PARTICLES SEGREGATION IN FLUIDIZED BED BINARY SYSTEMS

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Received March 28th, 1985

Binary systems have been divided into six groups according to their minimum fluidization velocities, densities, and size of particles. A concentration profile of fluidized bed has been studied. Experimental results have indicated that interval (45–90 sec.) is necessary for concentration profile generation. The profile appears to be uninfluenced by original arrangement of system components, the composition of bulk and grid region being in mutual equilibrium. Superficial velocity strongly affects system equilibrium, especially at higher jetsam concentrations. The best segregation of the system was achieved at velocities close to the minimum fluidization velocity of the binary system. The binary systems of the 3rd and 6th types change from segregated to mixed fluidized bed if gas velocity increases. The binary system of the 1st type was difficult to mix up since flotsam entrained partially if velocity of air was increased. The equilibrium concentration profile was uninfluenced by the size of the equipment — provided fluidized bed height was above a critical limit.

The segregation of particles in fluidized bed is a technological operation that modifies classification methods according to differences in sizes and specific gravities of particles. This method is a dynamic phenomenon, what means, that the segregation of the fluidized bed starts after a time interval only. The segregation of fluidized bed may be therefore defined as several layers of particles that are arranged in different levels above the distributor. Sometimes, to simplify reality – polydisperse systems are supposed to be either ideal mixed beds (*e.g.* fluidized bed transport, combustion, heat transport, reactors) or completely segregated layers (*e.g.* fluidized bed classification). It is obvious that both examples are extreme limits (Fig. 1*a*,*b* for binary systems). A real case is found usually somewhere between these two limits, where particle segregation and mixing are in equilibrium which depends on the initial batch composition and gas flow (Fig. 1*c*).

Minimum fluidization velocity is an important characteristic of a monodisperse fluidized bed. For binary system three distinctive points, and to these points corresponding velocities, may be observed in a standart Δp *vs* u chart. The highest velocity is indicated usually as the total fluidization velocity (u_{tf}) and it is defined as a velocity at which fluidized pressure drop startes if gas velocity is gradually decreased. If velocity of air is further reduced, the bed begins to be immobile at a point called the incipient fluidization velocity (u_{if}). For smaller air velocities, the pressure drop of the bed is approximately proportional to the gas velocity. The intersection of the straight lines lying beyond the experimental curve determines a hypothetical minimum fluidization velocity of binary system (u_{om}) (Fig. 2).

Almost all published papers deal with the segregation of binary system or systems considered to be binary (*e.g.* two narrow size fractions of the same material). Six fundamental types[1,2] of binary systems have been reported (see Table I) if the size of particles, their specific gravity and minimum fluidization velocities were taken into consideration. In accordance to the experimental results the fluidized bed of the binary system (after an interval necessary for equilibrium reaching) may be divided in two regions:

a) the grid region of the fluidized bed, where a component – called jetsam – tends to segregate;

b) the upper region of the fluidized bed – called bulk, where concentration of jetsam is constant, or at least, almost constant. The second component – flotsam – accumulates in this region. Jetsam is always defined[3] for given type of binary system in Table I.

Mixing and segregation of the fluidized bed are phenomena that take place simultaneusly. An equilibrium concentration profile originates after a time interval then composition of the bed changes in vertical direction and it is constant in horizontal level. Presence of bubbles in the bed is a necessary condition for both processes[2,4,5]. Rowe and coworkers[6] confirmed that every rising bubble drags solids behind it –

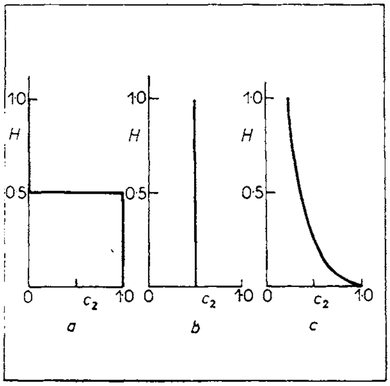

FIG. 1

Concentration profile in binary system, *a*) ideally segregated, *b*) ideally mixed, c) real conditions

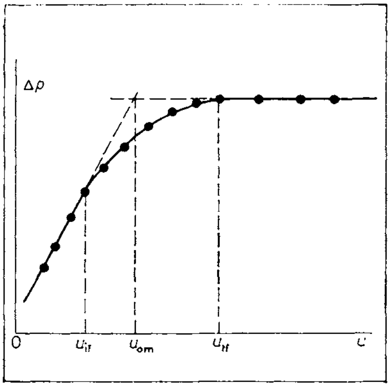

FIG. 2

Minimum fluidization velocities determination forming so called wake. Ratio of the wake to bubble volumes is reported to range from 0·25 to 0·35 in literature. The wake size shows substantial fluctuations but it does not change systematically along the height of the bed.

