EXPANSION OF A MOVING UNIFORM FLUIDIZED BED OF MONODISPERSE PARTICLES

M. HRDINA[a] and L. NEUŽIL[b]

[a] *Institute of Mineral Raw Materials, 284 03 Kutná Hora,*
[b] *Chemical Engineering Department,*
Institute of Chemical Technology, 166 28 Prague 6

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The description is given of a moving, uniform fluidized bed of monodisperse materials. The available relations for calculation of parameters of a fluidized bed are discussed and verified by original experimental data measured in the system sand-water in a column of 5 cm diameter and of maximum length 100 cm. It has been proved that expansion of the moving fluidized bed, both at the co- and counter-current motion of particles and water, can be calculated on basis of the known expansion of the non-moving fluidized bed and the correct definition of relative velocity of fluid to that of particles.

This study is a contribution to the solution of a wider research program aiming at the continuous classification of solid particles in a vertical column.

Classification of granular materials has been until recently performed by use of sieves, especially there where certain standardized granulometric product composition was required. Such classification stations[1,2] are very unreliable (damaged sieves), inefficient, they have low capacity and are thus ecconomically disadvantageous (because of large constructional area). Intensification of production of classified materials especially of glass and foundry sands resulted in considerations of more efficient and ecconomical methods which would guarantee granulometric composition of standardized products. Classifiers of granular materials based on the principle of classification in a fluidized bed are more advantageous due to relatively simple device used which has a large capacity at a small constructional area.

In this study available published information on the moving fluidized bed is critically evaluated and they are verified experimentally.

In Czechoslovakia, classification of granular material by use of the fluidized bed technique has been studied by Told[3] and Šimon[1,2,4,5]. Their studies are of experimental nature oriented to industrial application[4,5]. According to the patent by Šimon[6] a classification unit is produced where water as the continuous phase is employed. In Czechoslovakia there are also patented[3] some other classifiers[7-12] where both water and air are employed. By foreign literature a number of classifying units has been designed operated again both with air[13-16] and water[17]. Though the classification of granular materials by separation in a fluidized bed is industrially applied, the theory of this operation has not yet been fully comprehended[18-20]. There are not available suitable quantitative relations which would enable a satisfactory design of these classifiers as well as their simple and reliable operation. On the basis of our experience, the analysis of continuous fluidized classification must be based on the description of the moving fluidized bed. But the problem has not yet been satisfactorily solved.

Expansion of a Uniform Fluidized Monodisperse Bed

Let us consider the vertical direction of motion of particles and liquid. Positive direction is opposite to the direction of gravitational acceleration. As it concerns the one-dimensional resulting motion of fluid and particles, scalar quantities suffice. The cross-sectional area of the unit has the sign identical with the sign of the mean velocity of the fluid or solid particles.

Expansion of a moving fluidized bed belongs to basic fluidization information. Relatively well has been studied expansion of a stagnant fluidized bed. In literature[19-35] a great number of relations can be found for expansion of a stagnant fluidized bed, mostly in the form of relation

$$f(\mathrm{Re}, \mathrm{Ar}, \varepsilon) = 0\,. \qquad (1)$$

The form of relation (1) can be thus simply experimentally determined for each individual problem of a stagnant fluidized bed. But experimental determination of a similar dependence for a moving fluidized bed is much more complex. This problem can be solved by introducing a suitably defined relative velocity of fluid with respect to particles which would mean that the known or easily available relation for the stagnant fluidized bed could be used for the moving bed. By use of this relative superficial velocity denoted as w the Reynolds number is defined

$$\mathrm{Re} \equiv w\, d_e/\nu\,. \qquad (2)$$

Equation (1) should suit, in case the relative superficial velocity is correctly defined, both moving as well as the stagnant fluidized beds. In this study we have paid attention mainly to verification of a suitable definition of the relative superficial velocity.

