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Extension of the model of binary fluidization to beds confined in a packing of coarse spheres

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ABSTRACT

The prediction of the minimum fluidization velocity of beds of Geldart's group B particles confined in a packed bed of coarse spheres can be achieved by extending to this peculiar type of systems the theory developed for modelling the behaviour of segregating beds of simultaneously fluidized solids.

The approach is based on separate force balances on the fluid and the fine solids, capable to account for the peculiar nature of solid-solid interaction in a confined fluidized bed. Its validation is fulfilled by an extended investigation conducted in two columns (5 and 10 cm OD) packed with a fixed bed of 4.1 mm lead shots or 11 mm glass beads. The effect of particle size on the fluidization regime is investigated by comparing the results provided by experiments in which various cuts of glass ballotini, ranging from 100 to nearly 600 μm, are fluidized in two packings of fixed spheres; possible differences of behaviour due to particle density are analysed by series of experiments employing particles of ceramics, zirconium oxide, steel and bronze of the same diameter.

The results obtained confirm the effectiveness of the approach followed, in which an important role is played by the indirect interaction between the two solid phases.

1. Introduction

Fluidization of multicomponent beds has been employed in a large number of processes. In most cases the different solid species are brought into the fluidized state simultaneously, such as in combustion or gasification processes. A distinctive feature of these systems is the often unavoidable tendency of the solid components to segregate, giving rise to a non-homogeneous internal composition of the bed [1–5]. It has recently been shown that a key-role is played by solid-solid interactions in the mechanisms of binary fluidization [6]. In that work, assessing the component contribution to the total pressure drop allowed writing separate force balances on each component of the multiphase system. By this way, the authors derived an expression for the interaction force and confirmed a criterion, available from the literature [7], capable of providing the initial segregation direction of each solid in a well-mixed bed upon incipient fluidization. The authors also argued that the presence of solid-solid interactions explains the gradual nature of binary fluidization, which is accomplished along a fluidization velocity interval [8,9].

In other cases only one solid is to be fluidized, while the other component remains packed during the whole process. This system, often referred to as “packed-fluidized bed” or “confined fluidized bed” [10], has been raising an increasing interest as its fluid-solid contact mode is particularly suitable for operations in which maximization of the conversion of a gaseous reactant is crucial [11–13]. That is due to the ability of these fluidized systems to prevent the formation of bubbles, a route by which part of the gas feed by-passes the contact with the solid phase, whether it is another reactant or a catalyst.

A confined fluidized bed can be considered as a particular type of two-component mixture of solids, in which the interstitial network provided by the packed solid constitutes the confining environment in which the finer component achieves the suspended state and then expands without the formation of bubbles (Fig. 1). This fluidization technique seems likely to provide a very efficient fluid-solid contact mode, suitable for high conversion of gaseous reactants, nearly complete adsorption of specific components of the fluidizing stream, filtration or heat recovery from dust-laden gases [14–22]. Contact efficiency of operations of this kind improves over a broad velocity range without the handling problems orderly associated to the use of fine powders. That is even more true for applications in which the solid of interest (for instance a sorbent or a catalyst) is a powder obtained from a synthesis, then granulated in nearly spherical pellets of larger size.

In a recent work [23], equations were derived and validated to predict the relationship between the degree of expansion of the fine solid and the operating fluidization velocity, namely the key-feature of the technique. However, the authors did not address the prediction of the minimum fluidization velocity of solids under confined conditions.

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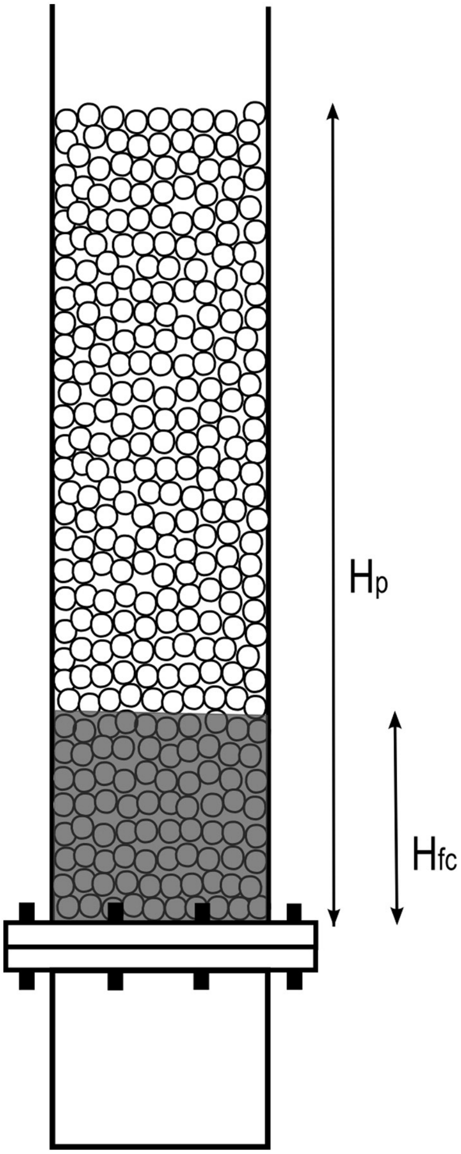

Fig. 1. Schematic structure of a packed fluidized bed.