Nienow and Naimer[7] studied segregation in continual arrangement. They found residence time to be, at least, double of time necessary for equilibrium creation in batch arrangement. Authors did not find influence of the residence time and height of the bed upon segregation. Results of the continuous segregating bed experiments are given in papers[8-10]. Experimental equipment was horizontal fluidized trough inclined 0·9° to horizon. Jetsam flew to the bottom end and flotsam was carried to the upper end of the equipment by blades submerged into the bed. Segregation degree of the binary system is expressed frequently as a mixing index[3,7]

$$M = \frac{X}{\bar{C}_2} . \qquad (1)$$

The index is equal to one – if system is mixed ideally – and equal to zero – if mixture of particles is totaly segregated.

Rowe and coworkers[11] supposed M to be proportional to relation $(\varrho_{SB}/\varrho_{SS})^{2\cdot5}$. $(d_{pB}/d_{pS})^{1/5}$. The subscript B means the bigger and S the smaller particles. Nevertheless mixing or segregation of the fluidized bed is more affected by the difference in specific gravity of solids than in particle size.

Nienow and coworkers[2] suggested relation (2) for mixing index calculation if average jetsame volume concentration is up to 50%:

TABLE I

Binary system types from segregation point of view

Binary system type	Component A			Component B			Jetsam
1	$\varrho_{SA} > \varrho_{SB}$	$d_{pA} > d_{pB}$	$u_{oA} > u_{oB}$	$\varrho_{SB} < \varrho_{SA}$	$d_{pB} < d_{pA}$	$u_{oB} < u_{oA}$	A
2	$\varrho_{SA} > \varrho_{SB}$	$d_{pA} < d_{pB}$	$u_{oA} > u_{oB}$	$\varrho_{SB} < \varrho_{SA}$	$d_{pB} > d_{pA}$	$u_{oB} < u_{oA}$	A
3	$\varrho_{SA} > \varrho_{SB}$	$d_{pA} < d_{pB}$	$u_{oA} < u_{oB}$	$\varrho_{SB} < \varrho_{SA}$	$d_{pB} > d_{pA}$	$u_{oB} > u_{oA}$	A, B[a]
4	$\varrho_{SA} > \varrho_{SB}$	$d_{pA} < d_{pB}$	$u_{oA} = u_{oB}$	$\varrho_{SB} < \varrho_{SA}$	$d_{pB} > d_{pA}$	$u_{oB} = u_{oA}$	A, B[a]
5	$\varrho_{SA} > \varrho_{SB}$	$d_{pA} = d_{pB}$	$u_{oA} > u_{oB}$	$\varrho_{SB} < \varrho_{SA}$	$d_{pB} = d_{pA}$	$u_{oB} < u_{oA}$	A
6	$\varrho_{SA} = \varrho_{SB}$	$d_{pA} > d_{pB}$	$u_{oA} > u_{oB}$	$\varrho_{SB} = \varrho_{SA}$	$d_{pB} < d_{pA}$	$u_{oB} < u_{oA}$	A

[a] 1) If order $[d_{pB}/d_{pA}] = 1$, A is jetsam. 2) For $d_{pB} \gg d_{pA}$ and C_A close to one B is jetsam for $\varrho_{SB} > \varrho_{FA}$, A is jetsam for $\varrho_{SB} < \varrho_{FA}$. 3) If $d_{pB} \gg d_{pA}$ and C_B close to one both A and B can be jetsam. In case that $d_{pA}/d_{pB} < 0{\cdot}35$ and $C_A < 0{\cdot}15$ A can be flotsam. If gas velocity and C_A are increased – a tendency to change A to jetsam appears.

$$M = \left\{1 + \exp\left[-\left(\frac{u - u_\mathrm{M}}{u - u_\mathrm{min}}\right)\exp\left(u/u_\mathrm{M}\right)\right]\right\}^{-1}. \tag{2}$$

In the same paper authors also supposed a relation for u_M calculation under condition that $\bar{C}_2 < 0{\cdot}5$, $d_\mathrm{pS}/d_\mathrm{pB} < 3$ and ϱ_S of the used materials are different.

