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Time-resolved characterization of a flat-base spouted bed with a high speed X-ray system

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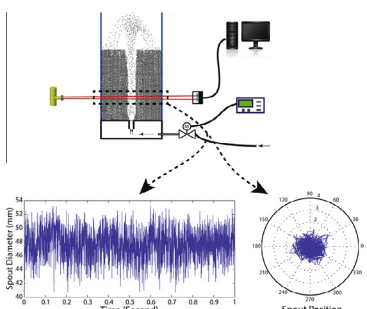
HIGHLIGHTS

- The spout size and position is measured with a high speed X-ray system.
- A novel data processing procedure is developed for the spouted bed.
- Averaged spout size in a full-cylindrical bed is obtained.
- The spout stability is analyzed.
- A simple particle circulation model is developed.

GRAPHICAL ABSTRACT



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ABSTRACT

Time-resolved measurements are carried out for determining the spout shape and position in several cross sections of a flat-base spouted bed filled with 2 mm polystyrene particles. A high speed X-ray image system, consisting of 3 X-ray sources and 2 layers of 32 detectors for each source, is employed to measure the spout shape with a temporal resolution of 2500 fps. The X-ray attenuation data are analyzed by both tomographic reconstruction and raw data analysis. The averaged spout diameters show good agreement with literature. A particle circulation model is made for validating the measured data. The fluctuations of the spout diameter are analyzed from the computed power spectral density. It is shown that the spout is most stable for $U/U_{ms} = 1.20$–1.37. From measuring the center movement of the spout, we found an oscillation of the spout position. Its intensity is related to the bed height and gas flow rate.

1. Introduction

A spouted bed is a system for contacting coarse granular solids (larger than 500 μm in diameter) and fluids. It is widely used in gas–solid processes such as drying, coating and granulation. The study of spouted beds started early by Mathur and Gishler [1]. Several systematic studies have been carried out for it. However, there are divergent predictions and measurements for the size of the spout region. Moreover, direct observations of the stability of the spout are limited. The stability of the spout is important for industrial application, in which it is crucial to keep the gas–solids contacting constant.

A horizontal cross-section of a spout is typically considered to be of circular shape. Spout diameters were measured directly in half-cylindrical beds by Malek et al. [2] and McNab [3]. Later, a fiber optic probe was used to measure spout diameters by He et al. [4,5] in both half and full column beds. Time-averaged spout diameters were measured by Wu et al. [6] with an X-ray CT scanner in a full column. Theoretical predictions were also made [2,3,7]. There are deviations for the predicted values between the half-column models and full-column models [5,8]. The principles to distinguish the boundary of the spouts also differ from model to model.

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In the early studies, three flow regimes of spouted beds were distinguished: packed, stable spouting, and unstable spouting. However, limited attention has been given to the dynamics of spouted beds. Malek et al. [2] mentioned that sometimes the spout oscillates around the axis of the column. The design factors to maintain the spouted bed in the stable mode were discussed by Olazar et al. [9,10]. Fluctuations of the pressure drop in spouted beds were measured by Xu et al. [11], Lopes et al. [12], Wu et al. [6] and Mollick and Sathiyamoorthy [13]. The standard deviation and PSD (Power Spectrum Density) are used for further analysis of these measurements. They found that the fluctuations of the pressure drop in different flow regimes are different.

X-ray tomography is an attractive tool for spout region measurements, since it can measure the interior of a non-transparent medium in a non-invasive way. It has been applied to the measurements of the fluidized beds [14–18] to find the time averaged solid concentration or gas hold-up. It has also been used for measuring the time-averaged spout diameter by Wu et al. [6]. For dynamic measurements, a high temporal resolution is required. The high speed X-ray tomography approaches developed by Mudde et al. [19] and Bieberle et al. [20] can provide a temporal resolution as high as 2500–7000 fps. These approaches are applied in time-resolved measurements of fluidized beds [21–24] with good potential of exploring the dynamics of those systems. This also suggests a good capability for time-resolved measurements of a spouted bed.