Modelling the transition to the fluidized state of these systems will therefore be the objective of the present analysis, now made possible by the availability of a general theoretical model of the fluidization behaviour of two-solid systems. To this regard, the theory developed for segregating beds of simultaneously fluidized solids, that makes use of separate force balances for each of the phases of interest, will be extended to the homogeneous fluidization of Geldart's group B particles in a packed bed of coarse spheres.

2. Theory

2.1. Separate force balances

Following what was suggested by Wallis [24], separate force balances can be written for each component of the multiphase system. In the case of one-dimensional steady-state flow, for a binary solid bed the form of these equations is:

$$-\frac{dP}{dz}+b_i+f_i=0 \tag{1}$$

where b_i's are the body forces per unit volume on the ith component and f_i's are the average surface forces per unit volume not contained in the pressure gradient. In a previous work [6], the term f_i in Eq. (1), written for the two solid species, comprised the pure drag force exerted by the fluid as well as the interaction forces between the two solids. For a bed of two simultaneously-fluidized solids, the force exerted by the packed component on the fluidized one (i.e. that with lower u_{mf}) delays its suspension. In other words, this force is responsible for the fact that the initial fluidization velocity of a well-mixed two-solid bed is generally larger than u_{mf} of its “fluidized” component. However, the presence of this interaction requires that both solids can be suspended at the same time, i.e. that they have comparable minimum fluidization velocities; this happens when none of the two species forms an independent structure, i.e. a structure in which any pair of particles of either component is virtually connected by a path through the contact points between particles of the same kind.

In a packed-fluidized bed the coarse particles form an independent structure and their weight is therefore directly discharged on the distributor rather than being exerted on the other solid. As far as the particle size ratio d_p/d_f is not lower than about 10 [20], the interstitial voids of this structure provide the space in which the fine particles can move freely. Thus, in this case the interaction force in Eq. (1) is null. In light of these considerations, Eq. (1) can be particularized for the fluid phase and the two solid components; once that the finer particles are fluidized and homogeneously suspended such relationships are written as:

$$\text{Fluid phase-gas(g)}\quad -\frac{dP}{dz}-\rho_g g-180\frac{\mu_g u}{d_{av}^2}\frac{(1-\varepsilon)^2}{\varepsilon^3}=0 \tag{2}$$

$$\text{Solid phase-fine component(f)}\quad -\frac{dP}{dz}-\rho_f g+180\frac{\mu_g u}{d_{av}d_f}\frac{(1-\varepsilon)}{\varepsilon^2}=0 \tag{3}$$

$$\text{Solid phase–packing(p)}\quad -\frac{dP}{dz}-\rho_p g+180\frac{\mu_g u}{d_{av}d_p}\frac{(1-\varepsilon)}{\varepsilon^2}+f_d=0 \tag{4}$$

where d_{av} is the Sauter mean diameter [8,9], defined as:

$$\frac{1}{d_{av}}=\frac{x_p}{d_p}+\frac{x_f}{d_f}. \tag{5}$$

$$\text{The fine solid fraction is}\quad x_f=\frac{\alpha_f}{(\alpha_f+\alpha_p)}=\frac{\alpha_f}{(1-\varepsilon)} \tag{6}$$

$$\text{with }\alpha_i\text{ calculated as}\quad \alpha_p=\frac{m_p}{(\rho_p A H_p)}=(1-\varepsilon_p) \tag{7}$$

$$\alpha_f=\frac{m_f}{(\rho_f A H_{fc})} \tag{8}$$

so that

$$\varepsilon=(1-\alpha_p-\alpha_f). \tag{9}$$

In Eq. (4) f_d is the unbalanced weight of the coarse particles (the packing) which is discharged on the distributor. In the force balances for the two solids, the drag force on each of them has been obtained from the Carman-Kozeny equation and partitioned according to their respective surface fractions [6].

2.2. Minimum fluidization velocity in confined conditions

As a result of having disregarded the interaction term between the two solids, the system of Eqs. (2) and (3) can be solved separately. However, indirectly the two solids do interact in that each of them modifies the fluid flow field in which the other one is immersed. Solution of