In literature, two relations have been found defining the relative superficial velocity which are recommended for the moving uniform fluidized bed of monodisperse particles or for the hindered sedimentation. From papers by Lapidus and Elgine[36], Kwauk[37], Gasparjan and Zaminjan[38] concerning fluidization and from the study by Kolář[28] on sedimentation of solid particles the relation has been obtained

$$w = w_f - u_c \varepsilon/(1 - \varepsilon)\,. \qquad (3)$$

In the books by Beránek and Sokol[33] and Zábrodský[19] is the relative superficial velocity w defined by equation

$$w = w_f - u_c/(1 - \varepsilon)\,. \qquad (4)$$

In favour of Eq. (3) it speeks that in studies of authors[28,36-38], different approach has been applied in the derivations giving the same result. On the contrary, Eq. (4) has been given in studies[19,39] without any profound reasons.

As Kwauk[39] has observed, Eq. (3) can be used for the moving fluidized bed only when motion of solid particles and of the fluid is with no acceleration. This means that Eq. (3) is suitable only for a moving fluidized bed whose porosity is independent both of the height of the fluidized bed along the column and of the time and is determined exclusively by physical characteristics of particles and of the fluid.

Since the only available experimental data of authors[40] are not sufficient, we considered it important to decide which of the two above given equations is in better agreement with the experiments. Therefore here an attempt has been made to verify experimentally both approaches to solution of expansion of a moving fluidized bed.

In order to have an idea on difference in description of a moving fluidized bed of monodisperse particles by Eqs (*3*) and (*4*), quantity E has been defined and the relation

$$E \equiv \varepsilon_{M(\beta)}/\varepsilon_{M(\alpha)} = E(\varepsilon_{M(\alpha)};\, u_c), \quad [\mathrm{Ar} = \mathrm{const}]\,, \tag{5}$$

has been considered, where $\varepsilon_{M(\beta)}$ or $\varepsilon_{M(\alpha)}$ are porosities of a moving fluidized bed calculated from Eqs (*4*) or (*3*).

An example of the dependence (*5*) is given in Fig. 1 for fluidization of a narrow fraction of sand by water (Ar = 4300). From Fig. 1 it is obvious that the following values can be reached: $E > 1$ for countercurrent arrangement of the moving fluidized bed, $E < 1$ for co-current arrangement of the moving fluidized bed and $E \to 1$ for the fluidized bed with the value $\varepsilon \to 1$ or for $u_c \to 0$.

From the plot of dependence (*5*) in Fig. 1 it is obvious that the quantity E differs most from one for high loads by granular material in the column and simultaneously for low porosity of the moving fluidized bed. Unlike for high porosities and small loads the difference in results obtained according to both Eqs (*3*) and (*4*) is very small.

EXPERIMENTAL

Apparatus. For experimental verification of Eqs (*3*) and (*4*), the vertical fluidization column of 5 cm in diameter was used and of maximum length 100 cm with a number of pressure taps situated along its height connected with manometers measuring the pressure differences along the column. From these values the porosity of the fluidized bed has been determined.

Fludization has been performed with water at a constant temperature 23°C, which is supplied from a storage tank by a centriffugal pump through the flow meter and supporting grid into the column and from there into the sedimentation vessel and back into the storage tank. Granular material was supplied through a slit with a damper or by a screw conveyor into the column. The

TABLE I

Characteristic Properties of Sand Fractions

Fraction	ϱ_s g/cm^3	d_e cm	d_m cm	w_0 cm/s	Ψ	Re_0	Ar	w_0/d_e s^{-1}
F1	2·594	0·0350	0·0417	4·64	0·84	17·3	763	132·57
F2	2·620	0·0391	0·0476	5·11	0·83	21·3	1 081	130·69
F3	2·624	0·0520	0·0611	7·21	0·87	39·9	2 549	138·65
F4	2·624	0·0619	0·0724	8·60	0·92	56·7	4 300	138·93
F5	2·616	0·0753	0·0876	10·73	0·86	86·0	7 702	142·50
F6	2·629	0·0990	0·1174	13·62	0·87	143·5	17 645	137·58
F7	2·625	0·1203	0·1404	15·70	0·78	210·0	31 583	130·51
F8	2·620	0·1678	0·2308	18·08	—	323·0	85 442	107·74

particles are leaving the column either through the upper overflow weir into the sedimentation vessel or through the bottom slit which has its lower edge in the plane of the supporting grid. The quantity of granular material leaving from the column through the bottom slit can be controlled by the damper.

