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The Relationship Between Fluidization Velocity and Segregation in Two-Component Fluidized Beds: A Preliminary Analysis

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THE RELATIONSHIP BETWEEN FLUIDIZATION VELOCITY AND SEGREGATION IN TWO-COMPONENT FLUIDIZED BEDS: A PRELIMINARY ANALYSIS

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ABSTRACT

Experiments are presented that provide the initial and final fluidization velocity of binary mixtures at varying composition. Introducing just one parameter to account for their segregation level, the theoretical equations of the two characteristic velocities are derived. These equations are then employed to predict the concentration profile obtained by slowly defluidizing the bed down to the fixed state.

INTRODUCTION

In many industrial processes in which fluidized beds are employed (combustion and gasification of coal and biomass, polymerization, etc.), solids of various kinds are simultaneously subjected to fluidization. During the process, gas-solid and solid-solid interaction determines the tendency of system components to segregate or mix up so as to give place to a characteristic axial concentration profile. Segregation phenomena may lead, in some cases, to strong inhomogeneities or even to partial defluidization of the bed with detrimental effects on process performance.

In spite of the huge number of experimental studies published in the last three decades, even for mixtures of only two components the relationship between fluidization regime and level of segregation is still poorly understood, so that no reliable quantitative theory of segregating fluidization is, to date, available. Attempts made to refer the state of mixing of a binary bed to the characteristics of its fluidization regime have led to a few relationships, mostly empirical. To this regard, a well-known equation is that proposed by Nienow et al. (1), valid for two-density mixtures and flotsam-rich systems, which expresses the variation with the fluidization velocity of a component mixing index defined by the authors as the ratio between the jetsam concentration in the upper region of the bed and its overall value. Modified versions of this equation, meant to extend its validity to two-size mixtures and to improve its accuracy, were proposed by Rice and Brainovich (2), Peeler and Huang (3) and Wu and Baeyens (4). All these works make use of the "minimum fluidization velocity of the mixture" u_{mf} and correlate the degree of bed mixing to the "excess gas velocity" $u-u_{mf}$. However, the concept of u_{mf}, taken from the theory of monosolid fluidization, has no meaning when applied to the suspension process of a binary bed, because of the gradual nature of the phenomenon (5,6).

This paper, instead, develops a novel approach, based on definition of the “initial” and “final fluidization velocity” of the binary mixture. As shown by previous studies (5-8), in a Δp versus u diagram u_{if} is determined where the pressure drop first deviates from the fixed bed curve, u_{ff} where it attains its final value. Introduction of these two characteristic velocities is suggested by the actual phenomenology of the fluidization process, analysed in detail elsewhere (5,6). The mechanism of binary fluidization is here summarized in Fig.1.

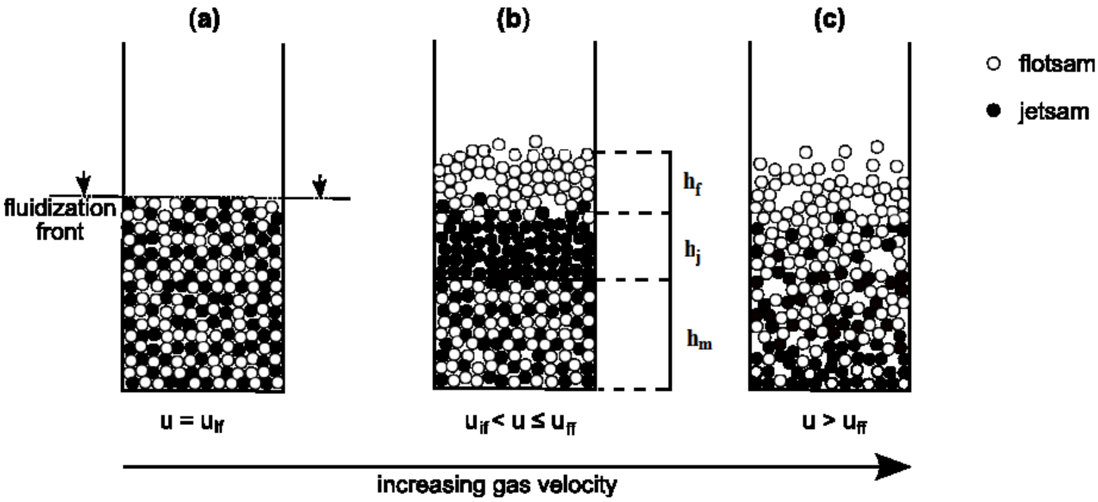

Fig.1 - Fluidization mechanism of a homogeneous bed of two solids.

