TOWARDS A THEORETICAL MODEL OF SEGREGATING FLUIDIZATION OF TWO-SOLID BEDS

Bruno Formisani* Rossella Girimonte† Vincenzino Vivacqua‡

*Università della Calabria, bruno.formisani@unical.it
†Università della Calabria
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Brunello Formisani, Rossella Girimonte and Vincenzino Vivacqua
Dipartimento di Ingegneria Chimica e dei Materiali, Università della Calabria,
I 87036 Arcavacata di Rende (Cosenza), Italy
T: +39-0984-496691; F: +39-0984-496655; E: bruno.formisani@unical.it

ABSTRACT

Fluidization of beds of two dissimilar solids is modelled by reworking the fundamental equations of fluidization. The approach followed illustrates the relationship between bed suspension and component segregation, as determined by differences in solid density and size. The need for empirical parameters is drastically reduced so that a unique representation of all types of mixture behaviour seems possible.

INTRODUCTION

Many industrial applications of fluidization technology (coal or biomass combustion or gasification, waste incineration, powder granulation, catalytic polymerization, etc.) employ solid mixtures made of particles which differ in density, size or shape. As a consequence of the specific reaction of each solid to the passage of the upflowing gas, these beds undergo a certain degree of separation of their components into segregated layers. The influence exerted by segregation phenomena on process performance is admittedly great and explains why the number of studies dedicated to this topic is noticeably large. Notwithstanding that, the present understanding of the mechanism of multicomponent fluidization is still unsatisfactory even when referred to the behaviour of two-solid beds.

On modelling the process of binary fluidization, the effort of many authors has been that of trying to adapt to two-solid mixtures the theory of monosolid fluidization, i.e. to develop models based on some proper definition of their minimum fluidization velocity (1-3). As discussed in a recent paper (4), however, the nature of this approach seems connected to the difficulty of setting up reliable models of segregating fluidization.

The most important difference with the case of monosolid systems is that fluidization of binary particle beds has place through a gradual process that continuously modifies the axial distribution of bed components (5-8): when, for example, gas is admitted through a homogeneous mixture of two solids (Fig.1a) and its flow rate is gradually increased, at a certain velocity value u_{if}, the initial fluidization velocity of the mixture, a mobile fluidization front establishes itself at the top of the bed while the total pressure drop starts deviating from the curve typical of the fixed state. A bubbling layer, made almost exclusively of the flotsam component, builds up in the upper region of the bed while the jetsam forms a defluidized stratum underneath. By progressively increasing the gas flow rate, the two layers grow in thickness (Fig. 1b). The suspension process ends when the final fluidization velocity u_{ff} is reached and the final pressure drop level is first attained. Therefore, while the velocity interval between u_{if} and u_{ff} is crossed, mixtures display their tendency to segregate whereas over u_{ff} the increase of gas velocity brings to a higher degree of component mixing (Fig. 1c), to an extent which depends on the specific nature of the binary bed.

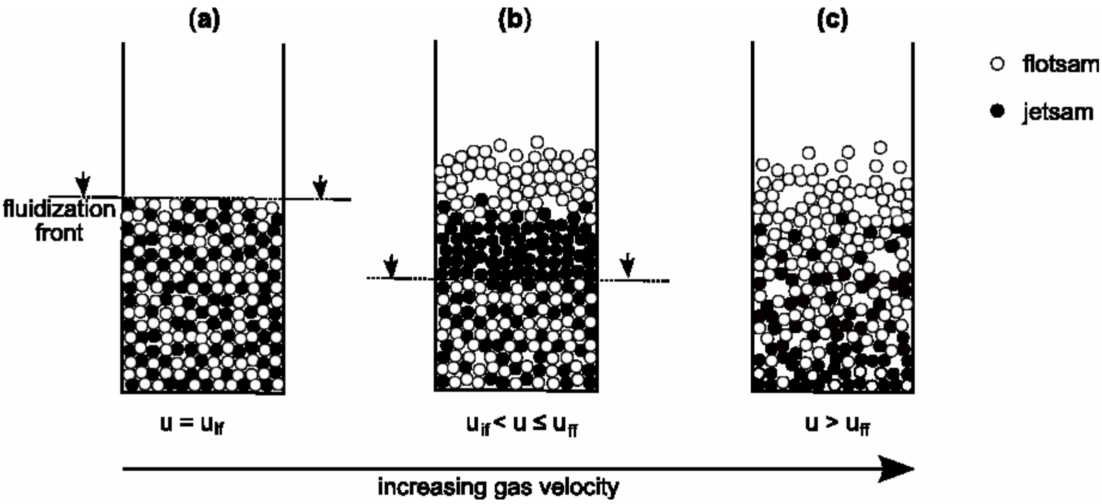


Fig.1 Fluidization mechanism of a homogeneous bed of two solids.