Granular materials. As monodisperse materials have been used size fractions prepared from the natural quartz sand from which were at first prepared on a continuous sieve device wider particle sizes which were further manually sieved in a wett process into narrower fractions. These fractions were classified by fluidization on a laboratory countercurrent water classifier so that from each sample prepared by sieving were separated particles with a higher and lower terminal velocity than had the main mass of particles in the given fraction of sand. In this way eight samples of size fractions were prepared. After drying a sample having the mass about 350 to 500 g was prepared by quartation from each fraction. These samples were used for experimental measurements of the needed characteristics of individual narrow sand fraction. Individual fractions were denoted as samples F 1 to F 8. Following physical properties of particles in each of the prepared fractions were determined: particle density ϱ_s by pycnometer method, equivalent particle dieameter d_e by taking the mass of the sample, particle diameter d_m by microscopic measurements, terminal velocity of particles in water w_0 by direct measurement, density spectrum of particles by separation in dense liquids, sphericity of particles by calculation from the equivalent particle diameter and their specific surface area, granulometric composition by a sieve analysis of individual fractions, expansion relation for the stagnant fluidized bed using water. Results of individual measurements are given in Table I to III. It can be seen from the values given in these Tables that individual sand fractions are really narrow fractions both from the point of view of particle sizes and densities.

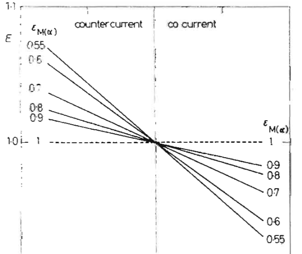

FIG. 1

Dependence of Quality E on Load of Column by Granular Material u_c for Different Porosities $\varepsilon_{M(\alpha)}$ and for Ar = 4 300

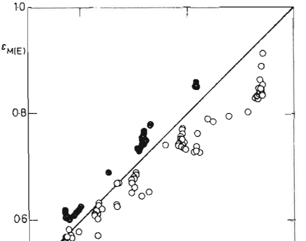

FIG. 2

Dependence of $\varepsilon_{M(E)}$ on $\varepsilon_{N(C)}$ for Sand Fractions

○ Co-current arrangement of moving fluidized bed, ● countercurrent arrangement of moving fluidized bed.

In the experiements in which expansion dependences of the stagnant fluidized bed were determined *i.e.* the concrete form of relation (*1*), porosity of the fluidized bed varied from the porosity at incipient fluidization up to the value 0·94. The results are in a good agreement with the data published in literature[25].

For calculation of the Re_0 and Ar numbers the equivalent particle diameter d_e was used which equals to the diameter of a sphere having the same volume as the particle. The mean particle diameter d_m determined microscopically is in all cases larger than the diameter d_e which is caused by deviations of the shape of particles from that of spheres and by the method of measurement.

The measurements in the moving fluidized bed were made separately for the co- and counter-current arrangement. In the co-current arrangement a denser moving bed has been established above the thinner stagnant fluidized bed. In the counter-current arrangement the surface of the moving fluidized bed was about in the height of the feed hole.

TABLE II

Spectrum of Particle Densities in Sand Fractions

Range of densities	Composition in mass fractions . 10^4							
	F1	F2	F3	F4	F5	F6	F7	F8
Over 2·91	8	2	2	1	2	2	9	7
2·91—2·80	—	—	1	—	2	1	—	2
2·80—2·70	2	1	1	4	5	2	48	52
2·70—2·58	9 195	9 002	9 088	9 271	9 354	9 445	9 322	9 536
2·58—2·52	409	580	800	596	550	470	531	327
Under 2.52	386	415	108	128	87	80	90	76

TABLE III

Sieve Analysis of Sand Fractions

Aperture mm	Mass fraction of particles remaining on the sieve							
	F1	F2	F3	F4	F5	F6	F7	F8
2·0	—	—	—	—	—	—	—	—
1·6	—	—	—	—	—	—	—	0·321
1·25	—	—	—	—	—	—	0·062	0·068
1·0	—	—	—	—	—	0·061	0·780	0·011
0·8	—	—	—	—	0·002	0·794	0·158	—
0·63	—	—	—	0·032	0·960	0·145	—	—
0·5	—	—	0·133	0·939	0·038	—	—	—
0·4	—	0·013	0·846	0·029	—	—	—	—
0·315	0·716	0·984	0·021	—	—	—	—	—
0·2	0·282	0·003	—	—	—	—	—	—
0·1	0·002	—	—	—	—	—	—	—
0·06	—	—	—	—	—	—	—	—

For the counter-current, moving fluidized bed it was necessary to use the grid situated closely below the inlet of granular material into the fluidized bed. At porosities larger than 0·6 it was not possible to obtain without this grid a uniform distribution of sand particles on the cross-sectional area of the column.

