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Refereed Proceedings

2013

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Recommended Citation

Maximilian H. Kohl, James R. Third, Klaas P. Prussmann, and Christoph R. Muller, "A Magnetic Resonance Imaging (MRI) Study of the Formation and Interaction of Spouts and Jets" in "The 14th International Conference on Fluidization – From Fundamentals to Products", J.A.M. Kuipers, Eindhoven University of Technology R.F. Mudde, Delft University of Technology J.R. van Ommen, Delft University of Technology N.G. Deen, Eindhoven University of Technology Eds, ECI Symposium Series, (2013). http://dc.engconfintl.org/fluidization_xiv/81

A MAGNETIC RESONANCE IMAGING (MRI) STUDY OF THE FORMATION AND INTERACTION OF SPOUTS AND JETS

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ABSTRACT

Magnetic Resonance Imaging (MRI) was used to image non-intrusively the formation and interaction of jets and spouts. It was found that the formation and interaction of jets is critically affected by the particle size and shape, the bed dimensions and the fluidization history.

INTRODUCTION

Fluidization is the process that transforms a static, packed bed of particles into a liquid-like state. The bed becomes fluidized when the pressure drop across the bed is equal to the weight of the bed per cross sectional area. One of the major advantages of fluidized beds over other gas solid reactors is their excellent heat and mass transfer characteristics. However, despite their widespread application, fluidized beds are still only poorly understood on a fundamental level. The poor physical understanding of fluidized beds can be explained, at least partially, by the small number of measurement techniques that can probe non-intrusively the dynamics of these systems, *e.g.* positron emission particle tracking [1], electron capacitance tomography [2], X-ray attenuation [3] or magnetic resonance imaging (MRI) [4],[5],[6]. An important phenomenon in gas-fluidized beds is the formation of jets and spouts since they critically influence bed mixing as well as heat and mass transfer. Thus, it is important to acquire detailed information about the geometry and interaction of jets and and spouts. For example, Rees et al. [7] studied the geometry of jets described by their jet half angle, their initial angle of a jet and jet height, forming at multi orifice distributors containing 15 - 37 holes. The jet parameters determined from the MRI measurements were subsequently correlated with the orifice velocity and the pitch size. Pore et al. [8] extended the work of Rees et al. [7] and studied jet-jet and jet-wall interactions. An attractive interaction between jets and jets and walls was reported for separating distances less than approximately 13 mm. However, an important jetting phenomenon which has not been considered in fluidized beds is the hysteresis in jet height. Indeed, the pressure drop across the bed [9],[10],[11] and the packing density of the bed [12] are not only a function of the gas velocity but also the fluidization history. This hysteretic behavior has also been observed recently in numerical simulations [13],[11],[10]. In this study we extend the work of [8],[7] by systematically investigating the effect of bed and particle parameter on the jetting characteristics.

