International Journal of Multiphase Flow 75 (2015) 237–249

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Influence of vertical internals on a bubbling fluidized bed characterized by X-ray tomography

Simon Maurer [a], Evert C. Wagner [b], J. Ruud van Ommen [b], Tilman J. Schildhauer [a,*], Sinan L. Teske [a], Serge M.A. Biollaz [a], Alexander Wokaun [a], Robert F. Mudde [b]

[a] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
[b] Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands

ARTICLE INFO

Article history:
Received 28 October 2014
Received in revised form 1 June 2015
Accepted 3 June 2015
Available online 10 June 2015

Keywords:
X-ray
Fluidized bed
Scale-up
Optical probe measurement
Sector scaling
Vertical tubes
Internals

ABSTRACT

An ultra-fast X-ray tomographic scanner is applied to study the hydrodynamics in a bubbling fluidized bed with and without vertical internals (e.g., heat exchanger tubes). The objective of this study is to understand the influence of vertical internals on hydrodynamic properties such as bubble volume, size and velocity and to provide measurement data for the design and scale-up of catalytic bubbling fluidized bed reactors with vertical internals. With these new measurements, correlations of bubble properties can be developed to reliably scale-up bubbling fluidized beds with vertical internals. For the investigated reactor with Geldart A/B particles, no relation between bubble size and velocity was observed for individual bubbles, i.e.; smaller bubbles tend to rise with higher velocities. A significant reduction in bubble size and sharpening of the bubble size distribution was generally obtained for a bed with vertical internals.

Introduction

Conversion and yield in catalytic bubbling fluidized bed reactors are often controlled by the mass transfer between the bubble and dense phase Beetstra et al. (2009). To design and reliably scale-up this type of reactor or to improve the computer models that describe it, the hydrodynamic properties with and without immersed vertical internals (e.g., heat exchanger tubes) must be measured and understood.

In the literature, a large amount of measurement data and correlations are available that describe the hydrodynamics of bubbling fluidized beds without vertical internals Clift and Grace (1972), Davidson and Harrison (1963), and Karimipour and Pugsley (2011). Those correlations generally provide mean values of bubble size, velocity and hold-up and are used for the development of computer models, such as the two-phase model Toomey and Johnstone (1952) and Kopyscinski et al. (2011). To describe the hydrodynamic properties of bubbling fluidized bed reactors with vertical internals, none of the existing correlations seem appropriate, and reliable data is rarely found in the open literature Rüdisüli et al. (2012b). Additionally, because these bubble correlations are frequently used to validate complex computational fluid dynamic models, a more quantitative and critical assessment would be of great value.

X-ray tomography can be applied to accommodate the need of more quantitative results with high-resolution measurements. Both spatial and temporal resolution of these systems have improved in recent years. Today, the flow within different fluidized beds can be visualized with high spatial resolution, as shown by Hampel et al. (2005), Bieberle et al. (2007), Fischer et al. (2008), and Verma et al. (2014). Another measurement technique suitable to visualize the flow within fluidized beds is the magnetic resonance imaging (MRI) technique Müller et al. (2006), Rees et al. (2006), Holland et al. (2008), Müller et al. (2010), and Walker et al. (2014). In this study, absorption contrast X-ray tomography combined with optical probe measurements is used to collect reliable hydrodynamic information of a single bubbling fluidized bed reactor with and without vertical internals; consult Mudde (2011) for more information about the X-ray setup. In the past, several other fluidized bed columns or similar systems have been successfully investigated using the same X-ray setup Brouwer et al. (2012), Saayman et al. (2013), and Rautenbach et al. (2013).

Correlations of bubble volume, size and rise velocity are developed. The aim is to report detailed measurement data for designing

* Corresponding author. Tel.: +41 56 310 27 06.
E-mail address: tilman.schildhauer@psi.ch (T.J. Schildhauer).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.06.001
0301-9322/

catalytic bubbling fluidized bed reactors with vertical heat exchanger tubes of different scales.

Experimental

Fluidized bed column and particles

Parts of the experimental design and image reconstruction have already been described in Maurer et al. (2015). Hydrodynamic experiments are conducted in a lab-scale bubbling fluidized bed reactor located in the center of an ultra-fast X-ray setup Mudde et al. (2008).

The settled bed height of the bubbling fluidized bed reactor is 51 cm and the reactor has an inner diameter of 14 cm with 16 removable vertical internals, four of which have a 1 cm outer diameter while the remaining 12 have a 2 cm outer diameter. The tube spacing is 1 cm, which results in a space of about 1.2 cm between the tubes and the reactor wall. The configuration of the internals is shown in Fig. 1(a) (top-view); the four 1 cm internals must be applied to ensure no gas bypass occurs near the reactor wall and to keep the hydraulic diameter approximately constant at all positions in the reactor. The configuration of the tube sizing and spacing of the internals was determined by maximizing the heat transfer area by maintaining proper fluidization as well as by economic considerations. Additionally, the pressure drop within the heat exchanger tubes has to be within an acceptable limit, which is the case for tubes with diameters of 2 cm. The reactor and internals are made of acrylic glass.

