Chemical Engineering Science 132 (2015) 22–31

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Investigation of a swirling flow nozzle for a fluidised bed gas distributor

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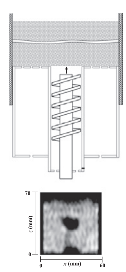
HIGHLIGHTS

- Hydrodynamics and pressure drop of a swirling flow nozzle distributor investigated.
- Swirl promotes lateral dispersion of gas and better gas–solid contact in bed.
- Pressure drop across swirling flow nozzle significantly higher than plain nozzle.
- Measured properties of the nozzle reasonably agree with theoretical predictions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form
30 March 2015
Accepted 2 April 2015
Available online 9 April 2015

Keywords:
Fluidised bed
Gas distributor
Hydrodynamics
Swirling flow
Pressure drop
Magnetic resonance imaging (MRI)

ABSTRACT

This paper relates to a multi-orifice distributor for a gas-fluidised bed, using many upward-facing nozzles, equally spaced in a horizontal plate. Each orifice contained a removable helical coil, which made the gas swirl as it entered the bed. For a single orifice in such a distributor, ultra-fast magnetic resonance imaging (MRI) and pressure measurements were applied to study: (i) the formation of jets and bubbles and (ii) the orifice pressure drop. Results from MRI show that the swirling flow induced by the helix significantly improves the fluidisation quality compared to a plain nozzle without spiral. The helix gives rise to secondary flow which increases pressure drop across the nozzle, the measured values of which are predicted satisfactorily by using a friction factor correlation for helical coils.

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1. Introduction

1.1. Fluidised bed and design of gas distributor

The performance of a fluidised bed is intimately linked to the design of the gas distributor since this influences the efficiency of gas–solid mixing, jet formation, the size and shape of gas bubbles as well as the pressure drop across the distributor. The role of the distributor is to disperse uniformly the fluidising gas over the entire cross-section of the bed and hence to initiate effective gas–solid contacting. Poor design of the distributor can cause severe gas bypassing resulting in channelling and non-uniform fluidisation. Despite various approaches aimed at improving gas–solid contact in fluidised beds, including flow pulsation (Koksal and Vural, 1998), vibration (Mawatari, Tatemoto, and Noda, 2003), mechanical agitation (Kim and Han, 2006), and the use of a rotating distributor (Sobrino et al., 2009; De Wilde and de Broqueville, 2008), the effect of the gas distributor design on the bed hydrodynamics is still poorly understood. The limitation of the aforementioned arrangements is that none of them appears suitable for a large industrial fluidised bed unit unlike the helical spiral nozzle investigated in the present paper, which has been

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http://dx.doi.org/10.1016/j.ces.2015.04.001
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used successfully in industrial-scale applications (Kleinfelder, 1969; Dunn, 1958). A number of studies have investigated an annular spiral distributor made of overlapping angled blades which produces a swirl motion of the bed material (Sreenivasan and Raghavan, 2002; Chyang and Lin, 2002; Shu, Lakshmanan and Dodson, 2000; Ouyang and Levenspiel, 1986); this concept has found use in industrial equipment such as the 'torbed' process reactor technology but the design is very different to the helical spiral nozzle distributor in this work. To the best of our knowledge there has been no published work on the helical nozzle distributor concept in the literature.

1.2. Magnetic resonance imaging of fluidised beds

The study of granular systems such as fluidised beds often involves difficult measurements due to the optically opaque nature of the media. This makes it difficult to observe the behaviour of gas and solids within the bulk of the bed. Some of the early experimental techniques that have been applied to study the dynamic behaviour of gas and solid particles in a fluidised bed include capacitance probes (Werther, 1974), visual observation (Merry, 1975), x-ray photography (Rowe, 1971), light probes (Wen, Deole and Chen, 1982) and electroresistivity probes (Choi, Son and Kim, 1988). The major limitation of the probes is that they are intrusive and tend to distort the flow.

More recently, other techniques have been developed which include positron emission particle tracking (Stein et al., 1997), electrical capacitance tomography (Dyakowski et al., 1997), particle imaging velocimetry (Chen and Fan, 1992), diffusing wave spectroscopy (Menon, 1997), and magnetic resonance imaging (Müller et al., 2008; Mantle et al., 2008; Pore et al., 2010). Of these techniques, MRI has emerged as a powerful tool for studying visually opaque 3-D systems of two-phase flow. It can provide both ultra-fast as well as time-averaged measurements of the distribution of gas and solids, which makes it useful for studying the phenomena of jets, bubbles, and slugs in fluidised beds and other multi-phase flows. MRI enables the imaging of gas–solid fluidised beds to high spatial and temporal resolutions. Furthermore, MRI allows direct measurement of particle distribution (i.e., voidage) as well as particle velocities, which can be used to identify dead-zones within the bed (Pore et al., 2012).

