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Modeling of solid–gas flow fields via a correlation study

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ABSTRACT

A correlation study for modeling of solid–gas flow fields is presented with an emphasis to the extents of single phase gas flow through stationary vertical packed beds of solid particles and dilute phase flow of suspended solid particles in horizontal channels. The experimental data in terms of local static pressure gradients dP/dx in flow direction are processed. The referred test cases are (i) horizontal air flow with fully suspended fine solid particles of the size range $75.5\ \mu m \le d_p \le 275\ \mu m$ for the magnitudes of superficial air velocity; $U \gg$ minimum fluidization velocity; U_{mf}, (ii) air flow through a vertical fixed packed bed of solid particles with $d_p = 6000\ \mu m$ for $U \ll U_{mf}$. The visual observations at $U = U_{mf}$ through the vertical beds of solid particles with d_p range; $150\ \mu m \le d_p \le 2750\ \mu m$ are also referred.

A non-dimensional mode parameter P^* is defined using well-known permeability parameter P_f, mixture density ρ_m and a time parameter t^* as an original contribution. The proposed relationships of P^* with air flow Froude Number, Fr and solid particle Froude number Fr_s determine the limits of the flow fields. The magnitude of P^* is 1150 for stationary packed solid particles with $Fr \le 2$. Meanwhile $P^* \le 2$ corresponds to the dilute phase flow of solid particles in air for $Fr_s \le 60$. The proposed equations can also be used for the determination of solids velocity U_s, U and U_{mf} in the cited limits of Fr_s, Fr with an acceptable error margin of $< \pm 24\%$.

1. Introduction

In spite of the available historical background in the field of multiphase flows [1], the measurement of velocities of particles and interfaces is still a fertile ground for experimental and theoretical research. In the last years, considerable progress in the fast imaging techniques for multiphase flow fields is denoted. Ultrafast X-ray tomography, magnetic resonance imaging, electrical tomography, fast gamma-ray tomography are on site besides the conventional particle image velocimetry and laser doppler anemometry. The measurement of disperse phase velocities is commonly by the application of cross-correlation techniques. Barthel et al. in their recent study [2] discussed on different methods to determine velocity information in a variety of two-phase fields. They developed a method and an algorithm apart from standard cross-correlation technique based on ultrafast X-ray tomography. They used the algorithm for the determination of single bubble velocities, on a gas–particle flow and in continuous-phase velocity fields. Ultrafast X-ray technique is a non-intrusive flow capturing one without an optical access to the field. Its major advantage is specified as its applicability to flows with solid particles such as in fluidized beds and particle conveying channels. Therefore velocity measurement (and/or determination of velocity) in a 2-phase flow field which is particularly defined as a solid–gas one in this paper, and development of a model have of significant scientific importance. Furthermore from the point of view of industrial applications a clear understanding of the velocity field is critical for the optimum conditions of design and operation of pneumatic conveying systems and fluidized beds. It is known that dense (fluidized dense phase or plug) and dilute phase flows are defined using either particle parameter or fluid–particle-based methods. The control of flow mode is due to the technological requirements (e.g. plug flow conveying is better for coarse particles' transport [3]). The dense phase flow capability has a stronger dependence on particle material and/or geometrical characteristics than the one of dilute phase which is mainly governed by particle–air flow interaction. There exists numerous efforts on the flow mode specification [4–7]. The preferred particle parameters are density ρ_p, and size d_p. Particle–air flow interaction is described by permeability, P_f, and loose poured bulk density ρ_{blp} whose definitions are given below:

$$P_f = U/(dP/dx) \tag{1a}$$

$$\rho_{blp} = \rho_p(1-\epsilon) \tag{1b}$$

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where ε is bulk voidage.

Permeability shows how air flows through a granulated material besides a number of other fluidization and de-aeration terms [8–10]. Although there are approaches to define the border between dilute flow and plug flow [4] as the one given by (Eq. (2)) there is no consensus and even no general correlation on the limits of P_f covering the extensive ranges of the relevant particle and flow parameters:

$$P_f = U_{mf}/\left(dP/dx\right)_{mf} = 20 \times 10^{-6} \tag{2}$$

where $(dP/dx)_{mf}$ is the critical magnitude of static pressure gradient at U_{mf}.

In some of the studies, characteristics of frictional field are used to investigate the differences in flow modes. The frictional force which models particle–particle and particle–wall interactions in pneumatic lines is usually sensed by pressure drop measurements [11–14]. Meanwhile Li et al. [15] evaluated particle flow pattern, gas pressure drop, solids concentration and particle velocity for a horizontal pneumatic conveying case numerically. The flow mode studies which are usually originated from the industrial necessities have a great range of the parameters with different experimental restrictions. If a general functional relationship between widely accepted non-dimensional parameters which set the extents of flow modes was available it would provide considerable practice.