While the value of u_{if} can be calculated once that the axial distribution of the two solids in the packed state is known, the prediction of u_{ff} is much more complicated due to the role played by segregation phenomena. To overcome this difficulty, this paper tries to address the problem of segregating fluidization in fundamental terms, by developing the approach based on the definition of the fluidization velocity interval of two-solid mixtures.

THEORY

As discussed in some recent works (4,9), the initial fluidization velocity of homogeneous mixtures can be predicted by rewriting the equations used for the calculation of the gas pressure drop in a monodisperse packed bed in a way suitable for accounting for the specific nature of the binary system.

For instance, as far as the Carman-Kozeny's equation holds, u_{if} can be calculated from the relationship

$$\frac{180\mu_g u_{if}}{d_{av}^2}\frac{\left(1-\varepsilon_{mf,m}\right)^2}{\varepsilon_{mf,m}^3}=\left[\left(\rho_f-\rho_g\right)x_f+\left(\rho_j-\rho_g\right)\left(1-x_f\right)\right]\left(1-\varepsilon_{mf,m}\right)g \qquad (1)$$

where d_{av} is the Sauter mean diameter of the two-solid system, calculated as

$$\frac{1}{d_{av}} = \frac{x_f}{d_f} + \frac{1-x_f}{d_j} \tag{2}$$

and $\varepsilon_{mf,m}$ is drawn from the experimental curve of bed voidage versus x_f.
At any operating velocity intermediate to u_{if} and u_{ff} the axial distribution of mixture components is approximately that sketched in Fig.1b, with rather sharp interfaces between the three layers, whose heights are indicated as h_f, h_j and h_m, respectively.
Since its formation at u_{if} the top layer of flotsam particles finds itself over its incipient fluidization point. A force balance on the remaining part of the bed can then be written, with the total drag force on its two sections, given by

$$F_d = \frac{180\mu_g u}{d_j^2}\frac{\left(1-\varepsilon_{mf,j}\right)^2}{\varepsilon_{mf,j}^3}Ah_j + \frac{180\mu_g u}{d_{av}^2}\frac{\left(1-\varepsilon_{mf,m}\right)^2}{\varepsilon_{mf,m}^3}Ah_m \tag{3}$$

that has to balance, at u_{ff}, its buoyant weight

$$W = gA\left\{\left(1-\varepsilon_{mf,j}\right)h_j\left(\rho_j-\rho_g\right)+\left(1-\varepsilon_{mf,m}\right)h_m\left[\left(\rho_f-\rho_g\right)x_f+\left(\rho_j-\rho_g\right)\left(1-x_f\right)\right]\right\} \tag{4}$$

By equating eqns (3) and (4) and considering that a mass balance on the jetsam component allows expressing h_j in function of h_m as

$$h_j = \left(h_0-h_m\right)\left(1-x_f\right)\frac{\left(1-\varepsilon_{mf,m}\right)}{\left(1-\varepsilon_{mf,j}\right)} \tag{5}$$

the final fluidization velocity u_{ff} of the fixed portion of the system can be calculated:

$$u_{ff} = \frac{\left[\left(\rho_f-\rho_g\right)x_f h_m + \left(\rho_j-\rho_g\right)\left(1-x_f\right)h_0\right]g}{180\mu_g\left[\frac{\left(1-\varepsilon_{mf,m}\right)}{\left(\varepsilon_{mf,m}^3 d_{av}^2\right)}h_m + \frac{\left(1-\varepsilon_{mf,j}\right)}{\left(\varepsilon_{mf,j}^3 d_j^2\right)}\left(h_0-h_m\right)\left(1-x_f\right)\right]} \tag{6}$$