THEORY

Any bed of two solids homogeneously mixed (Fig.1a) achieves suspension gradually, while the axial distribution of its components changes along with the increase of the fluidizing gas velocity. The process begins at u_{if}, whose calculation can be accomplished by a fully predictive equation devised in a previous stage of the research (5,6):

$$\frac{180\mu_g u_{if}}{d_{av}^2}\frac{(1-\varepsilon_{mf,m})^2}{\varepsilon_{mf,m}^3} = \left[(\rho_f-\rho_g)x_{f0}+(\rho_j-\rho_g)(1-x_{f0})\right](1-\varepsilon_{mf,m})g \qquad (1)$$

In it, d_{av} is the Sauter mean diameter, calculated from

$$\frac{1}{d_{av}} = \frac{x_{f0}}{d_f}+\frac{1-x_{f0}}{d_j} \qquad (2)$$

while the value of bed voidage is drawn from the experimental curve of $\varepsilon_{mf,m}$ 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. The bed consists of a top flotsam layer, a middle jetsam stratum and a residual homogeneous portion whose heights are indicated as h_f ,h_j and h_m, respectively. As the flotsam layer results fluidized since the beginning of its buildup at u_{if}, a force balance between the total drag force and the buoyant weight in the remaining two layers provides the following expression relating u_{ff} (Fig.1c) to the properties of the two solids, the mixture voidage and the level of segregation corresponding to the height h_m of the static mixed layer:

$$u_{ff} = \frac{\left[\left(\rho_f - \rho_g\right)x_{f0}h_m + \left(\rho_j - \rho_g\right)\left(1 - x_{f0}\right)h_0\right]g}{180\mu_g\left[\dfrac{\left(1-\varepsilon_{mf,m}\right)}{\left(\varepsilon_{mf,m}^3 d_{av}^2\right)}h_m + \dfrac{\left(1-\varepsilon_{mf,j}\right)}{\left(\varepsilon_{mf,j}^3 d_j^2\right)}\left(h_0 - h_m\right)\left(1 - x_{f0}\right)\right]} \tag{3}$$

In order to make eqn (3) deterministic, it is necessary to fix the value of the parameter h_m. In the absence of a fundamental theory, the following correlation has been devised for $h_{m,ff}$, that is at the final fluidization velocity, capable to give accurate predictions (9):

$$\frac{h_{m,ff}}{h_0} = k\frac{\left(1-\varepsilon_{mf,m}\right)}{\left(1-\varepsilon_{mf,j}\right)}\frac{\varepsilon_{mf,j}^3}{\varepsilon_{mf,m}^3}\sqrt{x_{f0}\left(1-x_{f0}\right)} \tag{4}$$

Eqn (4) relates the height of the residual homogeneous layer to mixture composition and to the gain in drag force effectiveness provided by the void condition typical of the mixed state. In it, k is a best fit parameter which does not depend on composition.

For a two-density mixture, assuming the invariance of voidage with composition, u_{ff} calculated from eqn (3) turns out to be equal to the velocity obtained by substituting in eqn (1) the value of the flotsam fraction in the system made of the jetsam and the mixed layer, of height h_j and h_m respectively:

$$x_{fb} = \frac{x_{f0}\left(h_{m,ff}/h_0\right)}{x_{f0}\left(h_{m,ff}/h_0\right) + 1 - x_{f0}} \tag{5}$$

The correspondence between the value of u_{if} evaluated at x_{fb} and that of u_{ff} calculated at the overall concentration x_{f0}, exact for density segregating beds, is well approximated also for two-size systems.