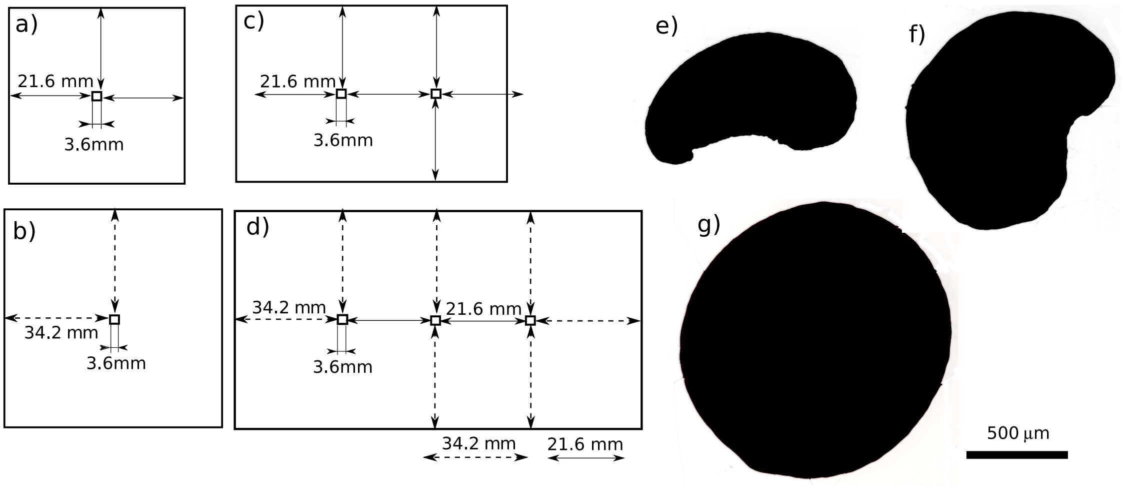

Figure 1: (a,b,c,d) schematic sketches of the distributor plates and (e,f,g) optical microscopy images of the seeds used: (e) Iceland poppy seeds, (f) opium poppy seeds and (g) mustard seeds.

Paticle type	Diameter d_p [mm]	Density ρ_p [kg/m^3]	Minimum fluidization velocity U_{mf} [m/s]	Sphericity[1] S
Iceland poppy	0.74 ± 0.08	1120	0.17	0.61
Opium poppy	0.94 ± 0.04	1090	0.24	0.84
Mustard	1.34 ± 0.18	1130	0.41	0.98

Table 1: Particle diameter, density and minimum fluidization velocity of the seeds used.

SETUP

The beds (square cross section) were constructed of poly-methyl-methacrylate (PMMA). The dimensions of the distributor plates used are shown in Fig. 1(a). The size of the orifice (square cross-section) was kept constant with a side length of L_o = 3.6 mm. The properties of the seeds used *i.e.* their diameter, density and minimum fluidization velocity (U_{mf}) are summarized in Table 1. The projected cross-sections of the seeds, obtained using optical microscopy, are given in Fig. 1. It is worth noticing that the poppy seeds are highly non-spherical, whereas mustard seeds are roughly spherical. Magnetic resonance imaging (MRI) was applied to image non-intrusively the formation of jets in a bed of seeds. For a detailed description of the MRI technique the interested reader is referred to *e.g.* [15]. Here, MRI measurements were performed in a Philips 3T Achieva system equipped with dual Quasar gradients. The maximal gradient strength and slew rate were 40 mT/m and 200 mT/m/ms, respectively. A 2D spin echo sequence of repetition time 1500 ms, echo time 12.4 ms and flip angle 60° was used to image the bed of particles. The voxel size was 1 mm × 1 mm × 1 mm. The MR signal was obtained from the seeds (grey-coloured voxels) whereas no signal was obtained from the gas (black voxels).

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[1] S = [(particle volume)/(volume of circumscribed sphere)]$^{1/3}$ [14]

OBSERVATIONS AND DISCUSSION

Shape of single jets

Fig. 2(a-d) shows jets forming at a single orifice. The jets possess a highly symmetrical shape. It was found that the height and the shape of the jets was affected by (i) the size of the bed particles (ii) the dimension of the bed (iii) and the fluidization history. For example, the images shown in Fig. 2(a,b) and (c,d) were obtained in a bed containing, mustard (d_p = 1.3 mm) and Iceland poppy seeds (d_p = 0.7 mm), respectively. From Fig. 2(a-d) it can be seen that jets forming in a bed of mustard seeds are wider and higher orifice velocities are required form a jet. The larger jet width in these, large particle, systems can be explained by an increasing gas expansion angle with increasing particle size [16], whereas the higher orifice velocities, are probably due to increased gas leakage with increasing particle size. Additionally, Fig. 2(a-d) shows that also the dimensions of the bed can dramatically influence the jet geometry, in particular for the case that jets form in a small bed containing large particles as in the system imaged in Fig. 2(b). We believe that in these jet height increases due to the confinement of the gas flow by the side walls, resulting in a bed (partially) approaching minimum fluidization. Filla et al. [16] measured jet angles in 2D beds and found that jets forming in beds of larger or particles have wider jet angles. It is assumed that the increased friction between non-spherical particles result in more "stable" packings and consequently in smaller jet angles. As shown in Fig. 2(e) the fluidization history of the bed also influences the jetting behaviour, *i.e.* if the jet height is plotted as a function of orifice velocity a hysteresis loop is observed. The hysteresis loop can be explained by the occurrence of different packing densities in beds subjected to increasing or decreasing velocities.

