon))$	is the equivalent hydrodynamic drag coefficient;
$Re_\varepsilon = Re/\varepsilon$	is the modified Reynolds criterion;
$(d_{max}/d_e)^{0.6}$	is the similarity criterion of granulometric composition;
ΔP_{cr}	is the pressure drop of the gases in the layer in the critical state, N/m^2;
φ	is the hydrodynamic particle form factor,

$$\xi \frac{\varepsilon^2}{1-\varepsilon}\left(\frac{d_{max}}{d_e}\right)^{0.6} = \xi_\varepsilon\left(\frac{d_{max}}{d_e}\right)^{0.6} = \xi_{\varepsilon, d}.$$

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