In the lack of a fundamental theory capable to establish a reliable relationship between the progress of binary fluidization and the value of the height h_m of the residual homogeneous mixture, the following correlation is proposed to correlate data relevant to any type of two-solid system:

$$\frac{h_m}{h_0} = k\frac{\left(1-\varepsilon_{mf,m}\right)}{\left(1-\varepsilon_{mf,j}\right)}\frac{\varepsilon_{mf,j}^3}{\varepsilon_{mf,m}^3}\sqrt{x_f\left(1-x_f\right)} \tag{7}$$

In it k is a constant whose value, determined by a best-fit procedure between predictions of the theoretical equation (6) and experimental data of u_{ff} at varying x_f, is found to depend on the specific mixture considered.
Irrespective of the density of its components, whenever the binary bed is made of spheres of the same size the values of voidage relevant to the pure jetsam

component ($\varepsilon_{mf,j}$) and to the mixture ($\varepsilon_{mf,m}$) result nearly equal, so that the voidage function in the right hand side of eqn (7) may always be assumed equal to 1.

EXPERIMENTAL

Experiments were carried out in a transparent column with an internal diameter of 10 cm, on two-solid beds whose aspect ratio h_0/D in the fixed state was constantly set equal to 1.7. Compressed air, whose flow rate was measured by a bench of rotameters, was admitted to the column through a plastic porous plate 4 mm thick, so that an even distribution throughout the column section was assured. A pressure tap located 1 mm above the distributor and connected to a U-tube water manometer was used to measure the total pressure drop across the bed, while three graduated scales spaced at 120° around the column wall allowed determining the average bed height at any velocity level. By means of these measurements the initial fixed-bed voidage was easily calculated from the relationship:

$$\varepsilon_0 = 1 - \frac{m}{\rho A h_0} \tag{8}$$

All the solids used in experiments are included in Geldart's group B so the fixed bed voidage ε_0 calculated by eqn (8) has been assumed to coincide with the minimum fluidization voidage ε_{mf}, after verification that the error connected to this procedure is negligible.
All the materials used in the experiments are practically spherical and closely sieved; their granulometric distribution was measured by a Malvern Mastersizer 2000 laser diffractometer, while a Quantachrome helium pycnometer was used for density measurements. Table 1 reports both the properties of the various solids and those of the mixtures involved in the experimental investigation.

Tab.1 – Properties of the experimental solids and mixtures

Solid	Density [g/cm^3]	Sieve size [µm]	Sauter mean diameter [µm]
Molecular sieves (MS)	1.46	600-710	631
Glass ballotini (GB)	2.48	600-710	631
		250-300	271
		150-180	154
Ceramics	3.76	500-701	605

Type	Mixture	ρ_j/ρ_f [-]	d_j/d_f [-]	ε_{mf} [-]	k [-]
Density-segregating	CE605-GB593	1.52	1.02	0.405	0.39
Size-segregating	GB631-GB154	1	4.1	See Fig.2	0.077
Dissimilar solids	CE376-GB271	1.52	1.39	0.405	0.65
	MS631-GB154	0.59	4.1	See Fig.2	0.14

VALIDATION AND DISCUSSION

As a major difference with the case of two-density mixtures, the voidage of binary beds whose components significantly differ in their diameter varies with their composition (10). Consistently with this difference of behaviour, mixtures for which the difference of size of the two solids is negligible or limited, namely CE605-GB593 and CE376-GB271, exhibit experimental values of $\varepsilon_{mf,m}$ that allow to assume this variable as practically unaffected by system composition. Accordingly, an average value of $\varepsilon_{mf,m}$, drawn from the experiments and reported in Table 1, has been used to model their fluidization pattern.

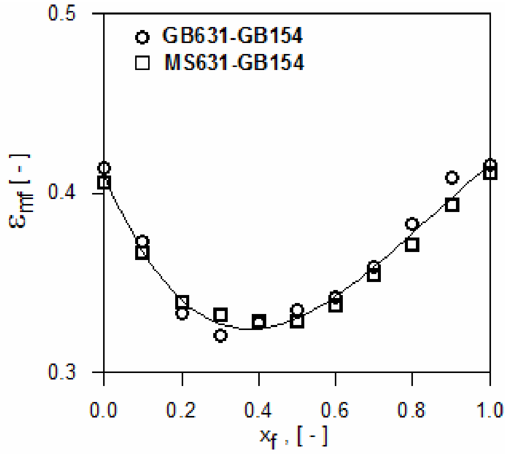


Fig.2 Voidage of the homogeneous mixtures GB631-GB154 and MS631-GB154 at varying composition.