Gibilaro and Rowe[12] derived a mathematical model that took into consideration the influence of following phenomena upon the bed concentration profile:

a) particles recirculation in the fluidized bed – particles are dragged up in a wake; particles are interchanged between wake and emulsion phase and particles descent back to the bottom finaly. In accordance with experiments a constant recirculation volume flow of solids is supposed. Only jetsam presence in wake is presumed.

b) interphase particle transfer including interchange of solids between wake and emulsion phase under presumption that transfer velocity is not dependent on vertical co-ordinate;

c) very little effect of axial mixing;

d) sedimentation.

Cheung and coworkers[13] proposed an empirical relation that made possible the calculation of u_om if the same material of different particle sizes was used

$$\frac{u_\mathrm{om}}{u_\mathrm{o1}} = \left(\frac{u_\mathrm{o2}}{u_\mathrm{o1}}\right)^{c_2^2} \quad \text{for} \quad \frac{d_\mathrm{p1}}{d_\mathrm{p2}} > 0{\cdot}3\,. \tag{3}$$

Kondukov and Sosna[14], Gelperin[15], Chen and Keairns[16], and Chen[17] proposed an analogy between segregation in fluidized bed and solid–liquid phase equilibrium. Three areas may be seen in "phase" diagram – a fixed bed for $u < u_\mathrm{if}$, segregated bed containing two phases if $u_\mathrm{if} < u < u_\mathrm{tf}$ and totaly mixed bed if $u > u_\mathrm{tf}$. Chen and Keairns[16] verified that segregation of binary system began if $u_\mathrm{o2}/u_\mathrm{o1} > 2$, for particles of the same material and different size. They found that u_if was unaffected, while u_tf was affected significantly by pressure. Increasing bed temperature increases bed viscosity, decreases u_tf and it results consequently in better mixing and worse segregation of the bed.

Yang and Keairns[18] found experimentally phase equilibrium (u–c_2) by analysis of particles in bulk and grid regions. Authors reported a considerable tendency to segregation for the fluidized bed (1st type in Table I) even if bed was in state of total fluidization $u = u_\mathrm{tf}$. From segregation point of view, therefore, u_tf is not important. On the other hand the predicted and experimental values fit quite well for u_if. Authors investigated velocity of equilibrium concentration profile generation and they found time intervals up to 30 seconds for their experimental set-up. They reported that segregation velocity was unaffected by the superficial velocity of gas and they derived a mathematical model for segregation velocity. Provided knowledge of the phase diagram u–c_2, authors divided the fluidized bed to the bulk and grid regions – presuming constant and time independent volume and constant jetsam concentration in both regions. Particles were supposed to be carried upward from the grid region to the bulk in wake of a bubble, downward – in the emulsion phase. Quite in contradiction to a former published model[12] pure flotsam in wake was supposed only. This assertion rests upon the fact that for particles of size 0·5 mm and bigger f_w = 0·03, what means that bigger particles are not present in wake. Nevertheless their f_w values were found to be in contradiction to the previously published values that ranged from 0·25 to 0·35.

EXPERIMENTAL

The basic experimental apparatus is shown in Fig. 3. The main part of it consisted of a glass tube I (D = 0·085 m, A = 5·675 . 10^{-3} m^2, h_0 = 0·03, 0·035, 0·05, 0·07, and 0·14 m), or a rectangular column II (0·2 × 0·3 m, A = 0·06 m^2, h_0 = 0·065, 0·1, 0·115, 0·15, and 0·165 m), or in a perspex-glass tube III (D = 0·14 m, A = 1·539 . 10^{-2} m^2, h_0 = 0·06 m).