Given that u_{ff} does not depend on the initial state of mixing of the two solids (5), x_{fb} may be also considered as the concentration of the first thin layer that settles down during the defluidizing procedure; eqn (5) can hence be regarded as a phase equilibrium relationship, where $h_0/h_{m,ff}=\alpha$ plays a role analogous to that of the relative volatility in gas-liquid equilibrium, in a way that:

$$x_{f0} = \frac{\alpha \cdot x_{fb}}{\alpha \cdot x_{fb} + (1 - x_{fb})} \tag{6}$$

When a packed portion of the bed is still present and the defluidization front has reached the height z, the average flotsam fraction in the overlying fluidized region is:

$$\overline{y_f} = \frac{\int_z^H (1-\varepsilon_{mf}) x_f \, dz}{\int_z^H (1-\varepsilon_{mf}) dz} \tag{7}$$

$\bar{y}_f$ can now be linked to x_f, i.e. the flotsam fraction of the thin layer which settles down by slightly decreasing the gas flow rate; the way to relate these two variables is suggested by eqn (6): x_{f0} is substituted with $\bar{y}$ and x_f with x_{fb}, so that

$$\overline{y_f} = \frac{\alpha \cdot x_f}{\alpha \cdot x_f + (1 - x_f)} \tag{8}$$

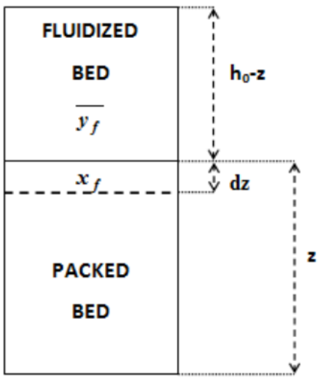

Fig. 2 - Sketch of the defluidization process.

Under the assumption of constant voidage ($H=h_0$), a simplification that introduces a negligible error:

$$x_f dz = -d\left[(h_0 - z)\cdot \overline{y_f}\right] = -(h_0 - z) d\overline{y_f} + \overline{y_f} dz \tag{9}$$

Introducing the dimensionless height $Z=z/h_0$ and considering that

$$\frac{d\overline{y_f}}{dZ} = \frac{dx_f}{dZ}\frac{dy_f}{dx_f} \tag{10}$$

eqn (9) gives rise to the first order differential equation:

$$\frac{dx_f}{dZ} = \frac{1}{(1-Z)} \frac{\overline{y_f} - x_f}{\partial \overline{y_f} / \partial x_f} \tag{11}$$

From eqn (7) it is then obtained:

$$\frac{dx_f}{dZ} = \frac{1}{(1-Z)} \frac{(x_f + \alpha)(1 - x_f)^2}{\left[\alpha^2 - 1\right]} \tag{12}$$

Once integrated with the condition Z=0, $x_f=x_{fb}$, eqn (12) allows calculating the axial profile of x_f as:

$$Z = 1 - \left[\left(\frac{1 - x_f}{x_f} \right) \Bigg/ \left(\frac{1 - x_{fb}}{x_{fb}} \right) \right]^{\frac{\alpha}{\alpha - 1}} \left[\left(\frac{\alpha x_f + 1 - x_f}{1 - x_f} \right) \Bigg/ \left(\frac{\alpha x_{fb} + 1 - x_{fb}}{1 - x_{fb}} \right) \right] \qquad (13)$$

EXPERIMENTAL

All the experiments of this study were carried out in a transparent fluidization column of 10 cm ID, equipped with a plastic porous distributor 4 mm thick. The pressure drop across the column was measured by means of a U-tube water manometer connected to a tap located 1 mm above the distributor plane. Bed heights were evaluated by averaging the values read on three graduated scales put at 120°C around the column wall, and then used for determining bed void fractions.
The concentration profiles were obtained by gently drawing the solids from the top of the column by means of a vacuum device, in horizontal layers of particles generally 2 cm thick (or 1 cm thick, when a higher resolution was needed). Each of these layers was then sieved to measure the mass fraction of either solid component by weighing. Concentration values were then referred to the average height of the relevant layers and used to trace the respective profiles in function of height.
Measurements involved mixtures of various spherical solids, closely sieved. The properties of each cut are reported in Table 1, together with those of the mixtures investigated. In all the experiments the aspect ratio h_0/D of the fixed bed was 1.7.

