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The measurement of powder flow properties with a mechanically stirred aerated bed

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ABSTRACT

This paper re-examines a set of experimental data published by Bruni et al. (2007a, 2007b) [Bruni, G., Barletta, D., Poletto, M., Lettieri, P., 2007a. A rheological model for the flowability of aerated fine powders. Chem. Eng. Sci. 62, 397–407; Bruni, G., Lettieri, P., Newton, D., Barletta, D., 2007b. An investigation of the effect of the interparticle forces on the fluidization behaviour of fine powders linked with rheological studies. Chem. Eng. Sci. 62, 387–396] carried out on a mechanically stirred fluid-bed rheometer (msFBR), which was developed to study the rheology of aerated and fluidized powders. The use of aeration below fluidization allowed to carry out experiments with powders at very low consolidation levels. Two mathematical models, based on the Janssen approach to evaluate stresses in powder containers, were developed in order to relate the torque measurements in the Fluidized Bed Rheometer to the flow properties of the powders measured with standard powder flow testers. Results indicate that the models were able to satisfactorily predict the torque measured by the msFBR. The larger complexity of the Walker (1966) [Walker, D.M., 1966. An approximate theory for pressures and arching in hoppers, Chem. Eng. Sci. 21, 975–997] and Walters (1973) [Walters, J.K., 1973. A theoretical analysis of stresses in silos with vertical walls, Chem. Eng. Sci. 28, 13–21] stress analysis adopted in one of the two models did not introduce significant improvements in the evaluation of the stress distribution to justify its use. A procedure for the inverse application of the model was developed and applied to estimate the powder flow properties starting from msFBR data. The application of this procedure provided good results in terms of effective angle of internal friction and is promising for the ability of the system to explore powder flow at very low consolidation states.

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1. Introduction

The flow properties of fine powders at very low consolidation levels are relevant to small scale industrial application of powder flow, such as in small process hoppers and mixers of pharmaceutical powders (Harnby, 2000), or in everyday applications such as toner flow in cartridges (Suri and Horio, 2009) and dosing and dispersion in dry powder inhalers (Daniher and Zhu, 2008).

Conventional shear testers are not suitable for testing flow properties of loosely consolidated powders unless special procedures are adopted (Schwedes, 2003). In particular, consolidation stresses lower than 500 Pa were obtained in annular shear cells by applying small normal loads and increasing the sensitivity of load cells (Schulze and Wittmaier, 2003) or by introducing a gas pressure gradient opposed to gravity through the powder sample (Klein et al., 2003; Johanson and Barletta, 2004; Barletta et al., 2007). Alternative techniques used to study the rheological properties of powders under loose conditions included the derivation of the tensile strength and of yield loci from fluidization experiments (Castellanos et al., 2004) and the derivation of cohesion and angle of friction from observations of the avalanching behavior of powders (Castellanos et al., 2007). Studies on the rheological behavior of slow dense powder flows were performed also by rotational rheometers of different geometries. In particular, Tardos and co-workers (Tardos et al., 1998, 2003; Kheiripour Langroudi et al., 2010) measured local normal stresses and the overall torque necessary to shear powders in a Couette device at different consolidation stresses obtained by varying the powder bed depth. Measurement results indicated that solid normal stresses show a linear hydrostatic profile from the bed free surface to the bed bottom while shearing both a low and at intermediate shear rates (dimensionless shear rates, defined as $\dot{\gamma}^* = \dot{\gamma}(d_p/g)^{0.5}$, between 0.1 and 1). These results differ from the experimental evidence that in static powder beds the solid normal stresses increase less than linearly up to an asymptotic value as predicted by the Janssen equation. Nevertheless, torque measurements confirmed a frictional behavior of powders at low shear rates and a "viscous" behavior at intermediate shear rates for which Tardos et al. (2003) and Kheiripour Langroudi et al. (2010) proposed

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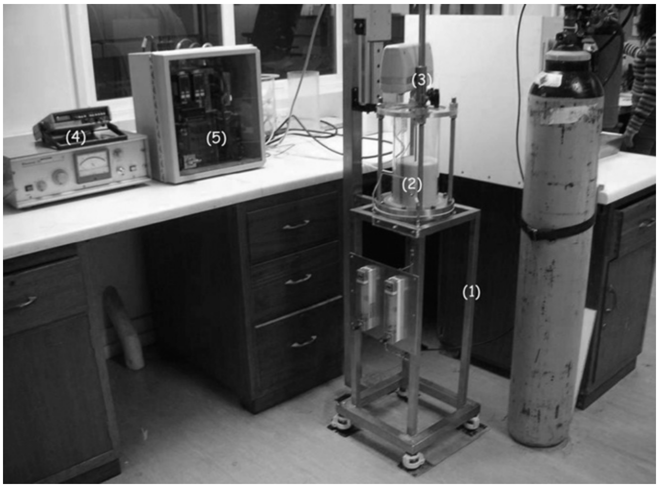

Fig. 1. The msFBR unit. It was mounted on a free standing, wheeled stainless steel frame (1), and consists of a fluidization unit (2), an agitating system (3), a data acquisition unit (4) and a control box (5).