Jet-jet and jet-wall interaction

Fig. 3(a) shows jets forming at a distributor containing two orifices. It can be seen that for these configuration the tips of the jets are pointing towards each other at higher orifice velocities. These particular jet shapes are probably indicative of jet-jet interactions leading to a 'merging' gas flow at the centre of the bed. Furthermore, at high orifice velocities the two jets are not of equal height, *i.e.* the left jet has a height of 19.3 mm whereas the right jet is 18.2 mm high. However, reducing the orifice velocity to U_o = 8.4 m/s resulted in straight jets of equal height, *i.e.* 25 mm Fig. 3(b). To prove that that bending of the jets towards each other is indicative of a jet-jet interaction, one orifice of the two-orifice distributor was blocked (Fig. 3c) Interestingly, in this configuration the tip of the jet turned towards the wall, indicating a jet-wall interaction. The distances between the two orifices and the orifice and the wall are 21.6 mm which is outside the range for jet-jet and jet-wall interaction given in Pore et al. [8]. Seeds were used as particles. They differ in size and shape that makes it difficult to identify a single particle property effecting the interactions. The void above the orifice is induced by the drag acting on the particles. The formation of multiple jets or the presence of a wall affects the flow profile of the gas entering the bed consequently also the drag force and the shape of the jets. As demonstrated by Filla et al. [16] and Koehl et al. [17] also the sphericity of the particles affects the jet shape. Jets forming in beds of large spherical particles are characterized by a larger jet angle.