As for the systems GB631-GB154 and MS631-GB154, instead, the experimental dependence of $\varepsilon_{mf,m}$ on x_f is plotted in Fig.2.

The fluidization velocity diagrams of the four experimental mixtures are plotted in Figs 3 and 4, together with the relevant model curves of u_{if} and u_{ff}.

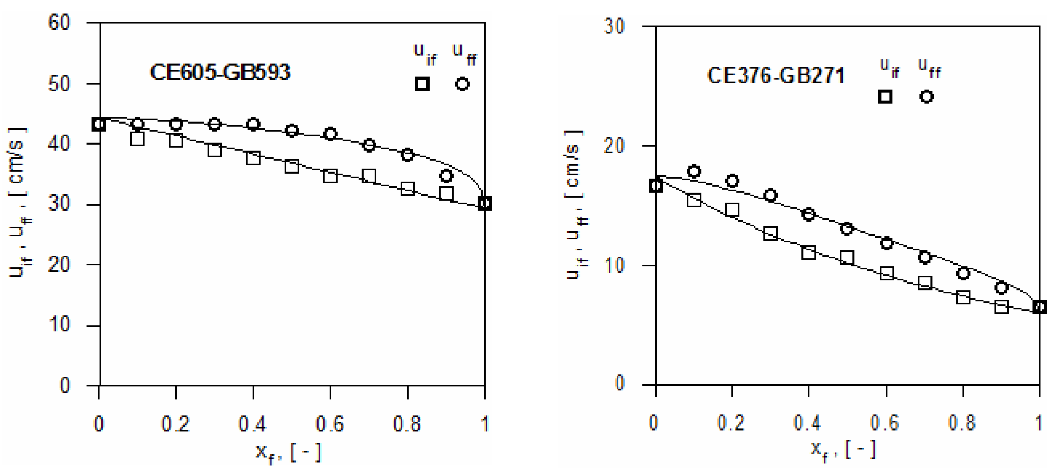
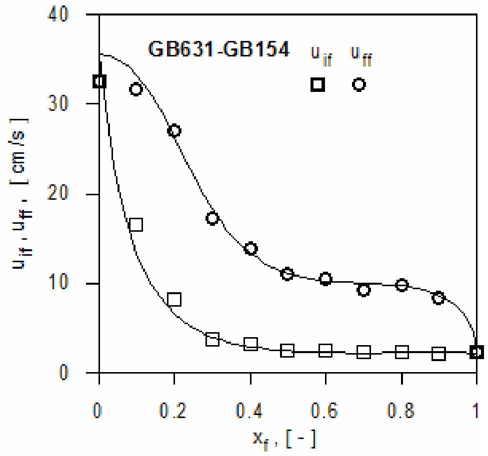


Fig.3 Fluidization diagram of the mixtures CE605-GB593 and CE376-GB271.

Unlike the trends of u_{if}, provided by the fully theoretical equation (1), those of u_{ff} are calculated by eqns (6) and (7), so that they make use of the values of the parameter k reported in Table 1.

In particular, Fig. 3 reports, both in the experimental and the calculated version (with k equal to 0.39 and 0.65 respectively), the velocity diagrams of the systems CE605-GB593 and CE376-GB271, whose components have a density ratio of 1.52 and a diameter ratio of 1.02 e 1.39 respectively, a limited variation that does not cause a dramatic change in the shape of the two diagrams.

When mixture components differ both in density and size the action of each of the two segregation factors may tend to strengthen or counterbalance that of the other. To this regard, Fig.4 illustrates the behaviour of the mixtures GB631-GB154 and MS631-GB154, whose jetsam component is, respectively, the denser or the lighter of the two solids. Notwithstanding the inversion of the jetsam-to-flotsam density ratio, the shape of the two diagrams is similar, a circumstance that reveals that also for the mixture MS631-GB154 size-segregation prevails. Both diagrams are well interpreted by the model equations, with values of the parameter k equal to 0.077 and 0.14 respectively.



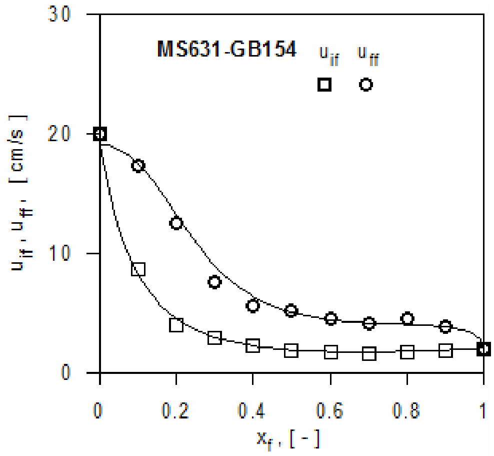


Fig.4 Fluidization diagram of the mixtures GB631-GB154 and MS631-GB154.

