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X-ray imaging for flow characterization and investigation of invasive probe interference in travelling fluidized bed

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ABSTRACT

X-ray imaging was employed to visualize the internal flow structures of the travelling fluidized bed (TFB), operating in the bubbling and turbulent flow regimes. The degree of interference of a 4-mm diameter intrusive probe inserted in the gas-fluidized bed was investigated by comparing the time-average voidage in a region of the bed operated with and without the probe being present. Transition from bubbling to the turbulent fluidization regime was visually inspected from images obtained by the X-ray system and quantitatively characterized in terms of statistical parameters associated with grayscale intensity probability distribution functions (PDF). Voidage data obtained by different measurement techniques are compared with time-average voidages obtained by X-rays and borescopic imaging. The hydrodynamic data provided by this study extend the benchmark database produced from the experiments performed on the TFB for validation of CFD and other models.

1. Introduction

Gas-fluidized beds are characterized by flow structures that confer unique features for widespread industrial applications. Important quantities that need to be measured to characterize gas-fluidized beds include hydrodynamic parameters such as voidage distribution, particle velocity, particle mass flux and gas velocity, in addition to gas concentration and temperature profiles related to specific applications. Measurement techniques are needed for control of industrial plant performance, analysis of operating problems and process optimization, as well as in research to understand the physical phenomena associated with gas–solid interactions (Werther, 1999).

Performing reliable and accurate measurements in gas-fluidized beds is extremely important to gain a deeper understanding of these systems and for validation of CFD and other mechanistic models. However, intrinsic features of industrial gas-fluidized beds such as optical opacity, harsh environments and mechanical stresses caused by continuous motion of solids that can erode or block immersed measurement instruments make it extremely challenging to obtain reliable experimental data. Research groups in many countries have developed various measurement techniques based on both invasive and non-invasive methods (Werther, 1999; Yates and Simons, 1994). While non-invasive techniques are mainly applicable to academic research, invasive techniques such as optical and capacitance probes have the potential to perform measurements in industrial units that are currently monitored exclusively by measuring temperature, pressure drop and overall concentration change. Development of advanced probes for obtaining direct information on instantaneous hydrodynamic features of commercial gas-fluidized beds could be useful for improving the performance, reliability and control of these systems.

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Nomenclature

d_{Sauter}	Sauter mean particle diameter (μm)
E	expectation operator (–)
h	height coordinate in X-ray images (m)
H	entropy defined by Eq. (5) (bit)
I	transmitted intensity (–)
I_0	incident intensity (–)
n	total number of classes of distribution (–)
p_i	probability of class i of distribution (–)
l	path length (m)
U_c	superficial gas velocity at onset of turbulent fluidization (m/s)
U_g	superficial gas velocity (m/s)
U_{mb}	minimum bubbling velocity (mm/s)
U_{mf}	minimum fluidization velocity (mm/s)
U_{ms}	minimum slugging velocity (m/s)
z	height (m)
β_2	kurtosis defined by Eq. (3) (–)
ε	voidage (–)
γ_1	skewness of voidage measurements defined by Eq. (4) (–)
γ_2	normalized kurtosis of voidage measurements (–)
μ_m	attenuation coefficient of solid material (m^2/kg)
μ	mean of voidage distribution (–)
μ_4	fourth moment about the mean (–)
ρ_p	particle density (kg/m^3)
ρ_b	bulk density (kg/m^3)
σ	standard deviation of voidage measurements (–)

The travelling fluidized bed (TFB) collaborative project (Dubrawski et al., 2013; Tebianian et al., 2014, 2015a, 2015b) aims to compare alternative advanced measurement techniques which characterize the hydrodynamics of gas-fluidized beds operating under identical conditions at different locations. Direct comparison of the results obtained by different techniques provides valuable information on the extent of uncertainty associated with each measurement method. In our previous TFB work (Dubrawski et al., 2013; Tebianian et al., 2015b), there was no discernible tendency of invasive probes to over- or under-estimate local voidages and particle velocities relative to data obtained by non-invasive measurement techniques. However, the degree of interference of intrusive probes with local hydrodynamics needs to be investigated to evaluate invasive probes as candidates for monitoring commercial gas–fluidized beds.

Transition from bubbling to the turbulent fluidization flow regime is characterized by the break-up of bubbles into transient voids, leading to more homogenous flow structures. Different approaches based on chaos analysis, power spectrum analysis, wavelet analysis and statistical analysis of time series of pressure fluctuations, local voidage and other hydrodynamic parameters have been proposed for characterizing fluidization flow regimes (Ellis et al., 2003; Van Ommen et al., 2011; Zhong et al., 2009). It is commonly accepted that the maximum of the root-mean square pressure fluctuation amplitude as a function of superficial gas velocity corresponds to the transition from bubbling to the turbulent flow regime (Bi and Grace, 1995). Kurtosis, skewness and Shannon entropy of time series of fluidized bed local hydrodynamic

Table 1 – Experimental particle properties in air at 20 °C and 101.3 kPa.

	FCC	Sand
Sauter mean diameter d_{Sauter} (μm)	107	292
Particle density ρ_p (kg/m^3)	1560	2644
Packed bed bulk density ρ_b (kg/m^3)	851	1250
Minimum fluidization velocity U_{mf} (mm/s)	6.06	79.6
Minimum bubbling velocity U_{mb} (m/s)	0.028	0.0796
Minimum slugging velocity U_{ms} (m/s) (Stewart and Davidson, 1967)	0.090	0.16
Onset of turbulent fluidization U_c (m/s)	0.68	0.78

parameters represent statistical tools that are sometimes also used for demarcation of the various flow regimes (Duan and Cong, 2013; Ellis et al., 2003; Zhong et al., 2009).

Lettieri and Yates (2013) provided a history of the application of X-ray imaging to the hydrodynamic study of gas-fluidized beds. In particular, they summarized how this technique can be deployed to investigate instantaneous and time-average voidage distributions, bubble size and velocity, interaction of bubbles with immersed surfaces and voidage distributions around bubbles.

This study extends our previous TFB work to X-ray visualization and analysis in order to further characterize the system for identical operating conditions. In particular, fast X-ray imaging is employed to:

- Investigate the effect of insertion of an intrusive probe on the local time-average voidage distribution.
- Study the change in flow structures corresponding to the transition from bubbling to the turbulent fluidization flow regime using statistical analysis of X-ray images.
- Compare the cross-sectional average voidage at different measurement heights of the travelling fluidized bed, derived from X-ray attenuation, with previously published results (Dubrawski et al., 2013; Tebianian et al., 2014).

The new X-ray results provide valuable insights for quantifying, at least in part, the degree of interference of intrusive probes with the flow. The unique hydrodynamic database extended in this study representing time-average voidage distribution and transition from bubbling to turbulent fluidization flow regime should be extremely useful for testing the validity of CFD and other predictive hydrodynamic models.

2. Experimental

Details of the travelling column are provided elsewhere (Dubrawski et al., 2013). In brief, it consists of a plexiglass column of 0.133 m i.d. and 0.96 m height above which is a freeboard section of larger diameter, all of which can be disassembled and re-erected simply to allow the facility to travel to sites where there are unique experimental measuring capabilities. The static bed height was 0.80 m for FCC and 0.82 m for sand particles. The key physical properties of the two types of particles investigated are given in Table 1. It can be observed that the Sauter mean diameter of the FCC particles was greater than the value usually found for this kind of powder. This is mainly due to the fact that spent FCC particles were utilized, with fines elutriated during the operation of the fluid catalytic cracking unit. The superficial gas velocity at the onset of turbulent fluidization (U_c) was measured experimentally