Tab.1 – Properties of the experimental solids and mixtures

Solid	**Density** [g/cm^3]	**Sieve size** [μm]	**Sauter mean diameter** [μm]
Glass ballotini (GB)	2.48	500-710	593
		450-600	499
		150-180	172
Ceramics	3.76	500-710	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	GB499-GB172	1	2.90	See Fig.1	0.18

VALIDATION

As a major difference with the case of two-density mixtures, the binary beds in which a significant difference of component diameters is present exhibit a voidage which varies with their composition (6,7). Thus, for the system CE605-GB593 $\varepsilon_{mf,m}$ can be assumed as practically constant with x_f, and an average values of 0.405 was used.

As regards instead the mixture GB499-GB172, $\varepsilon_{mf,m}$ varies with x_f according to the experimental curve of Fig.2.

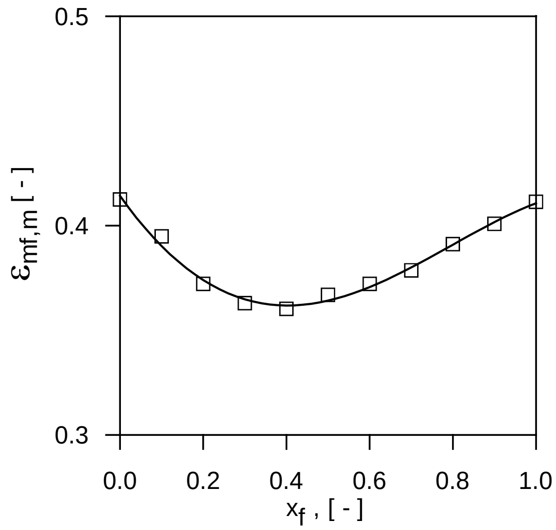

Fig.2 - Voidage of the homogeneous mixtures GB499-GB172 at varying composition.

In Fig. 3 are shown the velocity diagrams of the two systems investigated. Model curves for u_{if} are generated by the theoretical eqn (1), wheras u_{ff} is predicted from eqns (3) and (4), using the values of k reported in Table 1. The errors do not exceed 10% for both the density- and the size-segregating mixture.

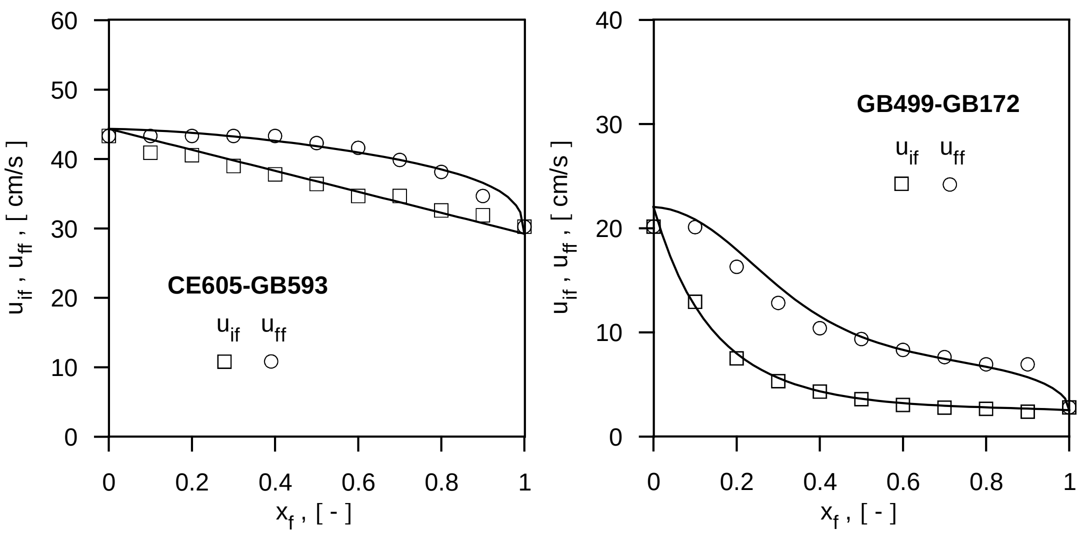

Fig.3 - Fluidization velocity diagrams of the homogeneous mixtures CE605-GB593 (density-segregating) and GB499-GB172 (size-segregating).