Binary mixture of particles of chosen concentration $\bar{C}_2$ and height h_0 was put in the column 1, equipped by the grid distributor 2. Fluidizing air, supplied from a pressure distribution frame, was controlled by the valve 3 and metered by the rotameter 4. The binary system had been mixed thoroughly at high superficial velocity and then the chosen volume flow was adjusted. Experiment finished, fluidizing air was turned off and samples of the horizontal layers of the bed were suctioned off by means of a vacuum pump 5 and a tube 6 into flask 7. Particles from the flask 7 were screened and volume of sample was measured. The accuracy of the suction sampling was verified by comparison with the mechanical sampling. Fig. 4 shows that the suction method may

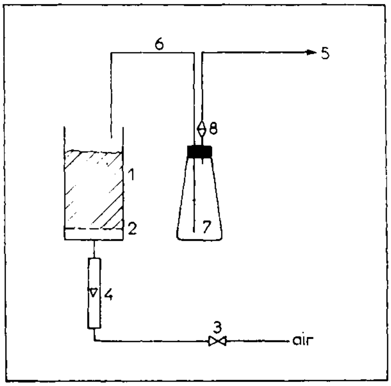

FIG. 3

Experimental set-up. **1** column, **2** grid, **3** flow control valve, **4** rotameter, **5** vacuum pump, **6** suction tube, **7** flask, **8** sintered disk

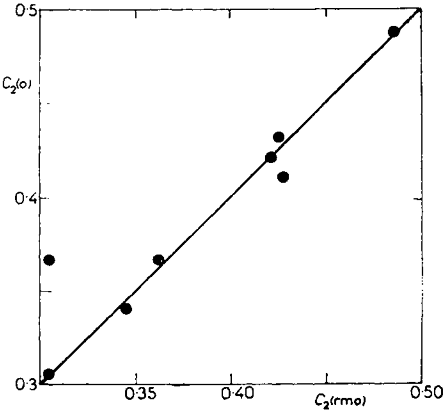

FIG. 4

Suction sampling verification. rmo — mechanical sampling, o — suction sampling be very well used for analysis of the fluidized bed composition. Physical properties of the used experimental materials and types of binary systems, including jetsam specification are shown in Table II. Experimentally found minimum fluidization velocities u_{om} of binary systems *vs* their composition are shown in Fig. 5.

TABLE II

Material used

Material	Shape	u_0 m/s	d_p mm	$\bar{d}_p$ mm	ϱ_s kg m^{-3}	Binary system type
glass	balls	0·2	0·35—0·6	0·475	2 673	3
iron[a]	balls	0·059	0·09—0·25	0·17	6 239	
glass	balls	0·027	0·15—0·25	0·2	2 673	6
glass[a]	balls	0·537	0·8 — 1·1	0·95	2 673	
sand	irreg.	0·04	0·09—0·2	0·145	2 650	1
iron[a]	balls	0·24	0·25—0·4	0·325	6 239	

[a] Jetsam.

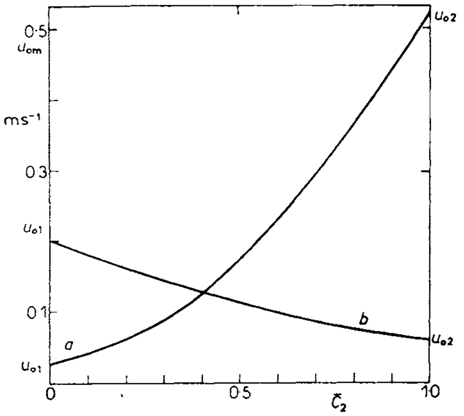

FIG. 5

Minimum fluidization velocities of binary systems *vs* composition. *a*) glass balls $\bar{d}_{p1} = 0·2$ mm, $\bar{d}_{p2} = 0·95$ mm, *b*) glass balls $\bar{d}_{p1} = 0·475$ mm, iron balls $\bar{d}_{p2} = 0·17$ mm