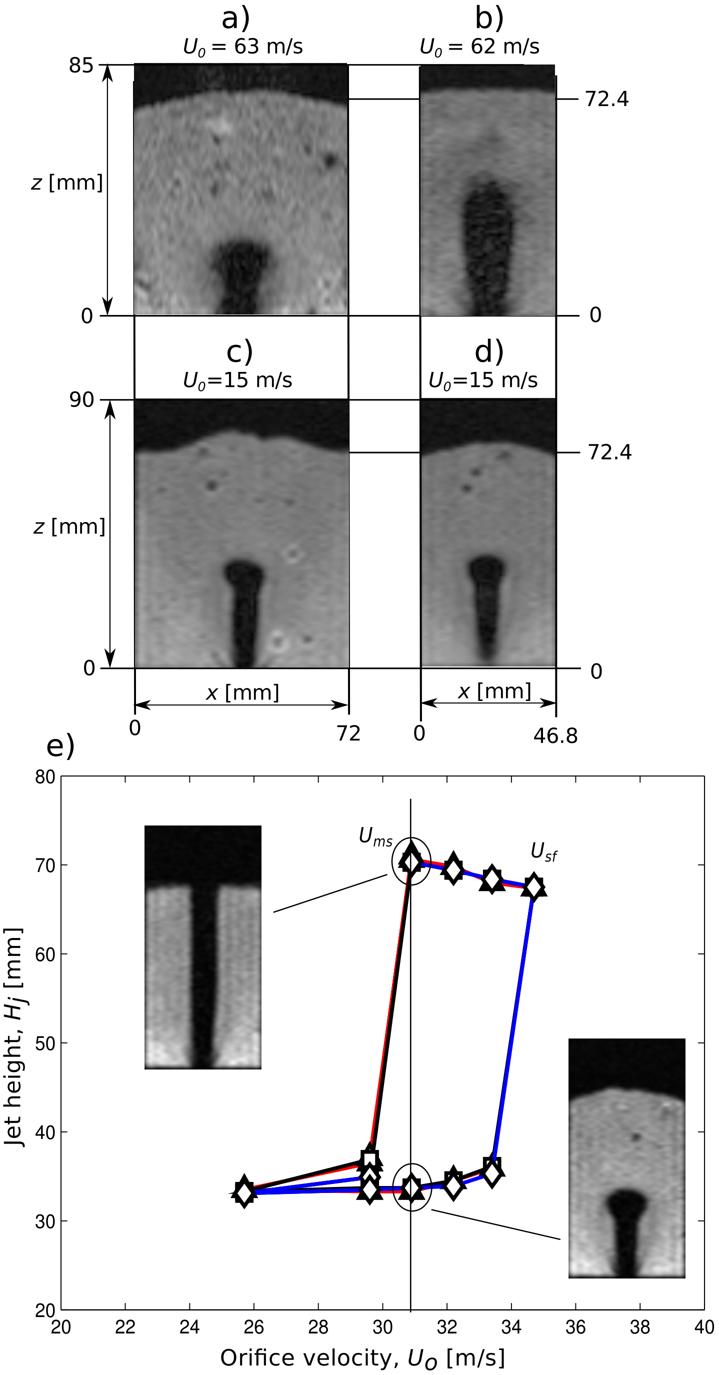

Figure 2: MRI images of jets forming at a single orifice distributor: (a,b) jets forming in a small (L = 46.8 mm) and wide bed (L = 72.0 mm) containing large particles (d_p = 1.3 mm) and applying an orifice velocity of $\sim$ 63 m/s; (c,d) jets forming in a bed containing Iceland poppy seeds (d_p = 0.7 mm) (e) plot of the jet height in a bed of opium poppy seeds as a function of orifice velocity.

