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Ultrafast X-ray computed tomography for the analysis of gas–solid fluidized beds

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ABSTRACT

Gas–particle flow in fluidized beds is generally complex and difficult to observe. But exact information on voidage distribution and solid transport is urgently needed for assessment, monitoring, modelling, and optimization of fluidized bed operation. So far, there was a lack of suitable measurement and imaging techniques to disclose the complex flow structures in fluidized beds with high spatial and temporal resolution. The ultrafast X-ray computed tomography technique, which has been developed in recent years, is superior for such types of multiphase flows and its performance for the analysis of fluidized beds has been demonstrated in this study. Spatial resolution of two millimetres and temporal resolution of several thousand cross-sectional images per second allow at the same time imaging and analysis of voidage structures as well as single particle movement. In this study, the capability of imaging fluidized bed behaviour at different column diameters and gas flow rates has been analysed.

1. Introduction

The fluidized bed principle is employed in a variety of process devices. Its application ranges from chemical processes, such as fluid catalytic cracking and polymerization, to drying, combustion, granulation, purification and coating. Yet, the behaviour of fluidized beds is not completely understood, for which reason it is a pending topic in current research. Although a lot of important work has been done, modelling and optimization of fluidized beds remain difficult due to the complex flow characteristics, which arise from gas–particle and particle–particle interactions. Furthermore, experimental investigations are hampered by the opaqueness of the bed. Traditional flow and process measurement techniques can provide only partial information on the behaviour of dense fluidized beds. Classical techniques, such as pressure drop measurements [1,2] provide important information, but give only little insight into the process itself. Optical imaging and laser-based methods are at the most able to capture the peripheral structure of the solids phase or to provide local information via optical probes [3,4]. As well as capacitance probes [5], the latter face the difficulty to apply probes within the bed without significantly disturbing the flow. One common workaround for this problem of limited access is to perform experiments in pseudo 2D columns, accepting the influence of the walls on the flow behaviour [6,7]. For the study of three-dimensional phenomena, tomographic imaging techniques are required. However, most tomography techniques do not reach the required temporal and spatial resolution at the same time. Electrical capacitance tomography (ECT) [8,9], for instance, is fast but substantially limited in spatial resolution and conventional X-ray or gamma ray tomography is far too slow. Recently, there appeared some innovative ideas to improve accessibility of fluidized beds. Dechsiri et al. [10] used positron emission tomography (PET) and positron emission particle tracking (PEPT) to study the mixing between radio-labelled and non-labelled particles in a fluidized bed. This technique is based on the pioneering work in PET and PEPT by Parker et al. [11,12]. Mudde developed different fast X-ray and gamma ray techniques for the study of fluidized beds [13,14] and in the end proposed a setup comprising three X-ray tubes arranged in one plane and detectors arranged in two planes to image voidage within a bubbly fluidized bed [15]. Finally, magnetic resonance (MR) imaging has been used to image fluidized beds with 750 1D profiles per second along a vertical line [16] as well as with 40 2D images per second [17]. The advantage of MR techniques is the option to also measure velocities.

Most recently a new ultrafast imaging X-ray tomography technology came forward which was particularly developed for the investigation of transient and optically intransparent processes. Ultrafast X-ray tomography [18] is based on a scanned electron beam principle. The electron beam is rapidly swept across a circular target to produce a moving X-ray source. A fixed detector ring synchronously captures the intensity of X-rays passing the object of investigation. From the resulting radiographic projections non-superimposed cross-sectional density distributions are reconstructed with spatial resolution down to 1 mm at sufficient contrast of the involved materials. Avoiding mechanically moving parts as in conventional X-ray CT scanners, an imaging speed of up to 10 000 frames per second can be achieved [19]. Beside its really fast scanning capability other advantages of this approach are the use of a

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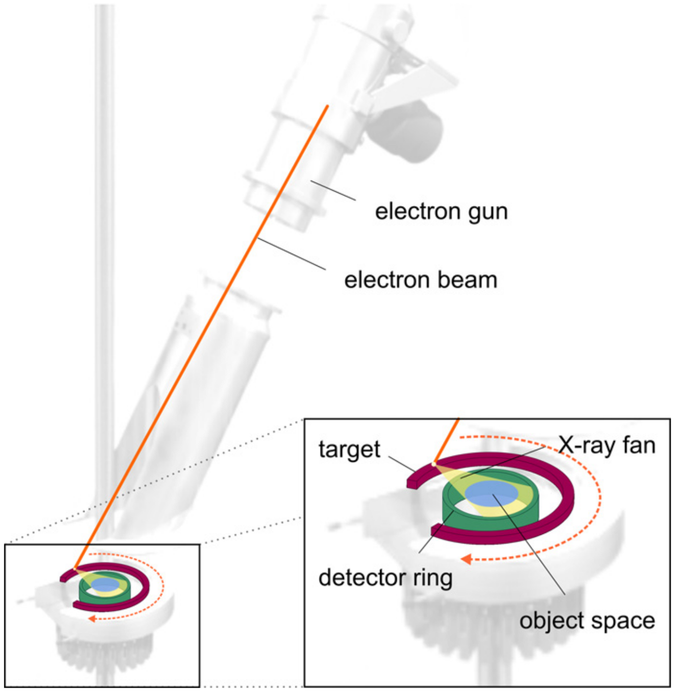

Fig. 1. Setup and principle of ultrafast electron beam X-ray tomography.

