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Coupling between countercurrent gas and solid flows in a moving granular bed: The role of shear bands at the walls

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ABSTRACT

We extended the standard approach to countercurrent gas–solid flow in vertical vessels by explicitly coupling the gas flow and the rheology of the moving bed of granular solids, modelled as a continuum, pseudo-fluid. The method aims at quantitatively accounting for the presence of shear in the granular material that induces changes in local porosity, affecting the gas flow pattern through the solids. Results are presented for the vertical channel configuration, discussing the gas maldistribution both through global and specific indexes, highlighting the effect of the relevant parameters such as solids and gas flowrate, channel width, and wall friction. Non-uniform gas flow distribution resulting from uneven bed porosity is also discussed in terms of gas residence time distribution (RTD). The theoretical RTD in a vessel of constant porosity and Literature data obtained in actual moving beds are qualitatively compared to our results, supporting the relevance under given circumstances of the coupling between gas and solids flow.

1. Introduction

Moving beds experiencing countercurrent gas–solid flow are commonly encountered in industry. Applications span from drying processes, moving bed granular filters (Seville and Clift, 1997), to direct reduction of iron ore (Parisi and Laborde, 2004), or even to pebble-bed nuclear reactors (Rycroft et al., 2006), just to cite few examples. In this work, attention will be focused on countercurrent moving beds below the fluidization threshold, when the mixture is rather dense, such that the granular medium can be treated within the context of dense granular flows (Midi, 2004). The simplest setup which can be imagined is a fully-developed channel flow: from the modelling point of view, steady, one-dimensional gas solid flow is a well established topic in the theory of flow through porous materials and in fluidization. If we consider a pipe or a channel filled with a moving granular bed experiencing a countercurrent gas flow, the classical analysis (Gidaspow, 1994) is developed assuming that a granular bed moves with uniform (plug) velocity profiles in the radial direction, with a gas flow which is uniform too. A drawback of such an assumption, which is a very useful simplification in many cases, is that it neglects radial profiles of solid velocity and porosity. This leads to a wrong estimation of the gas velocity and subsequently does not take into account gas maldistribution and contact time distribution, which come directly from the existence of such profiles. Previous studies on voidage variations in channels (Faderani et al., 1998a,b) used a simplified model, the so-called "Drift Flux Model" (Wallis, 1969), involving the assumption that the relative velocity of the solids and the interstitial fluid equals the terminal velocity, in order to describe the behaviour of nearly buoyant granular materials experiencing gravity driven flow; in this work, such a model cannot be used because (1) the effect of wall friction is going to be considered, which is neglected in the development of that model and (2) the assumption on the relative velocity is not correct because we refer to situations in which generally the bed is far both from fluidization and free settling. Therefore the full analysis involving the specification of forces on each single phase will be adopted. In the context of fixed beds, the importance of considering radial profiles of porosity in the bed was already introduced by Vortmeyer and Schuster (1983), who showed how they can affect the gas flow pattern. In this static situation, if the sample is accurately prepared, geometrical reasons alone can explain the development of a non uniform porosity profile. Geometrical constraints impose that for nearly spherical particles and in presence of flat walls, close to the boundary, porosity $\epsilon \to 1$, and ϵ typically fluctuates around a mean profile due to layering effects. This effect vanishes if the wall is fully rough (that is, if the roughness length is comparable with the dimension of the particles in the bulk).

When the granular material is moving in the channel, an additional source of dilation occurs: in order to allow the motion, the material needs to dilate close to the wall, where a shear band develops. In the centre of the channel instead the material remains unsheared and the porosity constant around the random packing limit. In this context, some studies concerning the importance of

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porosity profiles, for example in the drying process, or for heat transfer, have been carried out (Lacerda et al., 2005; Lira et al., 2007).

However, often an a prioristic porosity profile, coming from fixed-bed measurements, was assumed, and it was not discussed how this profile could vary with the controlling parameters of the system, such as solid and gas flowrate, material parameters such as wall–particle and interparticle friction, and the gas phase physical properties.

Moreover, to our knowledge, the coupling between solid rheology and gas flow, as described below, has never been taken into account previously.

It seems of great evidence that deeper understanding of the behaviour of the flowing granular material is needed to predict the porosity, and so the gas phase, velocity profile. Moreover, it is evident, for example looking at the experimental works on the dense flow of granular materials collected by the French group Midi (2004), that the dilation of the medium is strongly related to the flow pattern of the materials, and so the porosity profile cannot be considered as an a priori ingredient.