In the present paper, a novel approach is proposed to study the dynamics of spouted beds. We developed a raw data process, which provides much higher precision than the typical tomographic reconstruction, to obtain the spout diameter and position from the measurement of the high speed X-ray tomography system. A case study for a flat-base spouted bed is presented. The time-averaged spout diameter ($\overline{D_s}$) is compared with the prediction of McNab [3]. A particle circulation model is built based on $\overline{D_s}$. The time-resolved spout diameters (D_s) are analyzed with spectral methods. The motion of the spout center of gravity will be presented. The fluctuations of the spout size and the oscillation of the spout position will be discussed based on these observations.

2. Experimental setup

The experimental setup is composed of a flat-base spouted bed and a high speed X-ray tomography system, which is as shown in Fig. 1(a). A digital mass flow controller (Bronkhorst E-7100-AAA) provides the inlet gas flow rate with specific flow rates, with a maximum error of 2%.

2.1. The spouted bed

The flat-base spouted bed is a 0.24 m inner diameter perspex tube (wall thickness 5 mm). The gas inlet is a round hole with a

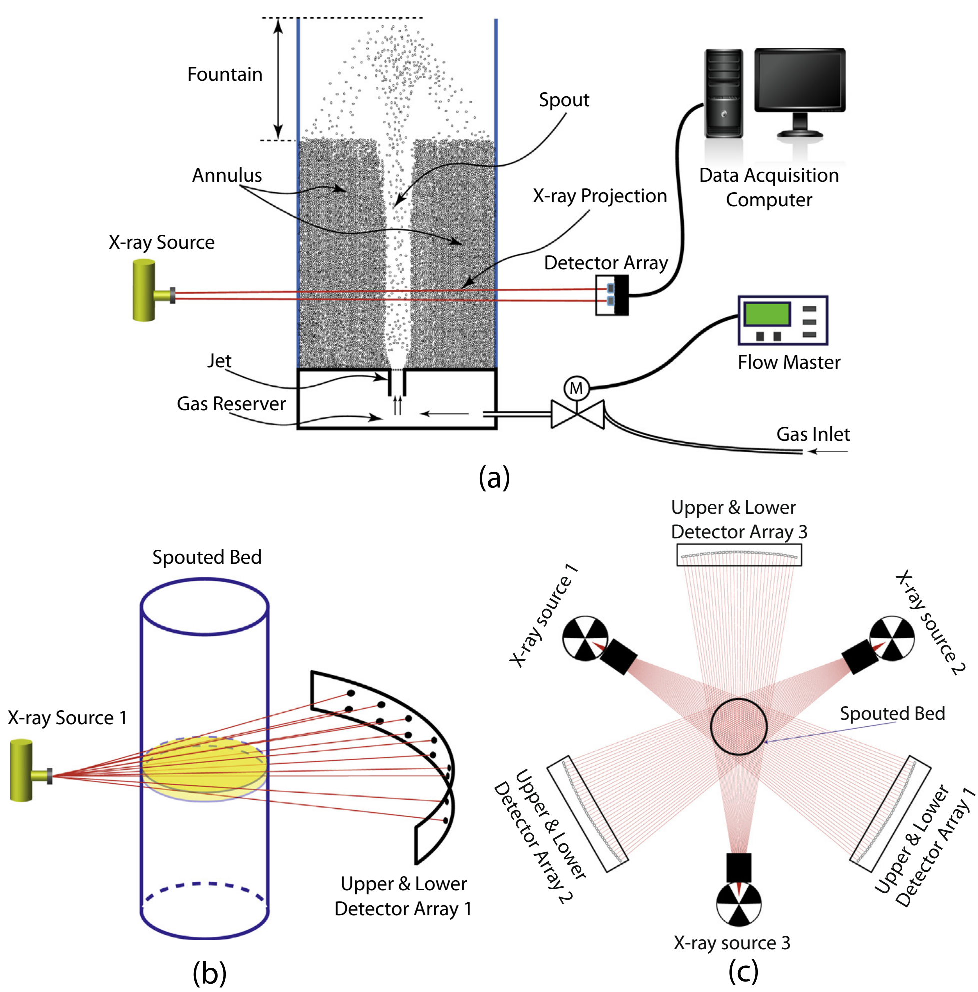

Fig. 1. Schematic diagram of experimental setup. (a) Overall; (b) 3-D view of X-ray source 1 and detector array 1 with double layers and (c) Top view of measurement system with spouted bed placed in the center.