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A comparison of magnetic resonance, X-ray and positron emission particle tracking measurements of a single jet of gas entering a bed of particles

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HIGHLIGHTS

- Magnetic resonance, PEPT and X-ray radiography were used complementarily.
- Length of jet of gas entering bed of Group B particles via 2 mm id orifice measured.
- Lengths were in good agreement for orifice velocities 50–100 m/s.
- Technique developed to use PEPT measurements to quantify jet length.

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ABSTRACT

Measurements of the lengths of a single jet of gas entering a packed bed were made using magnetic resonance imaging (MRI), positron emission particle tracking (PEPT) and X-ray radiography and the results compared. The experiments were performed using a Perspex bed (50 mm i.d.) of poppy seeds: air at 298 K was admitted to the base of the bed through a single, central orifice, 2 mm in diameter. Poppy seeds (Geldart Group B, measured minimum fluidisation velocity with air at 298 K and 1 atm of 0.13 m/s and particle density ~1060 kg/m^3) were used because of their high content of oil, which contains mobile protons and hence is suitable for MRI examination. The lengths of jet measured using the three techniques were in agreement between 50 m/s < U_o < 100 m/s, where U_o is the superficial velocity through the orifice. Below U_o=50 m/s, X-ray measurements of jet lengths were shorter than those measured using MRI. This was attributed to the minimum diameter of void, found to be 5 mm, detectable in a 50 mm bed using ultra-fast X-ray measurements. PEPT is most commonly used to calculate particle velocities, whilst jet lengths are usually calculated from determinations of voidage. However, the particle locations determined in this work by PEPT were used to calculate a fractional occupancy count, from which a jet length could be inferred.

1. Introduction

Advances in measurement technologies and computing power have led to a new generation of non-invasive measurement techniques, such as Magnetic Resonance Imaging, X-ray Computed Tomography and Electrical Capacitance Tomography, to investigate gas–solid fluidisation. Ideally, a non-invasive measurement technique would be capable of measuring both voidage and velocities of particles to a high spatial and temporal resolution across a range of length scales in three-dimensional beds. However, no such technique currently exists with all these attributes, thus a range of methods is needed to investigate fluidisation phenomena. In order to use different methods reliably, they must be cross-validated to ensure that the same phenomena are seen identically. Here, three techniques were cross-validated: Magnetic Resonance Imaging (MRI), ultra-fast X-ray radiography and Positron Emission Particle

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Tracking (PEPT). To reduce discrepancies arising from the experiment itself, the techniques were compared by imaging the same, temporally-stable system: a single, axisymmetric jet in a packed bed of Geldart Group B particles. This system is reproducible and gives the same jet shape and size when set up in different laboratories.

Previous investigations of jets in 3D beds have used pressure signal analysis (Vaccaro et al., 1997), optical probes (Wen et al., 1981, Blake et al., 1990), triboelectric probes (John et al., 1980; Berruti et al., 2009) and thermal tracer methods (Berruti et al., 2009, McMillan et al., 2005, Zhu et al., 2000). These methods are easy to use in large-scale, opaque industrial systems, but require the use of probes that distort the jet flow. X-ray radiography has been used to image beds non-invasively but early work was limited to projections through the bed which did not allow local values of properties to be calculated in 3D beds (Cleaver et al., 1995, Rowe et al., 1979). Magnetic resonance imaging (MRI) allows non-invasive imaging of gas–solid fluidised beds to a high spatial resolution, hence making it suitable for geometrical studies of jets (Müller et al., 2009). MRI is, generally, limited to measurements in small, non-metallic beds. However, the technique offers a new approach to studying, non-intrusively, the impact of walls on the behaviour of jets (Pore et al., 2012).

Much of the early work on jetting was conducted in 2D beds to allow visual measurement. However, when correlations from 2D and 3D beds (*e.g.* Blake et al. (1990), Müller et al. (2009) and Merry (1975)) are compared, those based on observations in 2D beds usually predict longer jet lengths than those from 3D beds. This suggests that the wall effects in 2D beds are significant and act to stabilise jets. Wen et al. (1981) also noted that longer jets were formed in 2D or semi-cylindrical beds compared to those in 3D beds, and therefore concluded that jet length correlations developed for 2D beds could not be applied to 3D systems. Even allowing for the difference between 2D and 3D, there remain large discrepancies amongst the correlations, arising from:

(1) The definition of a jet.
(2) The definitions of the geometrical parameters of jets.
(3) The experimental arrangement used.
(4) The measurement technique and method of data analysis used.