a constitutive equation following a continuum mechanics approach. A mechanically stirred fluid-bed rheometer (msFBR) (Fig. 1) was developed by Bruni et al. (2005) to study the rheology of aerated and fluidized powders. This device, consisting in a fluidized bed column provided with a two-flat-bladed paddle impeller immersed in the powder bed and connected to a rheometer, was used for powders under aerated conditions below the fluidization threshold, allowing to measure powder flow properties at very low consolidation levels. In fact, the upwards gas flow produces a vertical gas pressure gradient, which acts on the solids as a body force opposed to gravity. The torque necessary to rotate the impeller was measured at different powder bed depths and gas pressure drops. Results obtained at very low shear rates (0.754 rpm, corresponding to a dimensionless shear rate between 3.5×10^{-5} and 7.5×10^{-5} depending on the particle size) revealed that torque vertical profiles followed the Janssen equation. Consequently, Bruni et al. (2007a) developed a model based on the method of differential slices (Janssen's approach) and on a Mohr–Coulomb description of the powder rheology to describe the powder stress state and the applied torque in the msFBR.

In the present study, the introduction of the Walker improvements (Walker, 1966; Walters, 1973) for the stress state in the model developed by Bruni et al. (2007a) following the Janssen approach was assessed. Moreover, a sensitivity analysis is performed in order to estimate the relative weight of the angle of wall friction on the prediction of torques. Finally, an inverse procedure to evaluate powder flow properties from torques is proposed.

2. The model

In order to predict the torques measured by the msFBR, a rheological model had been developed by Bruni et al. (2007a). To determine the stress distribution in the msFBR the original Janssen analysis for silo stress distribution had been generalized taking into account the air flow through the bed. According to this analysis, stresses had been assumed uniform across any horizontal section of the material. Furthermore, the axial and radial stresses, σ_z and σ_r, had been assumed as principal stresses.

The stress state in the msFBR had been evaluated solving the balance force on a differential slice of the cylindrical vessel as sketched in Fig. 2, which gives the following differential equation:

$$\frac{d\sigma_z}{dz}+\frac{4\tau_W}{D}=\rho_b g-\frac{dP}{dz} \tag{1}$$

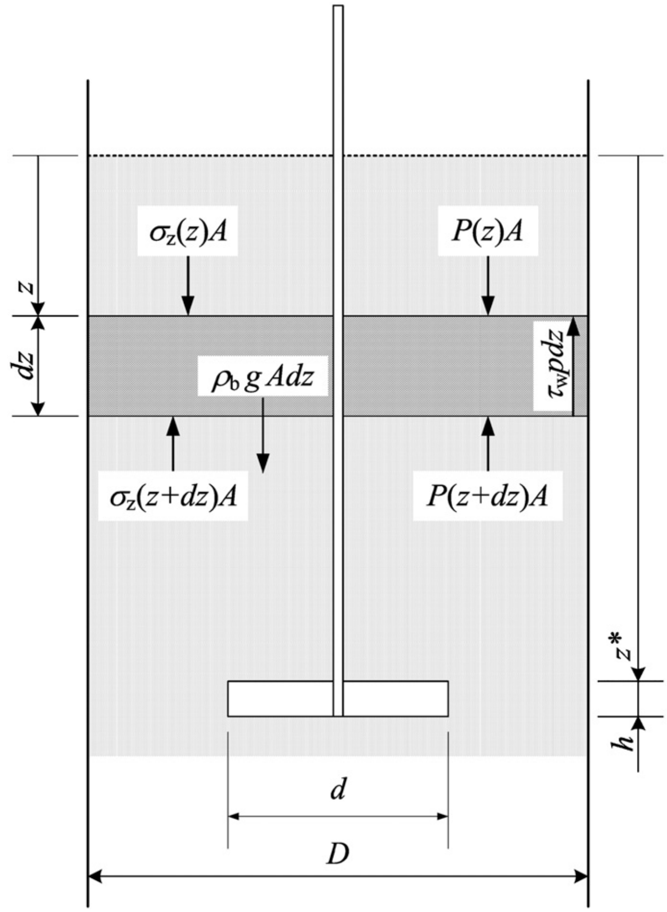

Fig. 2. Scheme of the msFBR with the most significant variables used in the models.

where τ_W is the shear stress acting on the wall, ρ_b is the bulk density of the powder and dP/dz is the pressure gradient of the air flowing through the bed and exerting a drag force opposed to the gravity. In order to solve this equation, a relationship between the wall shear stress τ_W and the vertical normal stress σ_z had been necessary, since ρ_b and dP/dz had been measured in each experiment and considered constant along all the bed. Following Janssen (1895), the wall yield locus and the ratio of the axial and radial stresses, K, had been introduced as the two relationships, which had allowed to solve the problem

$$\tau_W=\sigma_r(z)\tan\phi_W \tag{2}$$

$$K=\frac{\sigma_r}{\sigma_z} \tag{3}$$

where ϕ_W is the angle of wall friction.

Finally, the top surface of the bed of material had been assumed open to the atmosphere so that

$$\sigma_z(z=0)=0 \tag{4}$$

To evaluate the torque acting on the impeller in the msFBR, the shearing surface around the impeller had been assumed to be shaped like the flat cylinder described by the impeller rotation, having height h and diameter d equal to the height of the impeller paddle and to the double of the distance between the paddle tip and the shaft axis. It is assumed that the largest shearing action produced by the impeller is likely to be close to the impeller itself.

The resistant torque will be the sum of the contributions of the stresses acting on the upper surface, the lower surface and the

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