The aim of this paper is to investigate a novel fluidised bed gas distributor. The distributor plate contains many upward-facing nozzles, each of which is a vertical pipe incorporating a helical coil that makes the gas swirl as it enters the bed. A model of this distributor design was built with a single nozzle containing a helix, replicating the full-scale design. An MRI technique was used to study the flow patterns in the region above the distributor in order to answer the following questions:

i. What is the effect of the swirl on the flow pattern, jet penetration and bubble properties (size and frequency of formation) as the gas enters the fluidised bed and how does bed hydrodynamics compare with a nozzle distributor without swirl?
ii. What is the effect of the helix design on pressure drop across the distributor? How does the pressure drop relate to the gas velocity through the nozzle?

2. Experimental

2.1. Fluidisation column with swirling flow nozzle distributor

A schematic diagram of the fluidisation column made of polyether ether ketone (PEEK) is shown in Fig. 1. It consists of a 50 mm diameter distributor plate containing 61 holes, each 0.4 mm diameter, arranged in three evenly spaced concentric circles as well as a 10 mm diameter central nozzle containing a 5 mm diameter rod with a six-turn helical coil at the top. Table 1 contains key geometrical dimensions of the spiral nozzle design. The helix is designed to make the inlet gas swirl as it enters the bed and to retain particles when the fluidising air is switched off. The vertical height of the spiral in the nozzle can be adjusted up or down, or it can altogether be removed to give a simple nozzle without swirl. Without the spiral helix, the arrangement has some similarity to a spout-fluid bed (Mathur and Epstein, 1974). On the side of the bed at the gas inlet into the nozzle is a pressure tapping to measure the pressure drop across the helix with respect to the top of the distributor. Fluidising air is supplied through two inlets, one to the main bed and the other to the nozzle containing the helix. The nozzle containing the helix was connected via two Roxspur Platon NGX rotameters (2–25 L/min and 10–100 L/min), calibrated using the soap film method, to the main air supply at 1 bar.

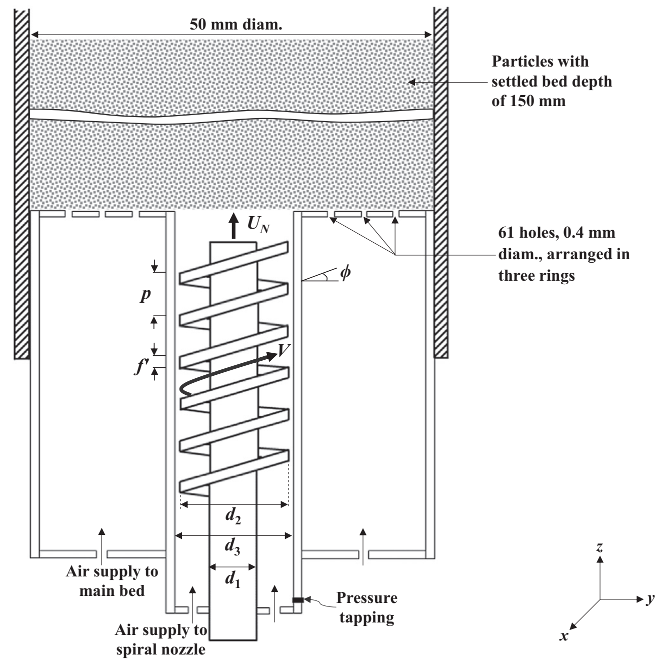

Fig. 1. Schematic representation of the fluidisation column showing the spiral nozzle gas distributor.

Table 1
Geometric parameters of the helical spiral.

Parameter	Value
Number of turns, n	6
Flight, f	0.65 mm
Pitch, p	4 mm
Core diameter, d_1	5 mm
Outer diameter, d_2	9.8 mm
Central nozzle diameter, d_3	10 mm
Inclined angle, ϕ	11.5°

2.2. Magnetic resonance imaging

2.2.1. Materials, experimental set-up and procedure

For this study, poppy seeds (diameter 500 μm; density ~950 kg/m^3; measured minimum fluidisation velocity, U_{mf}, 0.13 m/s corresponding to a distributor flow rate of 15.3 L/min; Geldart Group B particles (Geldart, 1973)) were used for MRI experiments because

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