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Determination of the solid concentration in a binary mixture from pressure drop measurements

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A new and simple method to estimate the concentration of solids in a binary solids mixture is proposed and experimentally tested in a small fluidized bed set up. In the proposed method, it is necessary to measure the pressure drop in different sections of the bed at different gas velocities so as to be able to determine local minimum fluidization velocities using the Ergun equation. Because the minimum fluidization velocity of a solids mixture is known to be dependent on its weight fraction, a calibration curve can be derived by means of the Cheung equation and this is shown to be sufficient to obtain reasonably good estimates of the axial solids concentration profiles inside the bed. This methodology has been applied to three different mixtures of iron oxide ore of varying size with limestone or glass spheres. Satisfactory agreement between the experimental and calculated concentrations as well as pooled relative standard deviations lower than ±7%, are obtained in all three cases. This technique could facilitate future experimental research on solids mixing and segregation phenomena in fluidized beds, as it is a very low-cost, non-destructive and very fast method to determine solids concentration bed profiles.

1. Introduction

Fluidized-bed reactors containing solids mixtures are widely used in many industrial processes, such as, the chemical, food and pharmaceutical industries, as well as, in power plants and gas purification systems [1–3]. The presence of solids with different characteristics (i.e., size, density and/or shape) makes the hydrodynamic behaviour of these systems more complex to predict [4, 5]. Mixing and segregation phenomena may coexist during fluidization, giving rise to non-homogeneous solids distributions in axial and radial directions. In binary mixtures, the denser (and/or larger) particles (typically called jetsam) tend to fall to the bottom of the bed, while the lighter (and/or smaller) solids (usually referred to as flotsam) migrate to the top [6, 7]. A knowledge of local solids concentrations therefore is important for the design of the reactors and for the operation and optimization of the plants [8]. Also, models for the mixing and segregation of the solids in fluidized beds still require a substantial input of experimental information for validation purposes. Therefore, the accurate measurement of the concentration of solids in different parts of the fluidized bed is essential. Sampling or extraction of selected sections of the bed is perhaps the simplest and lowest cost method when investigating solids segregation in fluidized beds. This consists in taking samples from different points of the fluidized bed using a suction probe [9, 10]. The solids are subsequently sieved (or separated by other mechanical procedures) and weighed to obtain the local concentrations. However, this is a tedious, time-consuming, and highly intrusive measurement technique [11, 12].

Numerous techniques have been reported in the literature for quantifying the local concentrations of solids in fluidized beds, although only a few of them are suitable for binary mixtures [1, 8, 13–15]. There are sophisticated methods used not only to measure local solids volume concentrations, but also to accurately determine the axial and radial distribution of solids inside the bed in dynamic conditions, as well as solids mass flow profiles. Tomography methods are used to obtain images per section using X-ray radiation [16], magnetic resonance [17] or by measuring the electrical capacitance of the solids in motion [18]. These methods use a rotating sensor or several sensors arranged around the studied plane and the linear algorithms obtained allow a cross-sectional image of the plane to be reconstructed [19]. These techniques that have been applied to the study of the mixing and segregation of binary mixtures have been demonstrated to have a good penetration capability [14]. However, tomography techniques are generally complex and expensive, and their accuracy depends to a great extent on the sensitivity of the sensors [14, 15]. Attenuation and scattering methods based on x-rays, gamma-rays or sound waves are another alternative for measuring the spatial distribution of solids via the detection of changes in the absorption of radiation or the noises generated by particle collisions [1, 20]. These techniques are readily applicable in a wide range of experimental conditions, but in many cases they are expensive due to the

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complexity of the sensor and the need for protection against the radiation [14, 15]. Capacitance measurement techniques can be used to obtain the concentration of solids by means of several electrodes that register the changes in the dielectric constant of the phase present between the electrodes [21, 22]. Electrostatic probes, on the other hand, measure the electrical charge acquired by the particles during fluidization when they impact against the walls [23]. Both capacitance and electrostatic probes are generally inexpensive and simple to implement but too sensitive to moisture content and particle size [14].

When the solids have different visual characteristics and the experiments can be carried out in transparent wall apparatus, digital imaging analysis can be used to study solids circulation patterns and to calculate extensive or local properties in fluidized beds [24–27]. This is a non-intrusive visualization method in which physical flow disturbances (typically created by intrusive probes) are avoided [28, 29]. Images are taken by high-speed digital cameras and specific software is used for image acquisition, data processing and analysis. The local concentrations of solids can be directly obtained from an analysis of image properties (i.e., when the particles are sufficiently large to be identified in the image) [30] or by means of calibration procedures in which the concentration is related to pixel luminance [31, 32].

In this work, a simple non-destructive procedure is proposed to calculate the concentration of solids in binary mixtures in fluidized beds from the measurement of the pressure drop at different sections along the bed. Below, we outline the principles underlying the method and describe the experiments carried out for its validation.

2. Method

The method proposed for calculating the concentration of solids in a binary mixture is based on the empirical correlation (Eq. (1)) reported by Cheung et al. [33], which shows the dependence of the minimum fluidization velocity of the mixture (u_{mf}) on the minimum fluidization velocity of the pure components (u_p and u_f) and the weight fraction of the solids in the bed (x_p, $x_f = 1\text{-}x_p$).

$$u_{mf} = u_f \left(\frac{u_p}{u_f}\right)^{x_p{}^b} \tag{1}$$

where the subscript *p* refers to the component with the highest minimum fluidization velocity, *f* refers to the component with the lowest minimum fluidization velocity and the parameter b is a constant value ($b = 2$) in the original equation [33]. However, in the procedure proposed here, b is considered an adjustable parameter which depends on the characteristics of the solids mixture and it should therefore be determined by calibration.