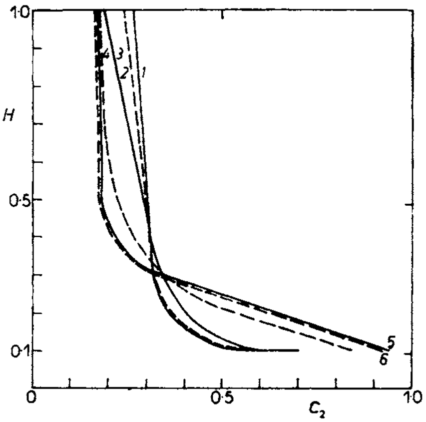

FIG. 6

Velocity of equilibrium stabilization. *1* $u/u_{om} = 1·727$ first arrangement; *2* $u/u_{om} = 1·727$ second arrangement; *3* $u/u_{om} = 1·006$ after 15 sec.; *4* $u/u_{om} = 1·006$ after 45 sec.; *5* $u/u_{om} = 1·006$ after 90 sec.; *6* $u/u_{om} = 1·006$ after 180 sec. Binary system of the 3rd type, flotsam-glass balls, jetsam-iron balls

RESULTS

Time interval necessary for generation of the equilibrium concentration profile in the bed was determined. Rowe[19] reported the following relation

$$t_c = \frac{h_0}{0 \cdot 6(u - u_o)(1 - u - u_o/u_b)} . \tag{4}$$

A new quantity u_b – velocity of bubbles – that has not been known to us up to now occurs in the relation (*4*). That is why time necessary for equilibrium generation was found experimentally (Fig. 6). Particles were fluidized for 3 minutes at $u = 0 \cdot 285$ m/s ($u/u_{om} = 1 \cdot 727$). At the first case, the initial arrangement was following: layer of glass at bottom, layer of iron balls above it, mean jetsam concentration $\bar{C}_2 = 0 \cdot 33$. At the second case the arrangement was quite opposite. The initial arrangement was found to have a very little effect on the final concentration profile as shown in Fig. 6. Superficial velocity was decreased to 0·166 m/s after 3 minutes and concentration profiles after 15, 45, 90, and 180 sec were measured. Fig. 6 shows that the steady state was set after 45–90 sec. Yang and Keairns[18] reported intervals up to 30 sec sufficient for binary system of the 1st type, which tendency to segregation is higher than our binary system of the 3rd type. Fig. 6 demonstrates that interval 180 seconds is long enough for equilibrium stabilization and therefore this interval was taken as sufficient for all the remaining experiments.

The effects of fluidized bed height and column diameter on segregation are shown in Fig. 7. It is obvious that distributor size has no effect on equilibrium profile. Segregation degree is unaffected by the bed height – if it is higher than a critical one and simultaneously the concentration profile fits the predicted curve. The transition region between bulk and grid regions disappears if h_0 is lower than a critical value and composition of the bed turns into a function of bed height where the segregation degree increases if h_0 decreases.

The effect of superficial velocity of air on concentration profile is considerable in the fluidized bed. Quantity u_{om} is an important one characterizing the segregation degree. The best segregation was found at velocities close to u_{om}. The concentration profiles of the segregated bed at $u/u_{om} = 1 \cdot 1$ are shown in Fig. 8. The composition of the fluidized bed is constant in bulk at low mean jetsam concentrations (*a*). For high $\bar{C}_2$ the fluidized bed is formed mainly by the constant concentration grid region (*b*). For high u/u_{om} ratio the fluidized bed is, on the other hand, mixed well (see concentration profile for $u/u_{om} = 14$ shown in Fig. 8). Increasing u/u_{om} ratio suppresses components segregation as it is shown in Fig. 9. More distinctive effect of the superficial velocity on concentration was found for the higher jetsam concentrations.

As mentioned earlier, after a time interval the concentration in the grid region is in equilibrium with the bulk concentration. Idea of analogy with phase equilibrium has already been published[14-18] and it led to u–c_2 diagram construction. According to this idea, it should be possible to determine jetsame concentration in the grid region and in the bulk, at a chosen superficial velocity, on the basis of the diagram u–c_2 only. This statement is, nevertheless, in contradiction to our experimental results. We have found that above mentioned concentrations depend on mean jetsam concentration and the u–c_2 diagram construction is therefore necessary for every $\bar{c}_2$.

