Refereed Proceedings

The 13th International Conference on Fluidization - New Paradigm in Fluidization Engineering

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Engineering Conferences International *Year* 2010

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ABSTRACT

Confining a bed of relatively fine particles in a packing of coarse spheres prevents the onset of bubbly flow past their point of incipient fluidization. To improve present representations of confined fluidization, experiments on several cuts of solids of various density are analysed and interpreted by adapting some fundamental relationships of the fluidization theory to the peculiar geometry provided by the confining environment.

INTRODUCTION

Beds of relatively fine particles fluidized in the void matrix of a coarser packing of solids are commonly referred to as “confined fluidized beds” or “packed-fluidized beds”. Thanks to this fluidization technique, even solids that belong to Geldart’s group B become capable of reacting to any increase of the gas velocity over u_{mf} by homogeneously expanding up to unusually high values of voidage.

Systems of this kind can be of interest for applications in which bubbly flow plays a detrimental role on process efficiency, but many aspects of their fluid dynamics are still uncertain. Recently, confined fluidization has been proposed also as a possible alternative to the conventional way of operating circulating fluidized beds (1-4). Authors who have investigated the transition to the state of incipient fluidization and the expansion regime of confined beds fluidized by either a gas or a liquid (5-9) have often introduced empirical parameters whose meaning or determination criterion is somewhat unclear; moreover, the expansion properties of these systems have not yet been given a satisfactory description.

By means of an experimental analysis performed on several samples of fine particles, prepared in cuts of two different sizes and subjected to fluidization in the same packing, this work investigates the dependence of the characteristic variables of the regime of homogeneous expansion on particle density; it also shows how some classical equation of the fluidization theory can be reworked to interpret the essential properties of the confined bed both in the fixed and in the expanded state.

EXPERIMENTAL APPARATUS AND MATERIALS

The experimental investigation was performed in a perspex column 49 mm ID, equipped with a plastic porous distributor.

The column was packed with lead spheres (PB, ρ_p=11.2 g/cm^3) with a diameter d_p of 4100 μm up to a height of 27.5 cm; the voidage ε_p of this packing was 0.38. A suitable amount of finer spherical particles was then poured onto the voids of this packing, to form a confined fixed bed 5 cm high. The experiments involved two closely sieved cuts (200÷250 μm and 250÷300 μm) of four spherical solids whose properties, together with their conventional fluidization parameters, experimentally determined, are reported in Table 1.

Table 1. Properties of the experimental solids

	Particle density ρ_f [g cm^{-3}]	Sauter diameter d_f [μm]	Conventional minimum fluidization velocity u_{mf} [cm s^{-1}]	Conventional minimum fluidization voidage ε_f [-]	u_{mf} predicted by Ergun equation [cm s^{-1}]
GB 200-250 μm	2.48	228	5.2	0.408	5.7
GB 250-300 μm	2.48	271	6.8	0.400	7.6
CE 200-250 μm	3.78	230	8.4	0.399	8.5
CE 250-300 μm	3.78	268	10.3	0.396	10.8
ZO 200-250 μm	6.15	245	12.4	0.391	11.7
ZO 250-300 μm	6.15	261	14.0	0.386	13.8
BR 200-250 μm	8.75	229	16.3	0.399	18.5
BR 250-300 μm	8.75	272	21.6	0.394	23.6

GB glass ballotini, CE ceramic spheres, ZO zirconium oxide spheres, BR bronze spheres.

The flow rate of air was regulated by a set of rotameters covering the range 0÷2600 Nl/h and the total pressure drop was measured by a U-tube water manometer connected to a pressure tap located just above the gas distributor. Two external graduated scales were used to measure the variation of height of the confined bed of solids over its minimum fluidization point.

RESULTS

The experimental analysis of the behaviour of the fine solids spans over a wide range of fluidization velocities, from the fixed bed state to the maximum perceptible degree of expansion within the confined environment provided by the coarse packing.

At any gas velocity, the value of the bed voidage ε is calculated from the height of the confined bed H_{fc} by the following relationship:

$$\varepsilon = 1 - \alpha_f - \alpha_p = 1 - \frac{m_f}{\rho_f A H_{fc}} - \frac{m_p}{\rho_p A H_{fc}} \tag{1}$$

As for the pressure drop across the confined fluidized bed, it is evaluated by subtracting to the experimental value of the overall ΔP that relevant to the upper part of the fixed coarse packing, devoid of fines:

$$\Delta P_{conf} = \Delta P_{tot} - \Delta P_{p,sup} \tag{2}$$

Therefore ΔP_{conf} accounts for the presence of the whole mass of fine solids and as well as for that of the submerged part of the packing, so that its value is related to the variation of H_{fc} with u.