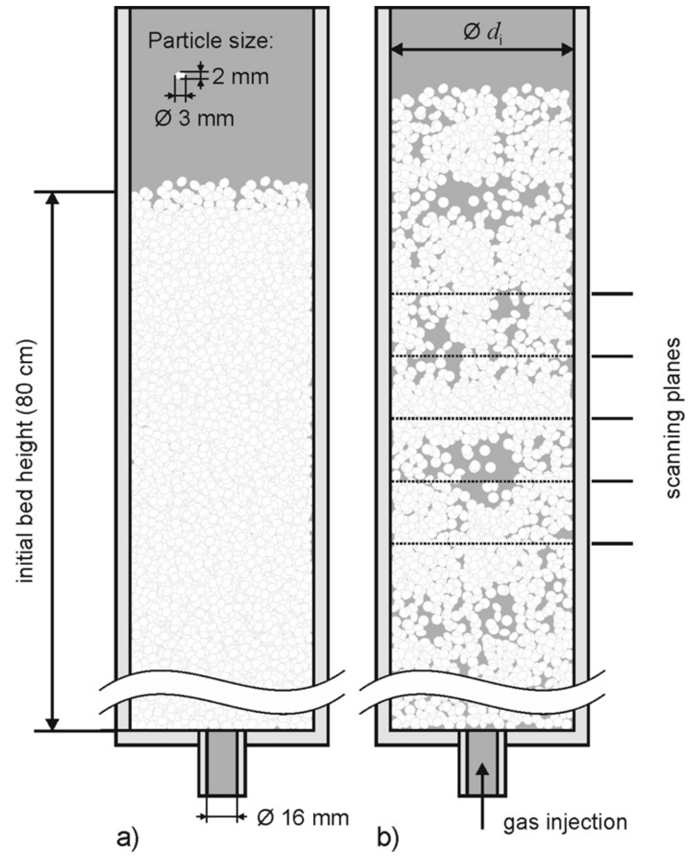

Fig. 2. Sketch of experimental fluidized bed setup before (left) and during fluidization (right).

single electron beam generator and the high versatility of the electron beam with respect to scan patterns and scanning speed. After having evaluated a limited-angle version of this electron beam X-ray CT for imaging particle motion in a fluidized bed setup [20], we have made the full-angle CT available for scanning laboratory scale fluidized beds. In two different column diameters we have used this new technology to demonstrate its capability to assess the gas as well as the particulate structures in the bed for different fluidization situations.

2. Ultrafast X-ray computed tomography

The ultrafast X-ray computed tomography system [18], which is subject in this study, was originally developed for the imaging of transient two-phase flows in smaller diameter pipes (50 mm) [21,22]. Fig. 1 illustrates the measuring principle. An electron beam of 150 kV acceleration voltage and up to 10 kW power is circulated across a ring-like metal target by means of an electromagnetic deflection system. The focal spot on the target has a diameter of around 0.8 mm. A fast X-ray detector statically arranged nearly coplanar to the focal spot path acquires radiographic projections from different angular views. The detector signals of each revolution of the electron beam provide the projection data for one cross-sectional image. The detector comprises 240 room-temperature semiconductor pixels of 1.33 mm^3 size, whose current-mode signals are converted and digitized with 1 MHz sampling rate and 12 bit resolution.

The measured projection data is subject to tomographic image reconstruction which recovers cross-sectional images of the linear X-ray attenuation coefficient μ, i.e. effectively the density distribution, within the tomography plane. For a single ray from a given focal spot position s to any of the detector elements d the integral ray attenuation p_{sd} (projection value) is given by

$$p_{sd} = -\ln \frac{I_{sd}^{(meas)} - I_{d}^{(dark)}}{I_{sd}^{(ref)} - I_{d}^{(dark)}}, \quad (1)$$

approximating the attenuation of the X-ray energy spectrum by the mean attenuation coefficients in the respective energy range. Therein $I_{sd}^{(meas)}$ is the measured X-ray intensity of an unknown distribution, $I_{sd}^{(ref)}$ the X-ray intensity for a reference state (such as an empty vessel) and $I_{d}^{(dark)}$ is the detector's baseline value. The

Table 1
Main parameters of the fluidized bed experiments.

	Column diameter (mm)				
	Ø50			Ø94	
Gas flow rate (l/min)	100	110	120	333	350
Superficial gas velocity (m/s)	0.85	0.93	1.02	0.80	0.84
Scanning plane position above gas inlet (cm)	30	30	30	30	30
	40	40	40	40	40
	50	50	50	50	50
	60	60	60	60	60
	70	70	70	70	70