The required gas volume flow for minimum fluidization velocity (u_{mf}) is measured for the reactor without vertical internals and is calculated from the reduction of the cross-sectional area for the measurement with vertical internals. The distributor plate of the reactor has a pore size of 20 μm and has 5 mm in thickness (THOMAPOR® Sinterplatte, 12150, Reichelt Chemietechnik GmbH). The Sauter mean diameter of the γ-aluminum oxide particles (Puralox NWa155, 580131, Sasol Germany GmbH) was determined by a sieve analysis and laser diffraction measurements to be 289 μm (D10 = 50 μm and D90 = 405 μm), the particle density is 1350 kg/m^3. The particles are in the intermediate range between Geldart A/B Geldart (1972) and Geldart (1973). A detailed particle characterization has been previously reported Rüdisüli (2012). Compressed air is used for the fluidization. All experiments are conducted at room temperature and pressure.

X-ray setup and calibration

The applied X-ray tomographic scanner consists of three point sources (e.g., tube 1, 2 and 3) and three horizontal detector arrays in two rows above each other; see Fig. 1(b) (top-view). The detector array rows are separated by 40 mm vertically, indicating that the measurement planes through the column are 10.7 mm apart on average (8.4 mm when they enter the column, 13.1 mm at the other side, Fig. 1(c). Each of the six detector arrays is equipped with 32 detectors, resulting in a theoretical spatial resolution of 4.4 mm. The attenuation of the X-rays is measured with a frequency of 2500 Hz. Each measurement was conducted for two minutes, which commonly resulted in a statistically significant amount of data and a small standard error of the mean. The standard error of the mean is calculated by dividing the standard deviation by the square root of the sample size (i.e., the number of bubbles).

For calibration, seven segments are filled sequentially until the reactor is filled with bed particles (Fig. 2a). Performed in the three directions of the X-ray sources, this procedure links the measured intensity of every detector and the corresponding fraction of particles in each direction. The calibration is performed without vertical internals. The seven-point calibration helps to avoid beam-hardening effects of the polychromatic radiation Alles and Mudde (2007). Thus, the attenuation of the X-ray can be converted into a path-length of existing cavities (i.e., bubbles).

Image reconstruction

The simultaneous algebraic reconstruction technique (SART), which was already applied by Mudde (2011), is used for 2D image reconstruction. For the reconstruction the mean of 10 measurements was taken, which results in an effective time resolution of 250 Hz. For the measurement shown in Fig. 2(b) and (c), two empty thin-walled acrylic glass tubes with diameters of 2.2 cm and 5.2 cm were inserted into the setup to evaluate the technique's accuracy. In Fig. 2(b), the raw data have been converted into the path-length of the cavities using the calibration data set; in Fig. 2(c), the resulting reconstructed image is presented. It can be seen that the diameters in the reconstructed 2D image are approximately equal to the diameters of the acrylic glass tubes; however, a bubble diameter of 2 cm is the minimum size that can be reliably reconstructed. This limitation can also be observed later in the measurement results. The consequence of a maximum spatial resolution of about 4.4 mm is that the diameter of a bubble with 2 cm outer diameter can be determined with a maximum accuracy of about ±25%, whereas for a larger bubble of 10 cm outer diameter the accuracy is about ±5%.

With the internals used, we made use of the known positions and diameters of the internals in the reconstruction algorithm; in every loop of the iterative code, the bubble hold-up at the positions of the internals was set to zero, which enabled sharp edges and relatively well defined bubbles near the internals. Further, as soon as

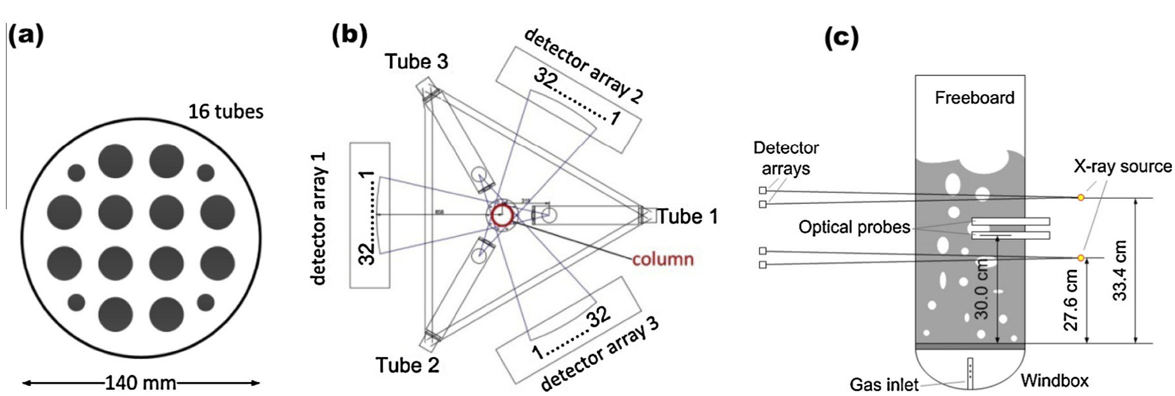

Fig. 1. (a) Top-view of the cross-section of the column with the vertical internals used; (b) top-view of the X-ray tomographic scanner with the column in the center; (c) side-view of the column with one X-ray source and the corresponding detector arrays as well as the optical probes being depicted (without vertical tubes).