A typical diagram of ΔP_{conf} is presented in Fig.1, which also includes the corresponding trend of ε at varying gas velocity.

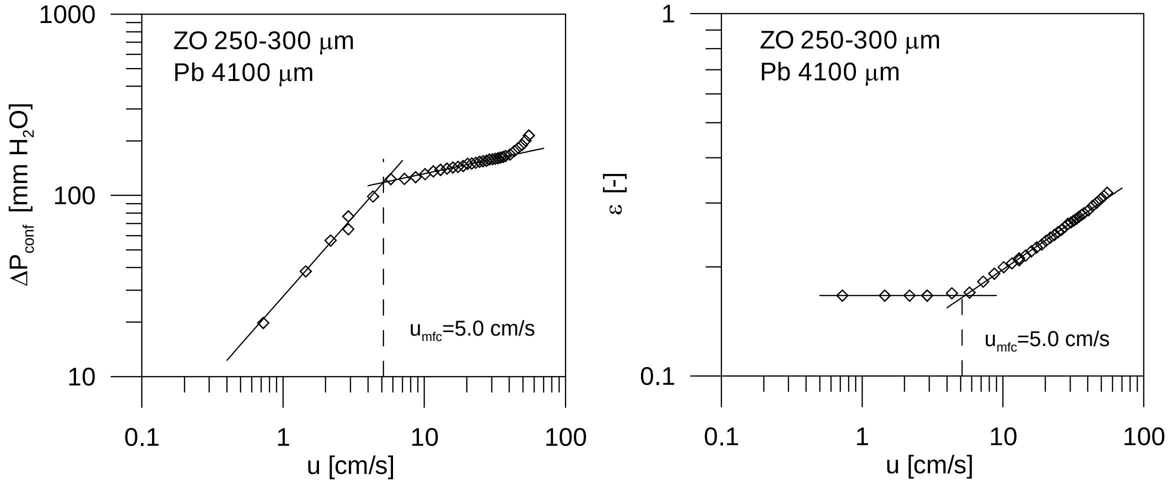

Fig.1 - Typical trends of ΔP_{conf} and ε during the process of confined fluidization

In these log-log diagrams two regions of linear dependence of ΔP_{conf} and ε on gas velocity are recognizable: at low flow levels, when the confined solid is at rest and ε is constant, the pressure drop linearly increases with u until bed suspension is achieved; at velocities higher than u_{mfc}, the solid homogeneously expands in the packing and the pressure drop increase is again linear, although its rate of growth is visibly lower. Eventually, at much higher velocities, the rate at which pressure drop increases grows again, as if a new regime ensues.

All the solid subjected to fluidization in the confining environment provided by the voids of the coarse packing exhibit a net transition to the suspended state, that is easily obtained at the intersection of the two linear trends of ΔP. For all of them, the experimental values of u_{mfc} of are reported in Table 2.

The two diagrams of Fig.2 show that at equal particle diameter the first linear variation is nearly the same for all the solids investigated so that the different values of u_{mfc} are attributable mainly to the different weight per unit section of the various solid samples. It can also be noticed that the expansion regime of the four materials is characterized by different rates of growth of the pressure drop.