In total 145 experiments were made with the narrow sand fractions. Out of this number 111 experiments were made in the co-current arrangement of the moving fluidized bed and 34 experiments with the counter-current moving fluidized bed.

In the experiments with the co-current arrangement of the moving fluidized bed the loads of the column by granular material had mostly varied in the range $u_c \in \langle 0{\cdot}005; 0{\cdot}31 \rangle$ cm/s. These loads u_c were obtained with the feed slit; the experiments were performed at lower values of u_c and at lower porosities of the fluidized bed ε. But for verification of relations (*3*) and (*4*) it is necessary to operate at low porosities and larger loads of granular material (Fig. 1). To reach this state the feed slit was substituted by the screw feeder. By this arrangement values of u_c up to 0·51 cm/s weie obtained.

In counter-current arrangement of the moving fluidized bed the range of loads was in the range $u_c \in \langle -0{\cdot}07; -0{\cdot}27 \rangle$ cm/s. These experiments were performed only with the feed slit.

RESULTS AND DISCUSSION

In Fig. 2 the experimental porosities $\varepsilon_{M(E)}$ are plotted in dependence on porosities of the moving fluidized bed $\varepsilon_{N(C)}$ calculated for the given superficial water velocity in the column from a concrete form of Eq. (*1*) which was for each material determined by measuring the expansion of the stagnant fluidized bed. Empty points correspond to values of co-current flow and full points to the counter-current flow of particles

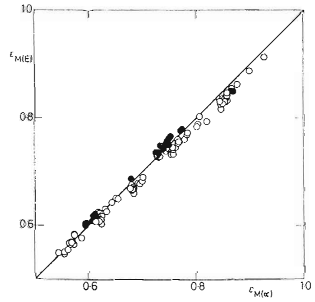

FIG. 3

Dependence of $\varepsilon_{M(E)}$ on $\varepsilon_{M(\alpha)}$ for Sand Fractions

Points are denoted as those in Fig. 2.

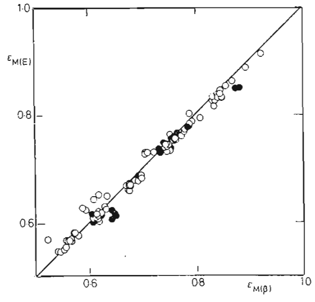

FIG. 4

Dependence of $\varepsilon_{M(E)}$ on $\varepsilon_{M(\beta)}$ for Sand Fractions

Points are denoted as those in Fig. 2.

and water. There is obvious a significant dispersion of points from the dependence $\varepsilon_{M(E)} = \varepsilon_{N(C)}$ represented by a straight line. This dispersion is greater with increasing loads of the column by granular material from zero.

In Fig. 3 there are compared experimental porosities $\varepsilon_{M(E)}$ with $\varepsilon_{M(\alpha)}$ calculated for individual sand fractions by solving simultaneously Eq. (*3*) and the concrete form of Eq. (*1*). The points represent the same conditions as in the last figure. Deviations according to the load of the column by the granular material have disappeared.

In Fig. 4 there are given results of comparison of experimental porosities of a moving fluidized bed $\varepsilon_{M(E)}$ of individual sand fractions with porosities $\varepsilon_{M(\beta)}$ calculated by simultaneous solution of Eq. (*4*) and the concrete form of Eq. (*1*). In Fig. 5 in comparison with Fig. 4 considerable deviations are visible of points from the diagonal which represents agreement of the calculated and experimental values. This disagreement corresponds to low porosities accompanied by large loads of granular material as expected.

From comparison of the experimental and calculated results as given in Figs 3 and 4 it can be concluded that for larger porosities and especially for lower absolute loads of the fluidized column by granular material (most of the experiments were performed with the slit feeder) both Eqs (*3*) as well as (*4*) can be practically used. For lower porosities and for greater absolute loads of the fluidized column by granular material Eq. (*3*) is in better agreement with the experiments.