In order to use Eq. (1), it is first necessary to calculate the minimum fluidization velocities of the individual components, u_p and u_f. A standard procedure [34] is followed, where the pressure drops measured at different points of the bed are recorded at increasing gas velocities. After that, the minimum fluidization velocity can easily be calculated by means of the Ergun equation [35], which for a laminar regime is as follows:

$$\left(\frac{\Delta p}{L}\right)_{max} = \left(150\frac{(1-\epsilon_{mf})^2}{\epsilon_{mf}^3}\frac{\mu}{(\phi_s d_p)^2}\right)u_{mf} \tag{2}$$

where d_p is the average particle diameter, μ is the gas viscosity, ϕ_s represents the particle sphericity and ϵ_{mf} the bed porosity for the conditions of minimum fluidization. The value of the maximum pressure drop of the bed (i.e., the value represented by a bold black line in Fig. 2a and b) is obtained according to Eq. (3):

$$\left(\frac{\Delta p}{L}\right)_{max} = \frac{M_s\, g}{A_{column}\, L} \tag{3}$$

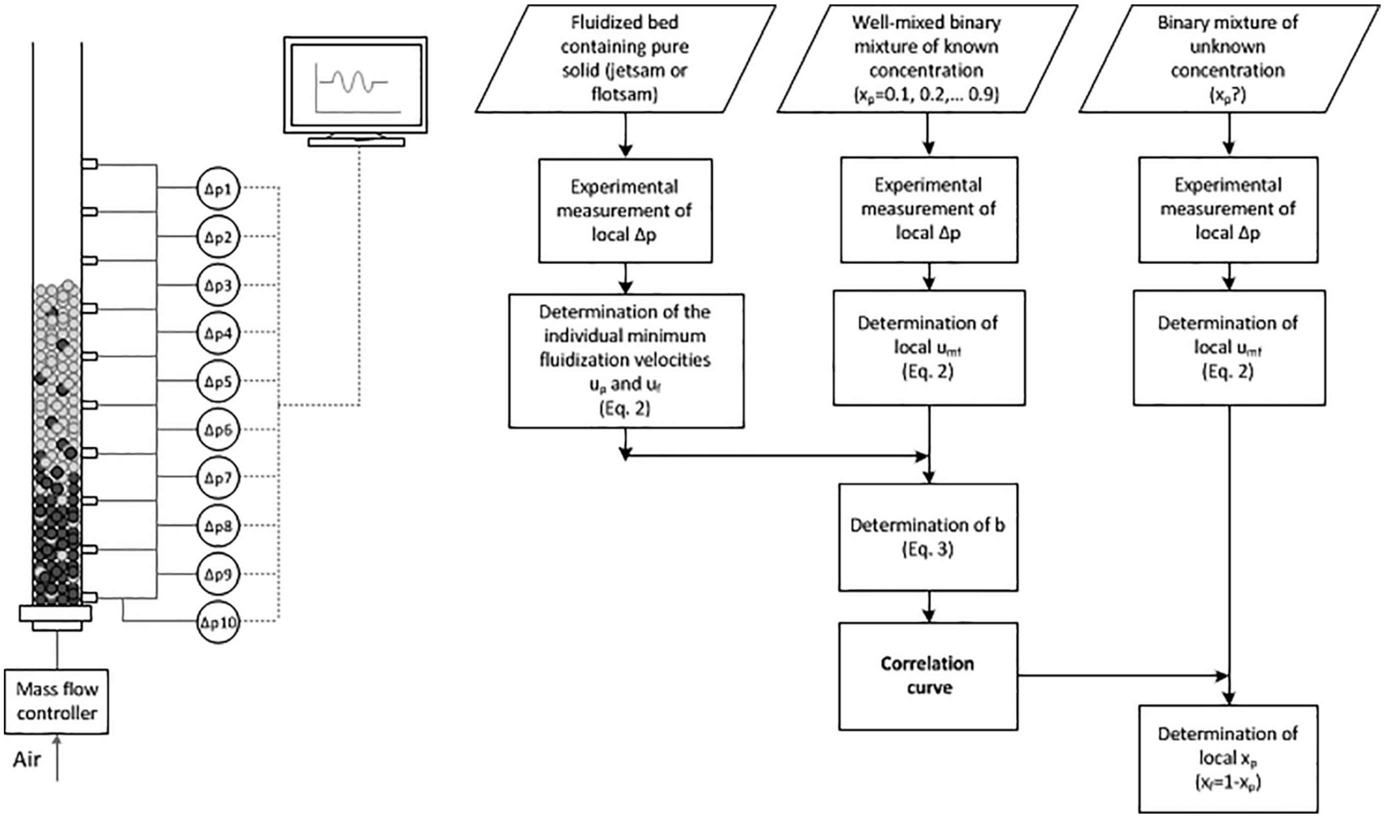

Fig. 1. Schematic diagrams of the experimental setup and of the procedure for the calculation of the solids concentration.