A simple method for the specification of the flow modes in the cases of solid–gas flow fields is aimed founded on Master of Science studies [16–18] and the research projects [19,20] completed under author's advisorship since 1999. The previously published experimental data in terms of measurements of dP/dx in a fully suspended flow of fine particles [21] in a horizontal line and through a fixed bed of coarse particles [22] in a vertical line are processed under the light of recent studies [23,24]. The model is checked in reference to the current experimental data at the minimum fluidization state of a variety of vertical packed beds [20]. The modeling route is ended by a correlation study through which the definition of a common non-dimensional parameter is introduced. Mode parameter, P^* is such that the influence of the flow direction, bulk voidage, superficial gas velocity U and the velocity of the solid particles, U_s are taken into account for a great range of d_p; $75.5\ \mu\text{m} \leq d_p \leq 6000\ \mu\text{m}$. The influence of solids particle, Fr_s and airflow Froude number, Fr on P^* are given via proposed functional relationships of $P^*=P^*(Fr_s)$ and $P^*=P^*(Fr)$. The equations fitted to the experimental data provide flow mode limits in terms of P^*, Fr_s and Fr and a practical mean for the measurement of velocity in solid–gas flows.

2. Outline of the referred experimental data

The flow measurements were conducted inside horizontal dilute phase flow of solid particles and through a variety of packed beds of solid particles. The informative sketches are given in Fig. 1. The measurements of local static pressure, P were done by using static pressure rings-tappings installed according to BS 1042 [25]. The local static pressure gradients, dP/dx were calculated in turn. The cross-sectional velocity field distribution was covered by a Pitot tube-traverse in combination with local P measurements [25]. Inclined leg alcohol micro-manometers were used in the measurements. The pressure measurement sensitivity was as low as 0.35 Pa and the sensitivity in the measurement of U was ± 0.24 m/s. The nature of flow for the considered studies was fully

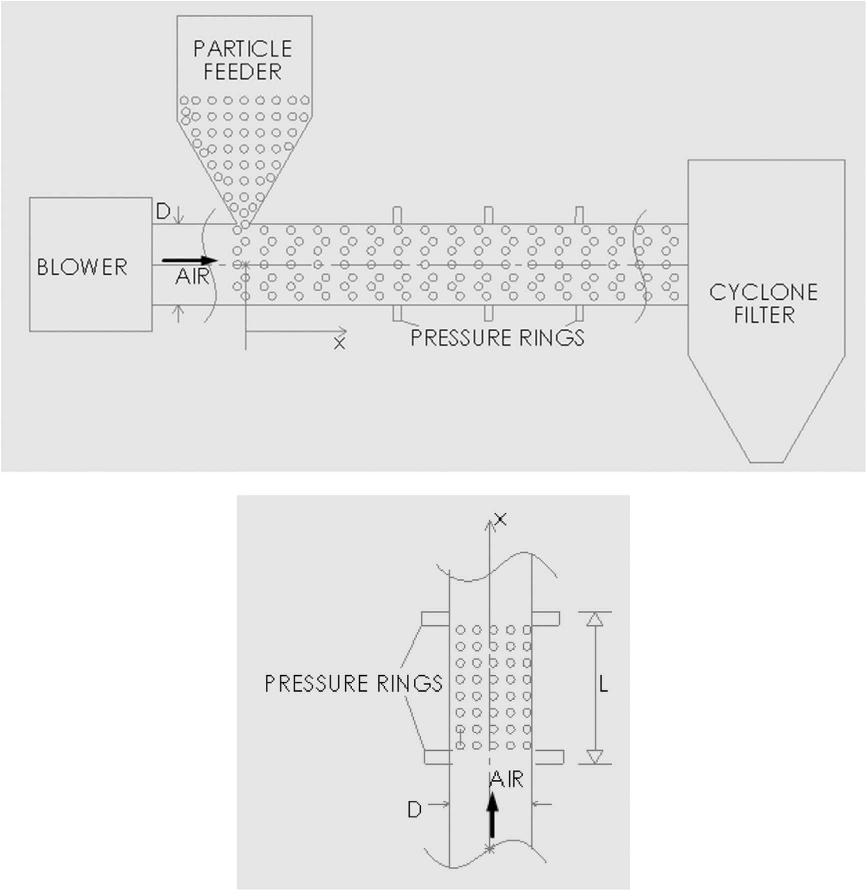

Fig. 1. Informative sketches.

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