An analogy with vapour–liquid phase equilibria has been supposed in this paper, provided, jetsam concentration in the grid region and bulk are in equilibrium – if the superficial velocity is constant (Y–X diagram). The phase equilibrium of binary system of the 3rd type, at $u = 1{\cdot}22u_{\max}$, is shown in Fig. 10. The binary systems of the 1st type are the most segregable ones of all 1–6 combinations. This type of

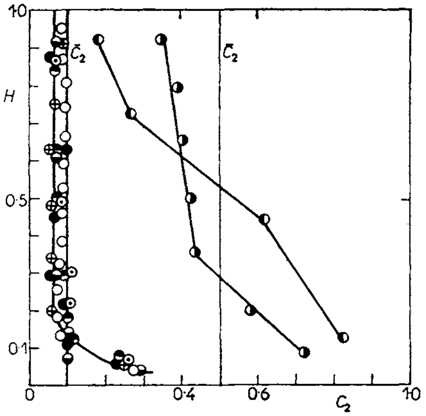

FIG. 7

Effect of apparatus scale on particle segregation. $u = 0{\cdot}214$ m/s; ● $h_0 = 0{\cdot}065$ m, grid $0{\cdot}2 \times 0{\cdot}3$ m; ⊙ $h_0 = 0{\cdot}1$ m, grid $0{\cdot}2 \times 0{\cdot}3$ m; ⊖ $h_0 = 0{\cdot}16$ m, grid $0{\cdot}2 \times 0{\cdot}3$ m; ○ $h_0 = 0{\cdot}14$ m, $D = 0{\cdot}085$ m, $h_0/D = 1{\cdot}647$ ⊕ $h_0 = 0{\cdot}07$ m, $D = 0{\cdot}085$ m, $h_0/D = 0{\cdot}824$; ◓ $h_0 = 0{\cdot}05$ m, $D = 0{\cdot}085$ m, $h_0/D = 0{\cdot}588$; binary system of the 3rd type, $\bar{C}_2 = 0{\cdot}1$, flotsam-glass balls $\bar{d}_{p1} = 0{\cdot}475$ mm, jetsam-iron balls $\bar{d}_{p2} = 0{\cdot}17$ mm; ◐ $h_0 = 0{\cdot}035$ m, ◑ $h_0 = 0{\cdot}07$ m; $D = 0{\cdot}085$ m, $u/u_{om} = 3{\cdot}2$, $u = 1{\cdot}04$, $u_{02} = 0{\cdot}558$ m/s, binary system of the 6th type, $\bar{C}_2 = 0{\cdot}5$, glass balls $\bar{d}_{p1} = 0{\cdot}2$ mm, $\bar{d}_{p2} = 0{\cdot}95$ mm

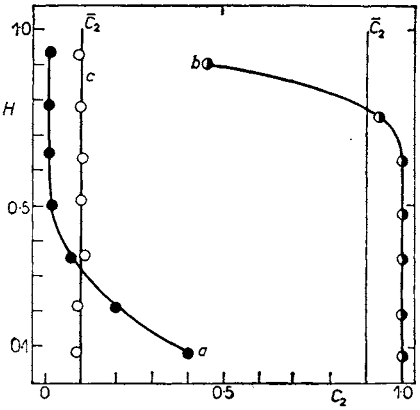

FIG. 8

Concentration profile in fluidized bed. $D = 0{\cdot}085$ m, $h_0 = 0{\cdot}07$ m, binary mixture of the 6th type, glass balls $\bar{d}_{p1} = 0{\cdot}2$ mm, $\bar{d}_{p2} = 0{\cdot}95$ mm; *a*) ● $u = 0{\cdot}044$ m/s, $\bar{C}_2 = 0{\cdot}1$, $u/u_{om} = 1{\cdot}1$; *b*) ◑ $u = 0{\cdot}491$ m/s, $\bar{C}_2 = 0{\cdot}9$, $u/u_{om} = 1{\cdot}1$; *c*) ○ $u = 1{\cdot}04$ $u_{o2} = 0{\cdot}558$ m/s, $u/u_{om} = 14$, $\bar{C}_2 = 0{\cdot}1$

binary system is very difficult to mix since flotsam is entrained if air velocity is increased.