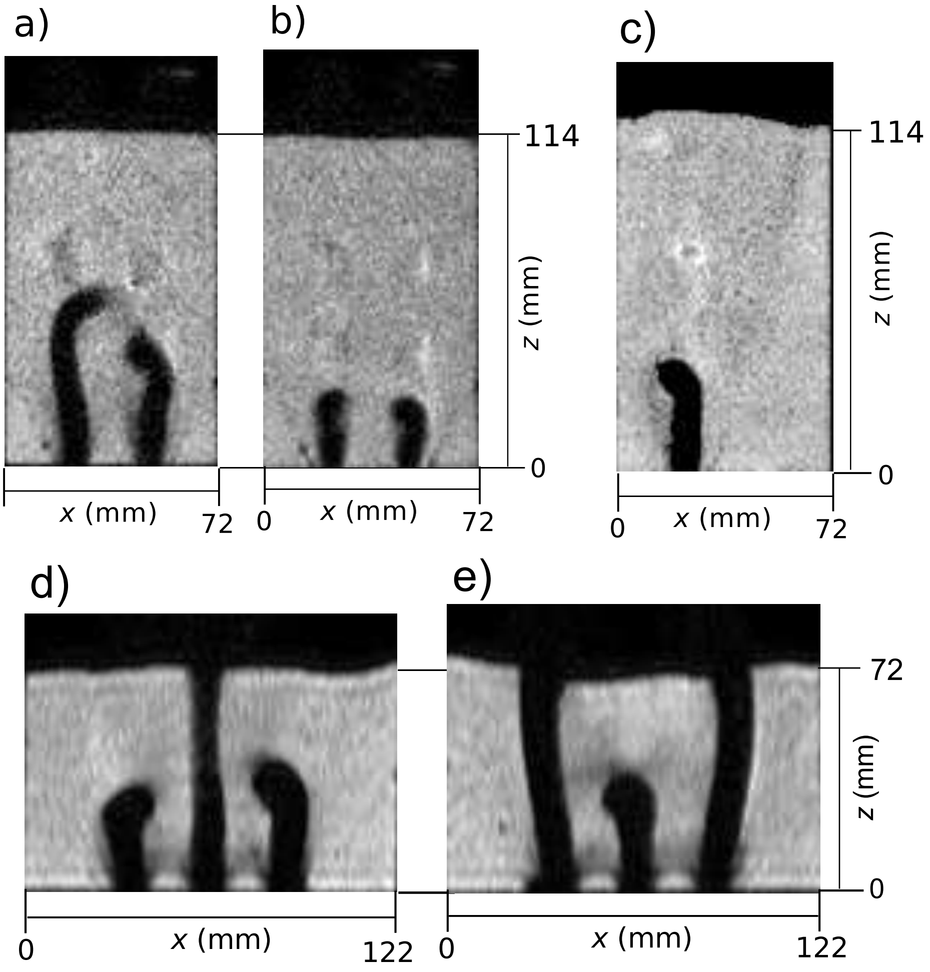

Figure 3: MRI measurements of jets forming at multi-orifice distributors. The fluidizing gas was introduced via two (a,b), one (c) or three orifices (d,e). Fig. 3(a) shows the bending of the tips of at an orifice velocity of U_o = 17.8 m/s, whereas very little jet interaction can be observed at an orifice velocity of U_o = 8.4 m/s (Fig. 3(b)) in a bed of Iceland poppy seeds. Fig. 3(c) shows a jet forming at a two-orifice distributor when one orifice was blocked (opium poppy seeds and U_o = 17.8 m/s.) Jets forming at a three-orifice distributor (Fig. 3 d,e) using opium poppy seeds (d_p = 0.9 mm), and an average orifice velocity of (d) U_o = 33.0 m/s and (e) U_o = 35.3 m/s

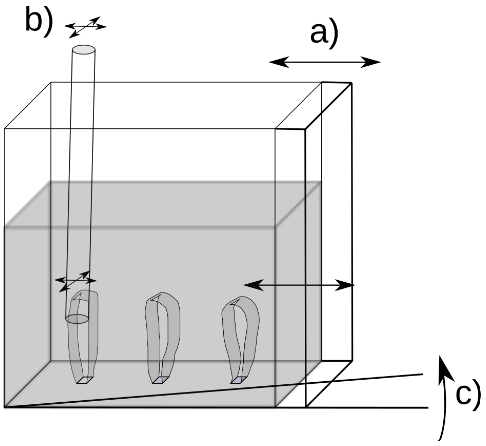

Figure 4: Methods applied to induce jet and spout transitions

Jet spout transition

Fig. 3(d,e) shows jets forming at a distributor plate containing three orifices. In this configuration, a mixture of jets and spouts can be observed. The jets are roughly half as high as the bed height. As shown in Fig. 3(d,e) it was possible to transform jets into spouts and vice versa. Based on our observations, the use of non-spherical particles is a requirement to allow this mechanically induced jet-spout transition. Furthermore, the the orifice velocity has to be in the range in which both jets and spouts can form, c.f. hysteresis loop. Three methods have been applied successfully to induce a jet-spout or spout-jet transition (Fig. 4)

a) Oscillation of the entire bed perpendicular to the flow direction. This induces a particle motion “unbalancing” the spout structure and, thus, results in a jet. The oscillation had approximately amplitude of 30 mm and a frequency of 2 hertz.

b) Penetration of the bed with a cylinder with a diameter similar to that of the spout. The cylinder was then moved horizontally through the upper section of the void and jet covering particles and subsequently slowly removed vertically from the bed.

c) Tilting of the beds. this results in a bed height that varied along the width of the bed. Thus, the pressure drop is reduced at the “lifted” side resulting in the formation of a spout at the orifice covered by a bed of comparatively small height. The used tilt angel was approximately 20 degree.

CONCLUSIONS

Magnetic Resonance Imaging (MRI) was used to image non-intrusively jets and spouts forming at single and multi-orifice distributors. It was found that jets in beds that contained larger particles are wider than jets forming in beds containing smaller particles. Additionally, narrow beds led to higher jets and the fluidization history critically affected the jet height. With regard to multiple jets, jet-jet interaction is indicated by the tips of jets tips towards each other and a local variation of jet height. We also observed that it is possible to introduce a jet-spout transition by mechanically disturbing the bed.

NOMENCLATURE

d_p	particle diameter [mm]
d_o	diameter [mm] based on equivalent orifice area
L	side length of the square distributor [mm]
L_o	side length of the square orifice [mm]
U_o	orifice fluidization velocity [m/s]
U_{ms}	minimum spouting velocity [m/s]
U_{sf}	spout formation velocity [m/s]

ACKNOWLEDGEMENTS

The authors acknowledge funding from the Swiss National Science Foundation (project 200021-132657). Maximilian Häberlin and Lars Kasper are acknowledged for their help with the experiments.

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