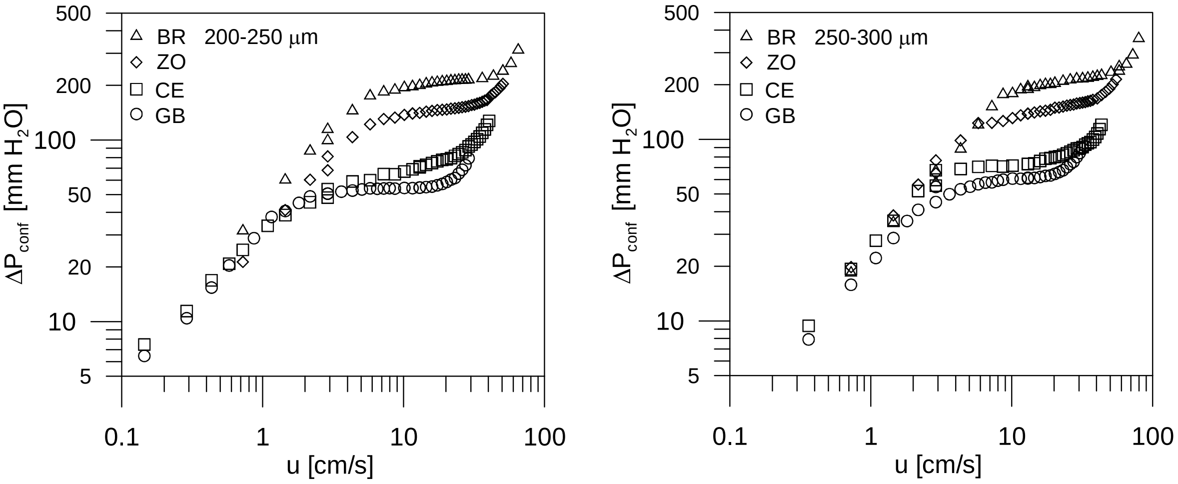

Fig. 2 - Fluidization diagrams of the experimental solids

Owing to the suppression of bubble formation operated by the of the fixed array of coarse spheres, any increase of the fluidization velocity over u_{mfc} brings the fine particles system to behave like a liquid-fluidized bed, i.e. to expand homogeneously up to unusually high porosities (7). Its voidage variation can thus be represented by a power low similar to that of Richardson-Zaki (10), as modified by Glassermann *et al.* (9):

$$\frac{u}{\varepsilon_p} = u_0 \cdot \left(\frac{\varepsilon}{\varepsilon_p}\right)^n = u_0 \cdot \varepsilon_{fc}^n \qquad (3)$$

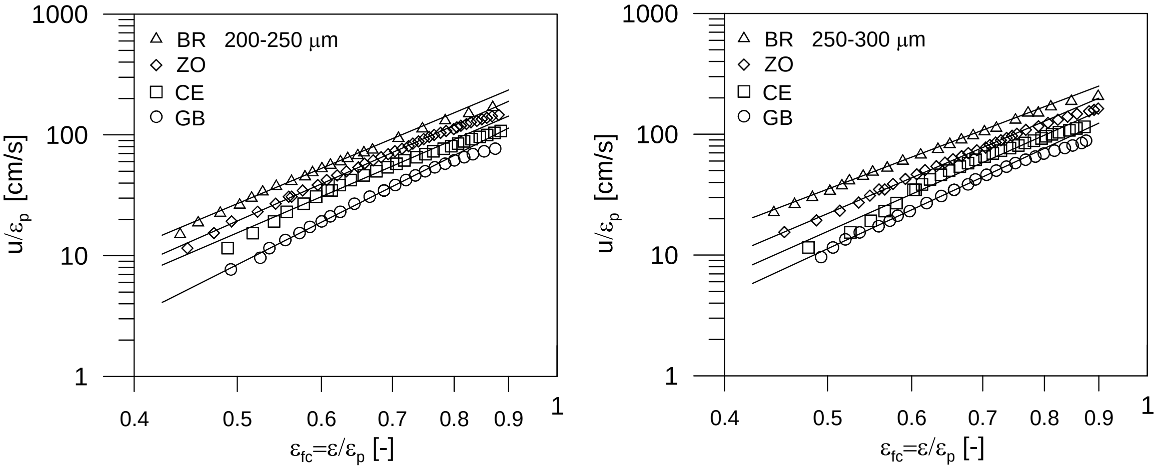

Fig. 3 - Expansion diagrams of the confined bed of solids

The ability of eqn (3) to interpret the behaviour of the solids subjected to investigation throughout their expansion field is shown in Fig.3. The procedure of fitting provides the values of u_0 and n for each solid cut, here reported in Table 2.

The two parameters of the correlation, u_0 and n, depend on the particle properties: like the terminal velocity, u_0 increases with the particle weight, whereas the exponent n shows (with some exception for ceramics spheres) a tendency to decrease for denser or larger particles.

Table 2. Summary of the experimental results

	Sauter diameter d_f [μm]	Confined minimum fluidization velocity u_{mfc} [cm s^{-1}]	Confined minimum fluidization voidage $\varepsilon_{fc} = \varepsilon/\varepsilon_p$ [-]	Expansion exponent n [-]	Confined terminal velocity u_0 [cm s^{-1}]
GB 200-250 μm	228	1.43	0.435	4.12	155
GB 250-300 μm	271	2.52	0.435	3.78	161
CE 200-250 μm	230	1.55	0.412	3.56	186
CE 250-300 μm	268	2.58	0.448	3.90	234
ZO 200-250 μm	245	4.38	0.448	3.70	260
ZO 250-300 μm	261	5.00	0.447	3.52	263
BR 200-250 μm	229	4.66	0.418	3.56	321
BR 250-300 μm	272	8.75	0.439	3.26	339