This shear-induced dilation needs to be evaluated by means of a rheology and a dilatancy rule for granular materials. At constant pressure drop, a more dilated medium means higher velocities of the gas, with consequent preferential channelling near the walls. This is a quite important industrial problem and it will be tackled by means of simple arguments. For the sake of simplicity, we will concentrate our efforts on the shear-induced dilation, which seems to be more important than the geometrical one, at least for sufficiently large channel to particle diameter ratios (Paterson et al., 2000). The dilated zone due to the shear band typically spans almost 10 particle diameters (Artoni et al., 2007), while the geometrical dilation, averaged over the fluctuations extends for maximum two particle diameters (Goodling et al., 1983; Mueller, 1992). Thus, it is reasonable to expect that if the channel is sufficiently large to allow the formation of shear bands ($D/d_p > 20$), the contribution of geometrical dilation is negligible with respect to the shear-induced one; in addition, it was shown (Paterson et al., 2000) that in such channels, not only the relative weight of the geometrical dilation is low, but also the absolute value is negligible on gas maldistribution.

In summary, this work deals with the prediction of the flow patterns in the gas and in the solid, when a proper rheology is considered for the solids. We show how a simple but effective model of granular materials, developed by the GDR MiDi (Midi, 2004; da Cruz et al., 2005), can be used to predict velocity and porosity profiles, which strongly affect the behaviour of a countercurrent gas flow. The main scope of the paper is to discuss the methodology for the coupling, and evaluate the predictions given by the approach in a simple configuration, with simple (though reasonable) assumptions for the rheology of the granular medium and the gas phase behaviour.

2. Physical problem and model

We will focus on a cylindrical, axisymmetric geometry, assuming that the flow field of both the gas and the solid is fully developed, and that due to the Janssen effect, stresses do not vary with height far from the top (Janssen, 1895; Nedderman, 1992). The case without gas has been referred as the *vertical chute problem* (Pouliquen and Gutfraind, 1996); countercurrent gas flow is exemplified in Fig. 1, together with the reference frame. It is important to stress that the coupling between granular flow and gas flow is given, in this simple configuration, by the following issues:

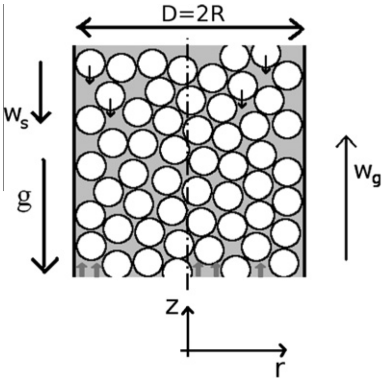

Fig. 1. Schema of countercurrent gas solid flow.

- Assuming constant pressure drop, variation in the porosity of the solid implies variation in the relative velocity between the gas and the solid, because the permeability of a granular medium is an increasing function of the porosity. As the velocity profile of the solid is determined from its momentum balance, once the latter is fixed, the velocity profile in the gas is given. On the other hand, varying total gas (and solid) flowrate implies a variation in the global gas phase pressure gradient.

- Gas phase pressure gradients (due to the frictional drag between the solid and the gas) correspond to drag forces in the solid; in a fully developed flow in a channel, with all gradients in one direction, the gas pressure drop has the effect of lowering the weight of the granular material.
- The action of lowering the weight of the material modifies internal stresses, and so in cascade influences shear rate and velocity profiles in the solid. Therefore, porosity is determined at this step because it depends on the amount of shear in the material.

Another mechanism inducing coupling between the dynamics of the two phases considered could be lubrication of the solid particles by the fluid: if the interstitial fluid is a gas and not a liquid, this effect is reasonably negligible.

2.1. Gas phase model

Let $\vec{v}_g\ (u_g, v_g, w_g)$ and $\vec{v}_s\ (u_s, v_s, -w_s)$ be, respectively, the gas and the solids velocity fields (defined, for example in a simple one directional flow, as the flowrate of each phase divided by the effective cross-area occupied by the phase, which for the gas correspond to the interstitial velocity); for the sake of analysing the case of countercurrent gas flow (with the solid discharging due to gravity), w_s is chosen to be positive when the solids flow downwards and w_g is chosen to be positive when the gas flows upwards, with respect to the absolute reference frame, or, in other words, with respect to the walls of the container.

The gas phase model chosen in this work is a continuum one, mimicking the interaction with the dense assembly of particles by means of lumped, locally averaged, terms. Indeed, the gas flow can be thought to belong to the category of flow in a porous medium, for which a vast Literature exists. The idea, which is common to many variable-porosity modelling attempts, is that the empirical laws expressing permeability in terms of porosity are considered to hold (locally) even in the case of variable porosity. Even if porosity often shows significant variations along few particle diameters (corresponding to the width of shear bands), it seems reasonable that a lumped empirical law can be thought as a height-averaged expression, thus it is local in the transversal direction, but contains global informations on the direction parallel to the flows.

In the following a perfect slip boundary condition will be used for the gas phase at the wall; for a more physically based calculation the no-slip boundary condition for the gas phase should be