In all the experiments with the moving fluidized bed and used sand fractions the deviation of experimental porosities from those calculated was at the maximum 3% for Eq. (*3*) and 9% for Eq. (*4*).

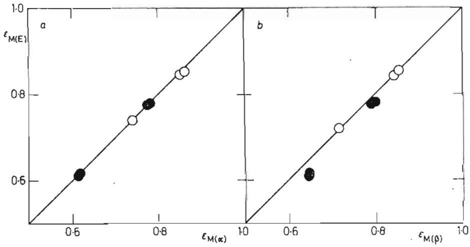

FIG. 5

Dependence of $\varepsilon_{M(E)}$ on $\varepsilon_{M(\alpha)}$ (*a*) and $\varepsilon_{M(E)}$ on $\varepsilon_{M(\beta)}$ (*b*) for Sand Fractions with Correction of the Calculated Porosity of Moving Fluidized Bed to Change in d_e in Holdup of the Moving Fluidized Bed in Respect to the Material Fed

Points are denoted as those in Fig. 2.

The results obtained with the screw feeder have not made possible due to the dispersion of experimental points to find an actual difference between the Eqs (*3*) and (*4*). Thus possibilities how to decrease this dispersion have been looked for. We have made an assumption according to which the granulometric composition of the sand fractions used has the largest effect. These narrow fractions were not of course exactly monodisperse. Thus it was possible to expect that in the holdup of the moving fluidized bed a change of the mean equivalent diameter of the particle system as compared to the material fed would take place because of classification. This means that in the hold up larger or smaller particles would accumulate according to the type of arrangement of the moving fluidized bed. Thus at co-current flow an increase of the equivalent particle diameter can be expected as compared to the material fed. On the contrary at counter-current flow a decrease of the equivalent diameter of particles in the holdup could be expected. The change in the equivalent diameter of particles will result in the change of their terminal velocity. For calculation of these values data on w_0/d_e given in Table I were used. Information on changes of the equivalent diameter d_e were obtained in some experiments with the slit feeder with the use of a special sampling probe.

In Fig. 5 there are given results of evaluation of experiments with the moving fluidized bed of those sand fractions for which the correction of the calculated porosities $\varepsilon_{M(\alpha)}$ or $\varepsilon_{M(\beta)}$ was taken into account on the change of the equivalent particle diameter d_e in the fluidized bed. It can be seen from this figure that the values of the quantity $\varepsilon_{M(\alpha)}$ are in better agreement with the experimental porosities $\varepsilon_{M(E)}$ than the values $\varepsilon_{M(\beta)}$. The experimental and calculated porosities in Fig. 5 correspond to the experiments with larger mass flow rates of granular material through the column.

It may be concluded that on basis of the experimental results presented in this paper for calculation of expansion of the uniform moving fluidized bed of monodisperse material Eq. (*3*) can be recommended under the assumption that the expansion dependence (*1*) of the stagnant fluidized bed is known. In industrial units values of u_c up to 0·4 cm/s or values even greater for lower porosities can be expected, when deviations of Eq. (*4*) from reality are already unacceptable.

LIST OF SYMBOLS

Ar $\equiv g\, d_e(\varrho_s - \varrho_f)/\nu^2\varrho_f$ Archimedes number
d_e equivalent particle diameter determined on basis of its mass
d_m characteristic particle diameter determined by microscopic measurement
E ratio defined by Eq. (*5*)
g gravitational acceleration
Re Reynolds number defined by Eq. (*2*)
$\mathrm{Re}_0 \equiv w_0 d_e/\nu$ Reynolds number for free fall of the particle
$u_c \equiv \dot{V}_s/S$ load of column by granular material defined as the velocity of a compact bed of particles ($\varepsilon = 0$)
$\dot{V}$ volumetric flow rate

w mean relative superficial velocity of fluid in respect to particles in a uniform moving fluidized bed
w_f mean superficial velocity of fluid
w_0 terminal particle velocity in unlimited space
ε porosity
ϱ density
ν kinematic viscosity
Ψ sphericity

Subscripts

C calculated
E experimental value
f fluid
M moving fluidized bed
N non-moving fluidized bed
s solid phase
α value calculated according to Eq. (*3*)
β value calculated according to Eq. (*4*)

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