DISCUSSION

In order to calculate the total pressure drop across the confined bed when the fine particles are in the fixed state, the contribution of both solids has to be evaluated separately. This is done by the relationship

$$\frac{\Delta P_{conf}}{H_{fc}}\cdot(1-\varepsilon)=\frac{\Delta P_f}{H_{fc}}\cdot(1-\varepsilon_{fc})+\frac{\Delta P_p}{H_{fc}}\cdot(1-\varepsilon_p) \tag{4}$$

Depending on the nature of the particles that form the two-solid system, each term is then evaluated by Carman-Kozeny's or Ergun's equation

$$\frac{\Delta P_{f,p}}{H_{fc}}=C\,\mu_g\,u\,\frac{1}{\varepsilon^3}\left(\frac{\alpha_p}{d_p}+\frac{\alpha_f}{d_f}\right)\frac{\alpha_{f,p}}{d_{f,p}}+1.75\,\rho_g\,u^2\,\frac{1}{\varepsilon^3}\frac{\alpha_{f,p}}{d_{f,p}} \tag{5}$$

where C=180 or 150 depending on which of the two relationships is used.

The comparison between experimental and calculated values ΔP_{conf} is illustrated in Fig. 4 for each of the two size of solids investigated and shows how these classical equations keep a satisfactory predictive ability also in the new geometric situation, a circumstance that should make possible to establish a fully predictive criterion for the minimum fluidization velocity of the fine particles in the confined state.

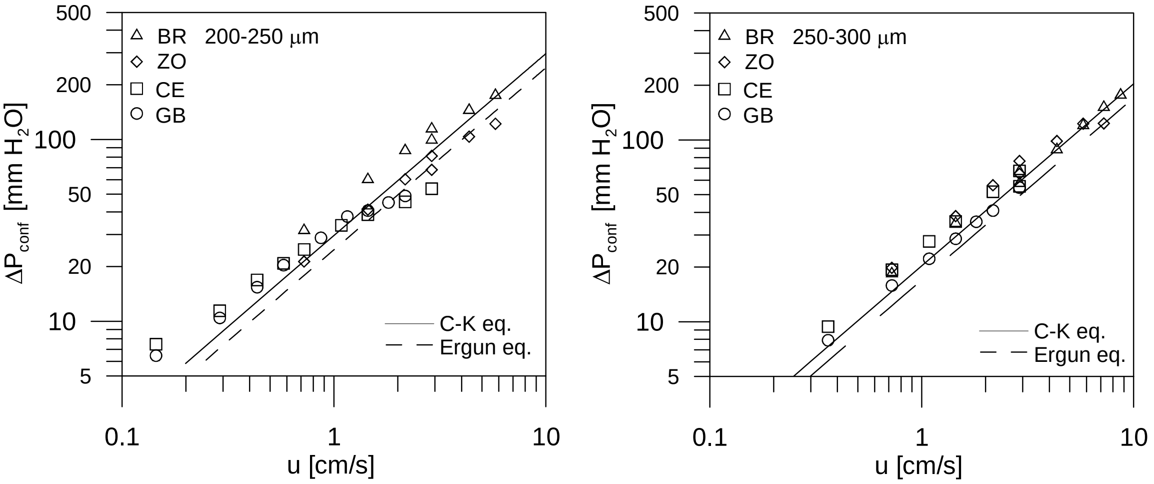

Fig. 4 – Comparison between experimental and calculate values of the pressure drop in the confined fixed bed

Analogously, on applying Richardson-Zaki's equation to model the variation of the height H_f of the confined bed of fine particles at increasing gas velocity, it is necessary to account for the presence of the walls of the channels provided by the interstitial voids of the coarse packing.

By defining the hydraulic diameter of these channels as

$$d_h = \frac{2}{3}\frac{\varepsilon_p}{(1-\varepsilon_p)} \cdot d_p \quad (=1680\,\mu m) \tag{6}$$

it proves possible to relate the terminal velocity of the fines in the confined environment, u_0, to its conventional definition (9):

$$u_0 = u_t \cdot 10^{-\frac{d_f}{d_h}} \tag{7}$$

As regards the expansion parameter n, it can be noticed that after definition of the Galileo and terminal Reynolds numbers

$$Ga_f = \frac{g d_f^3 (\rho_f - \rho_g)\rho_g}{\mu_g} \quad ; \quad Re_t = \frac{\rho_g d_f u_t}{\mu_g} \tag{8}$$

the following relation (11) holds:

$$Re_t = \left[-3.809 + (3.809^2 + 1.832\, Ga_f^{0.5})^{0.5}\right]^2 \tag{9}$$

and a relationship similar to that proposed by Richardson-Zaki (10), namely

$$n = \left(a + b \cdot \frac{d_f}{d_h}\right)\frac{1}{Re_t^{0.1}} \tag{10}$$

can be used to predict the value of n. The form of eqn (10) is that proposed by Schiaffino et al. (8); however, while the constant a is set equal to 4.45 like in the original correlation, the value of b (there equal to 18) has been changed into 5.74 after application of a best-fit procedure to the experimental data.

