Chemical Engineering Science 109 (2014) 276–283

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Magnetic resonance imaging (MRI) of jet height hysteresis in packed beds

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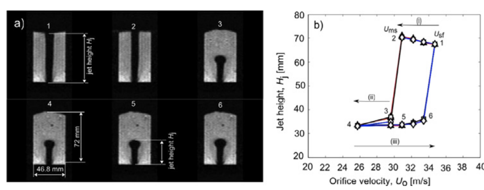
HIGHLIGHTS

- Magnetic resonance imaging is used to image jets and spouts in packed beds.
- We study the role of particle type, bed size and fill on the jet–spout transition.
- We propose a criterion to predict hysteresis in the jet–spout transition.
- The effect of particle sphericity on the minimum spouting velocity is shown.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 November 2013
Received in revised form
22 January 2014
Accepted 30 January 2014
Available online 13 February 2014

Keywords:
Packed beds
Spouting bed
Hysteresis
MRI
Jet height
Minimum spouting velocity

ABSTRACT

The hysteresis in the jet–spout transition in packed beds was systematically investigated using magnetic resonance imaging (MRI) and pressure measurements. Specifically, the hysteresis in the jet height as a function of the orifice velocity was studied as a function of particle type, bed dimension and fill level. In order to compare the hysteresis of different experimental configurations, a hysteresis coefficient $h=(U_{sf}-U_{ms})/U_{sf}$ was introduced. It was observed that an increase in the fill level or the bed dimensions resulted in higher values of h. It was also found that the hysteresis is most pronounced for non-spherical particles, whereas no hysteresis was observed for the most spherical particles when placed in the smallest bed. In addition, pressure measurements were used to explore the relationship between the pressure drop and the jet height.

1. Introduction

Injecting a gas through a single orifice with a sufficiently high velocity into a container filled with macroscopic, *i.e.* typically Geldart D, particles results in a bed with a fountain-like appearance. Such beds are commonly called spouted beds and are used in industry to dry, granulate, separate, mix, gasify, pyrolyse or combust solids (Epstein and Grace, 2010). However, despite their industrial relevance, various fluid-dynamic aspects of spouted beds are still not fully understood. This lack of fundamental understanding is well demonstrated by the large number of different correlations which have been proposed to determine the minimum spouting velocity (U_{ms}). A comprehensive review of correlations for U_{ms} was conducted by Bi et al. (1997). The minimum spouting velocity is defined as the velocity at which a spout collapses and an immersed jet is formed, *i.e.* the surface of the bed is flat and undisturbed. Interestingly, the transition from an immersed jet to a spout often occurs at a different orifice velocity, which is referred to as the spout forming velocity (U_{sf}). For the case that $U_{ms} \neq U_{sf}$ there is hysteresis in the jet–spout transition. This intriguing phenomenon was studied by Wang et al. (2005) and Wen and Bi (2011a, 2011b), who developed a numerical model to predict the jet height and the pressure drop across the bed as a function of the

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http://dx.doi.org/10.1016/j.ces.2014.01.038
0009-2509

injected flow rate of the gas. The authors tried to explain the observed hysteresis by considering particle interlocking and bed compaction. Additionally, Wang et al. (2005) and Köhl et al. (2013) found that, respectively, the pressure drop across the bed and the jet height were affected significantly by the measurement procedure employed.

Hysteresis in jet length can also be observed without the formation of a spout. In this case the jet length obtained by increasing the orifice velocity to a value U_o is different from that obtained by increasing the orifice velocity to above the desired value and then decreasing the velocity back to U_o. Jet length hysteresis for vertical gas injection was studied by Apte et al. (1988, 1990) and Gupta et al. (2005) studied the hysteresis caused by a horizontally injected gas stream. Based on a force balance for increasing and decreasing gas flows, Gupta et al. (2005) developed an analytic model to predict the hysteresis loop for a horizontally injected stream. Reasonable agreement between the model predictions and the experimental measurements was reported. The occurrence of a hysteresis loop was attributed to the changing direction of frictional forces between particles for increasing and decreasing gas velocities. Despite various reports concerning jet hysteresis, the effect of particle shape on hysteresis has not been studied in detail. However, it is known that the sphericity of the particles strongly affects their packing, *e.g.* Cho et al. (2006). Thus, it is likely that particle sphericity will strongly influence the minimum spouting and spout forming velocities and, in turn, the hysteresis characteristics of the system. The poor understanding of the formation of jets and spouts and the transition between these two operating regimes can be attributed to the very limited number of experimental techniques available to acquire 3D measurements in opaque particle systems. Non-intrusive measurement techniques capable of making these measurements include positron emission particle tracking, *e.g.* Stein et al. (1997), electron capacitance tomography, *e.g.* Marashdeh et al. (2008) and X-ray tomography, *e.g.* Rowe and Everett (1972). In this study we apply magnetic resonance imaging (MRI). MRI is a routine technique for medical diagnostics, and its unique capabilities in particle systems have been described recently by Müller et al. (2006, 2007, 2008) and Holland et al. (2008).