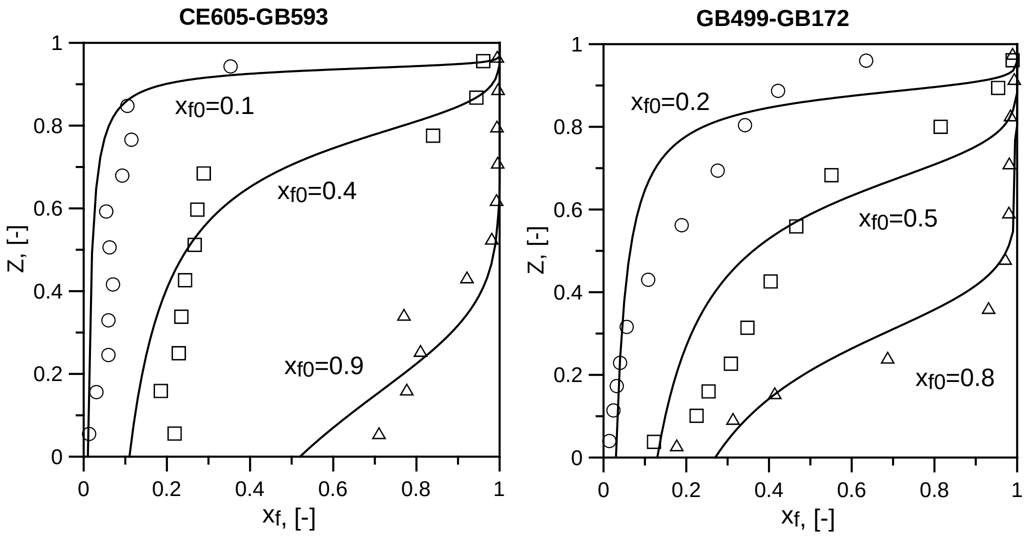

Fig.4 - Concentration profile of the fixed bed obtained by a slow defluidizing procedure at varying flotsam total concentration for the mixtures CE605-GB593 and GB499-GB172.

By introducing into eqn (4) the values of k used to correlate the velocity data, it is possible to calculate $h_{m,ff}$ at a given overall concentration and, thanks to eqn (6), the corresponding value of x_{fb}. Finally, the concentration profile of the fixed bed obtained after slow defluidization of the mixture is found by eqn (12). Model curves and experimental points are compared in Figs 4 for the two different types of mixtures under examination, over the whole field of system composition.
Although the agreement is not always satisfactory from the quantitative point of view, the model seems capable to reproduce the general trend of the component composition profiles. While confirming the potentiality of the approach followed, these preliminary results encourage the effort of addressing segregating phenomena occurring in multisolid systems in the light of the fundamental theory of fluidization.

CONCLUSIONS

Results relevant to mixtures subjected to segregation by difference of either density or size between their components show that a unique theory based on fundamental analysis proves capable to relate the progress of fluidization to the extent of segregation.
The model equations proposed in this paper successfully reproduce the effects of segregation by means of a parameter whose determination can be carried out with minimal experimental effort, by a single fluidization experiment.
In the prediction of the final fluidization velocity of a two-solid mixture, an important role is played by the fact that the force balance is applied to a realistic picture, even when some evident simplifications are introduced. The difference u_{ff}-u_{if}, i.e. the width

of the fluidization velocity interval of the binary bed, seems related to the concentration profile obtained from its slow defluidization down to the fixed state.

NOTATION

A	column cross section [cm^2]
D	column bed diameter [cm]
d	particle diameter [μm]
d_{av}	Sauter mean diameter (eqn.4) [μm]
g	gravity acceleration [cm/s^2]
H	total bed height [cm]
h_0	height of the fixed bed [cm]
k	best-fit parameter (eqn. 17) [-]
u_{if}, u_{ff}	initial, final fluidization velocity [cm/s]
u_{mf}	minimum fluidization velocity [cm/s]
x_f	solid fraction of flotsam [-]
x_{f0}	overall solid fraction of flotsam [-]
$\bar{y}$	average flotsam fraction of the fluidized portion of the bed [-]
z	axial coordinate [cm]
Z	dimensionless height z/h_0 [-]
ε_{mf}	minimum fluidization voidage [-]
ε_0	fixed bed voidage [-]
μ_g	gas viscosity [g/cm s]
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
ff	at the final fluidization conditions.

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