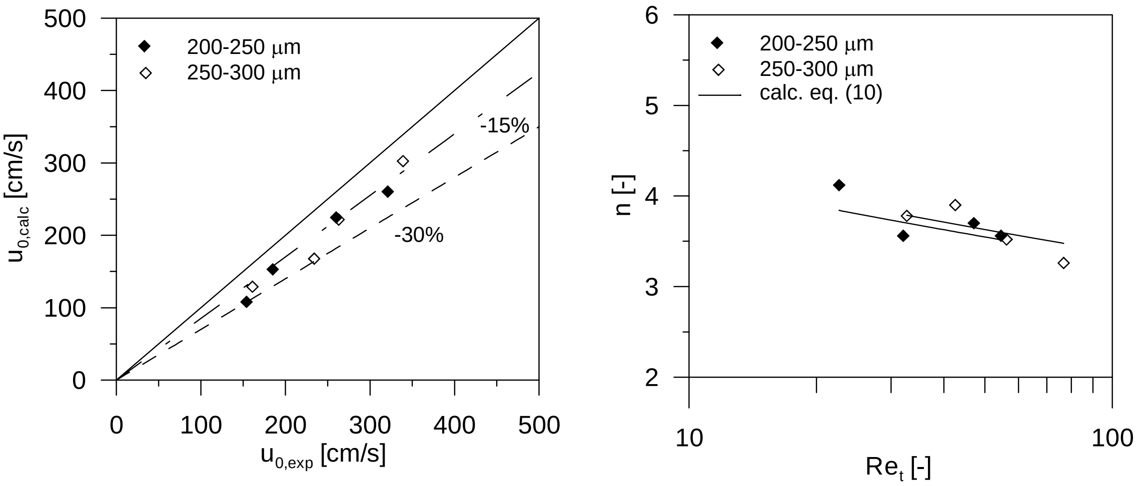

Fig. 5 – Comparison between experimental and calculated parameters of the homogeneous expansion process

The comparison between experimental and calculated parameters of the process of homogeneous expansion is illustrated in Fig.5; although affected by a certain degree of approximation, whose origin also lies in the difficulty of correctly reading the bed height at high degrees of expansion, eqns (7) and (10) appear to offer a reasonable basis for developing a predictive model of the behaviour of a confined fluidized bed.

CONCLUSIONS

The analysis of the bubble-free expansion of fine particles fluidized in a packing of fixed coarse spheres shows that the process can be described by a modified form of the Richardson-Zaki's equation. To this purpose, the original parameters of the correlation have to be redefined, so as to account for the peculiar geometry the confined environment. The agreement between theoretical predictions and experimental data relevant to several solids of different density and size is fair and gives support to the effort of developing a fully predictive theory of confined fluidization.

NOTATION

a, b	parameters of eqn (10)	Re_t	terminal Reynolds number, -
A	bed section, cm^2	u	gas velocity, cm/s
d	particle diameter, μm	u_{mf}	conventional minimum fluidization velocity, cm/s
d_h	hydraulic diameter, μm	u_{mfc}	confined minimum fluidization velocity, cm/s
g	gravity acceleration, cm/s^2	u_t	terminal velocity, cm/s

Ga	Galileo number, -	u_0	terminal velocity in the confined environment, cm/s
H_{fc}	height of the confined bed, cm	α	solid volume fraction, -
m	solid mass, g	ε	voidage, -
n	expansion parameter, -	ε_{fc}	voidage of the confined bed of fines, -
ΔP	pressure drop, mmH_2O	μ_g	gas viscosity, g/(cm s)
ΔP_{conf}	pressure drop in the confined state, mm H_2O		
ΔP_{tot}	overall pressure drop, mm H_2O	ρ	particle density, g/cm^3
$\Delta P_{p,sup}$	ΔP in the superior (empty) part of the packing, mm H_2O	ρ_g	gas density, g/cm^3

Subscripts

exp, calc	experimental, calculated	f,p	of the fluidized, packed solid

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