Jets can also be formed in fluidised beds, particularly when a perforated plate is used as a distributor. The formation of jets in these systems and the interaction between jets have been studied by Rees et al. (2006) and Pore et al. (2012).

The MRI measurements acquired in this study, complemented by measurements of the pressure drop in the bed, allowed us to study the effect of particle type, bed dimension and fill level on the hysteresis in the relationship between the jet height and the orifice velocity in spouted beds.

2. Experimental setup

Beds of square cross-sectional area were constructed from sheets of poly-methyl-methacrylate (PMMA). A schematic of the square distributor plates is given in Fig. 1(a, b). The side-length of the central square orifice was $L_o = 3.6$ mm, whereas the side-lengths of the distributor plates were either $L = 72$ mm or $L = 46.8$ mm. The distributor plate had a thickness of 4 mm and the pressure drop across the orifice was at least 150 Pa for all measurements. The orifice velocity was controlled using flow-controllers. For the Iceland and opium poppy seeds an Analyt GFC47 flow-controller was used. For the orifice used in this work this flow-controller allowed the orifice velocity to be controlled with an accuracy of ± 0.13 m/s. For the mustard seeds an Aalborg GFC57 flow-controller was used due to the larger flowrates required. For these experiments the orifice velocity could be determined with an accuracy of ± 1.3 m/s.

The diameter, density, minimum fluidisation velocity (U_{mf}), angle of repose and sphericity of the particles used are summarised in Table 1. The particle diameters reported in Table 1 have each been averaged from 10 particles and the standard deviation of this sample is reported for each particle type. The projected area of the seeds as shown in Fig. 1(c–e) was obtained using optical microscopy. It is important to notice that the shape of the different seeds used covered a wide spectrum ranging from highly non-spherical (Iceland poppy seeds) to almost spherical (mustard seeds). The sphericity, defined as $S = (V(d_p)/V_{measured})^{1/3}$ by Mohsenin (1986), was determined by calculating $V(d_p) = \pi d_p^3/6$ from the projected area-equivalent particle diameter d_p and the volume $V_{measured}$ determined by measuring the volume of water displaced by the particles.

3. Measurement procedure

The formation of a jet or a spout in a bed of seeds was imaged non-intrusively using magnetic resonance imaging (MRI). A detailed

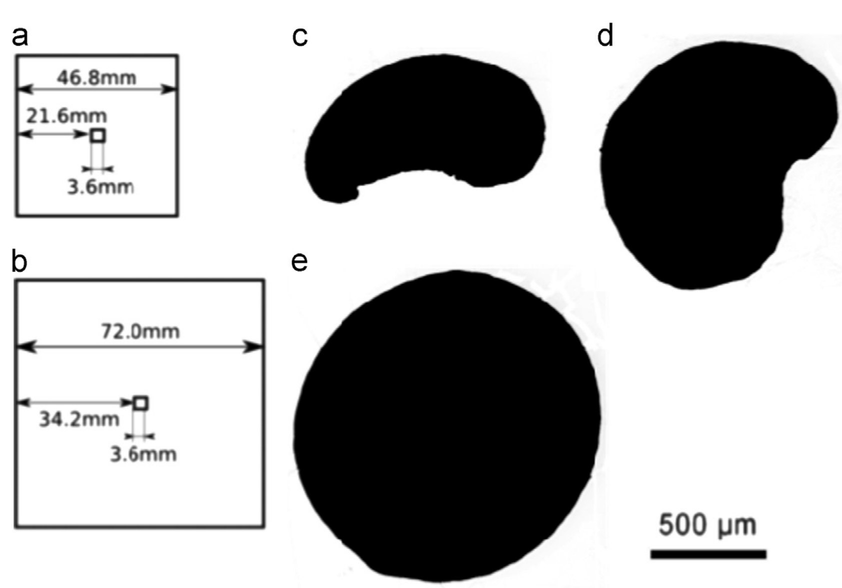

Fig. 1. (a, b) The distributor plates and particles used in this study, (c) Iceland poppy seeds, (d) opium poppy seeds and (e) mustard seeds.