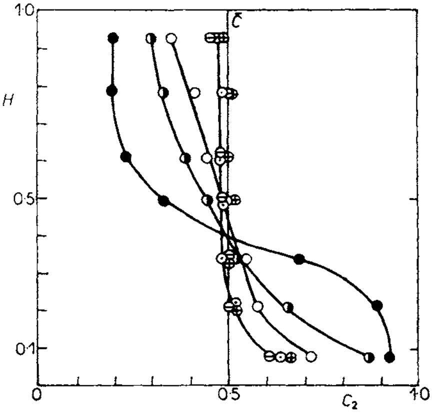

FIG. 9

Effect of superficial velocity of air on concentration profile. $D = 0{\cdot}085$ m, $h_0 = 0{\cdot}07$m, $h_0/D = 0{\cdot}824$, binary mixture of the 3rd type, flotsam-glass balls $\bar{d}_{p1} = 0{\cdot}475$ mm, jetsam-iron balls $\bar{d}_{p2} = 0{\cdot}17$ mm, $\bar{C} = 0{\cdot}5$ ● $u = 0{\cdot}126$ m/s, $u/u_{om} = 1{\cdot}11$; ◑ $u = 0{\cdot}152$ m/s, $u/u_{om} = 1{\cdot}33$; ○ $u = 0{\cdot}166$ m/s, $u/u_{om} = 1{\cdot}46$; ⦶ $u = 0{\cdot}187$ m/s, $u/u_{om} = 1{\cdot}64$; ⊙ $u = 0{\cdot}214$ m/s, $u/u_{om} = 1{\cdot}88$; ⊕ $u = 0{\cdot}285$ m/s, $z/u_{om} = 2{\cdot}50$

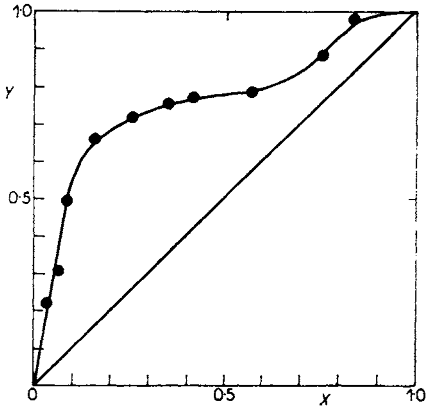

FIG. 10

Phase equilibrium. Binary system of the 3rd type, flotsam-glass balls $\bar{d}_{p1} = 0{\cdot}475$ mm, $D = 0{\cdot}085$ m, $h_0 = 0{\cdot}03$ m, $u = 1{\cdot}22u_{o1} = 4{\cdot}15u_{o2} = 0{\cdot}245$ m/s, jetsam-iron balls $\bar{d}_{p2} = 0{\cdot}17$ mm

LIST OF SYMBOLS

A	fluidized bed cross section [m^2]
C	volume fraction
$\bar{C}$	mean volume fraction
c	mass fraction
$\bar{c}$	mean mass fraction
d_p	particle diameter [m]
$\bar{d}_p$	mean particle diameter [m]
D	column diameter [m]
f_w	bubble wake volume fraction
h	height [m]
h_0	minimum fluidization height [m]
H	dimensionless height
M	mixing index
p	pressure [Pa]

Δp	bed pressure drop [Pa]
t_c	fluidized bed mixing time [s]
u	superficial velocity [m/s]
u_{tf}	total fluidization velocity of binary system [m/s]
u_{if}	incipient fluidization velocity [m/s]
u_b	bubble velocity in fluidized bed [m/s]
u_o	minimum fluidization velocity [m/s]
u_M	superficial velocity at $M = 0{\cdot}5$ [m/s]
u_{max}	the maximum fluidization velocity of binary system [m/s]
u_{min}	the minimum fluidization velocity of binary system [m/s]
u_{om}	minimum fluidization velocity of binary system [m/s]
X	volume fraction of jetsam in bulk
Y	volume fraction of jetsam in grid region
ϱ_F	fluidized bed density [kg m^{-3}]
ϱ_S	particle density [kg m^{-3}]

Subscripts

1	flotsam
2	jetsam
crit	critical value
S	solid phase
o	minimum fluidization conditions

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Translated by the author (J.P.).