Although not yet fully predictive, the theoretical analysis proposed in the present investigation proves capable to give a correct interpretation of the fluidization properties of various categories of two-solid beds, with errors of prediction that seldom exceed 10%. That demonstrates the potentiality of the approach followed, whose essential characteristic is that of adapting the force balance equation to a more realistic representation of the binary fluidization phenomenology.

CONCLUSIONS

A more realistic representation of the structure assumed by any homogeneous two-solid bed during its transition to the fluidized state makes possible to analyse the process in the light of the fundamental theory of fluidization.

Whatever the nature of the mixture, i.e. that of the factors that drive the segregation process of its components, the initial and the final fluidization velocity of the binary bed, u_{if} and u_{ff}, can be calculated with good accuracy by reworking the force balance so as to account for the change in the axial distribution of the two solids. However, while the prediction of u_{if} is founded on the knowledge of the relationship between bed voidage and component concentration, that of u_{ff} requires quantifying the extent of segregation at varying velocity.
To overcome this difficulty, the model proposed in this work makes use of an experimental parameter, whose value is however independent of mixture composition.

NOTATION

A	column cross section, cm^2
D	column bed diameter, cm
d	particle diameter, μm
d_{av}	Sauter mean diameter, μm
F_d	drag force, g cm/s^2
g	gravity acceleration, cm/s^2
h	height of the particle layer, cm
h_0	height of the fixed bed, cm
k	parameter of eqn. 7, -
m	bed mass, g
u_{if}, u_{ff}	initial, final fluidization velocity, cm/s
u_{mf}	minimum fluidization velocity, cm/s
x	solid fraction, -
W	buoyant weight, g cm/s^2
ε_{mf}	minimum fluidization voidage, -
ε_0	fixed bed voidage, -
μ_g	gas viscosity, g/cm s
ϕ	particle sphericity, -
ρ	solid density, g/cm^3
ρ_g	gas density, g/cm^3

Subscripts

f,j	of the flotsam, jetsam component (or layer)
m	of the homogeneous mixture

REFERENCES

1. Cheung, L., Nienow, A.W., Rowe, P.N. (1974). Minimum fluidisation velocity of a binary mixture of different sized particles. *Chem Eng Sci.*, 29, 1301-1303.
2. Chiba, S., Chiba, T., Nienow. A.W., Kobayashi, H. (1979). The minimum fluidisation velocity, bed expansion and pressure-drop profile of binary particle mixtures. *Powder Technol.*, 22, 255-269.

3. Thonglimp, V., Hiquily, N., Laguerie, C. (1984). Vitesse minimale de fluidisation et expansion des couches de mélanges de particules solides fluidisées par un gaz. *Powder Technol.*, 39, 223-239.
4. Formisani, B., Girimonte, R. and Longo, T. (2008). The fluidization process of binary mixtures of solids: development of the approach based on the fluidization velocity interval. *Powder Technol.*, 185, 97-108.
5. Chen, J.L.-P. and Keairns D.L. (1975). Particle segregation in a fluidized bed. *Can J Chem Eng.,* 53, 395-402.
6. Vaid, R.P. and Sen-Gupta, P. (1978). Minimum fluidization velocities in beds of mixed solids. *Can J Chem Eng.*, 56, 292-296.
7. Carski, M., Pata, J., Vesely, V. and Hartman M. (1987). Binary system fluidized bed equilibrium, *Powder Technol.*, 51, 237-242.
8. Olivieri, G., Marzocchella, A. and Salatino, P. (2004). Segregation of fluidized binary mixture of granular solids. *AIChE J.*, 50, 3095-3106.
9. Formisani, B., Girimonte, R. and Longo, T. (2008). The fluidization pattern of density-segregating binary mixtures. *Chem Eng Res & Des.*, 86, 344-348.
10. Yu, A.B. and Standish, N. (1987). Porosity calculations of multi-component mixtures of spherical particles. *Powder Technol.,* 52, 233-241.