Jets have been defined in various ways. Thus, a jet could be (a) a permanent, temporally-stable void formed above the orifice (known as a permanent jet), or (b) a permanent region of high voidage above the orifice from which bubbles are formed and detach (known as a pulsating jet), or (c) a stream of bubbles formed at the orifice. As a result, the definitions of geometric parameters, such as jet length (L_j), jet diameter (D_j) and jet angle (θ), vary significantly between studies, *e.g.* those of Müller et al. (2009), Rees et al. (2006) and Cleaver et al. (1995). Various types of experimental arrangement have been used to measure jet phenomena, including a wide range of types of distributor, and with the bed held at various fluidising velocities.

Finally, the measurement technique and analysis of the subsequent results can also lead to discrepancies among studies. Early studies measured jet parameters using optical or probe measurements, which require relatively simple analysis of the raw results. Advances in computing and hardware have led to the use of tomographic techniques, which have the capability to image optically-opaque, three-dimensional systems non-invasively, unlike earlier optical and probe measurements. However, there is still potential for discrepancies between measurements using different imaging techniques, due either to the capability of the measurement technique itself or the reconstruction and analysis of images.

2. Experimental

2.1. Fluidised bed

Experiments were performed using a bed of poppy seeds fluidised with air at 298 K. Poppy seeds were used because of their high content of oil, which contains mobile protons and hence are suitable for MRI examination. The seeds had a diameter of 0.5 mm and particle density ~1060 kg/m^3 (Geldart Group B) with a measured minimum fluidisation velocity (U_{mf}) with air at 298 K and 1 atm of 0.13 m/s. The height of the bed when slumped was constant at 115 mm. The bed was contained in a 50 mm i.d. Perspex (polymethyl methacrylate) column, fitted with a distributor with a single, central orifice of diameter 2 mm, (shown schematically in Fig. 1). The plenum chamber had a volume of ~200 cm^3 to dampen fluctuations in gas pressure from the compressed air supply (regulated at 1 barg). The same apparatus was used to make measurements with all three imaging techniques.

The particles were loaded by pouring them into the empty bed with gas flowing at the minimum superficial velocity, U_{mf}, a technique found to improve the reproducibility of the experiments (Müller et al., 2009). Measurements were made for a succession of gas superficial velocities, U, starting at 0.30 m/s (corresponding to a velocity through the orifice, U_o=187 m/s) and progressively reduced to 0.04 m/s (U_o=23 m/s), allowing ~100 s for the bed to stabilise after each reduction in the superficial gas velocity.

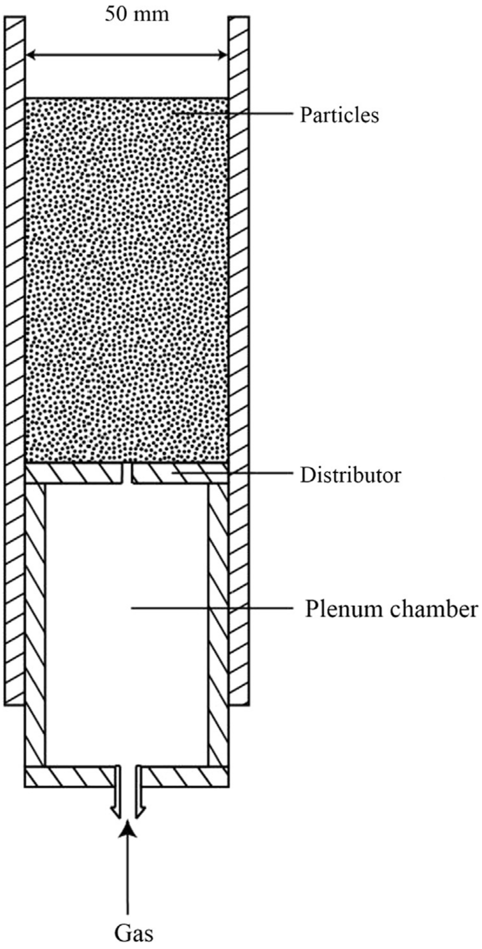

Fig. 1. Schematic diagram of the bed. The distributor contained a single, central orifice with an orifice diameter, d_o, of 2 mm.