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Correlating bubble size and velocity distribution in bubbling fluidized bed based on X-ray tomography

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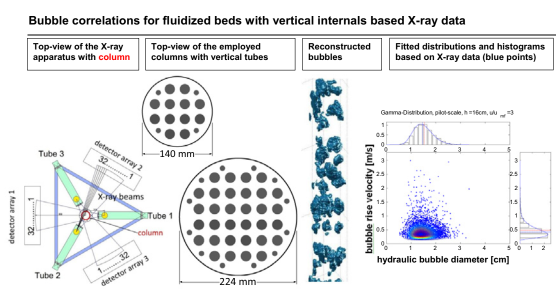
HIGHLIGHTS

- X-ray analysis of the hydrodynamics in lab- and pilot-scale bubbling fluidized beds.
- Distributions and averaged values of hydrodynamic properties provided.
- Empirical correlations as a function of the fluidization number and position.
- Link between bubble size and rise velocity proposed to improve bubble simulation.

GRAPHICAL ABSTRACT



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ABSTRACT

The design and scale-up of bubbling fluidized bed reactors remain an ongoing challenge, as the bubble size and velocity have to be known to enable a reliable design of this reactor type. Correlations between the average bubble size and rise velocity have been proposed in the literature, however, their distributions are rarely found. Especially the relationship between the distribution is usually unknown. Additionally, in catalytic bubbling fluidized bed reactors used for endothermic/exothermic reactions, bundles of heat exchanger tubes are employed, which are not considered by most correlations. In this work, the results obtained in a previous study and new data obtained using an ultra-fast X-ray apparatus were used to develop both a new type of bubble size and bubble rise velocity correlation, which include the distribution of these values. All of this data can be expressed as a function of the gas velocity and bed height. Two columns, one of laboratory scale and the other of pilot-scale, both with vertical heat exchanger tubes, were investigated.

1. Introduction

Catalytic bubbling fluidized beds are well suited for highly exothermic reactions, such as methanation. For such reactors, mass transfer between the bubble and dense phase usually limits the reaction rate [1]. Hence, large and fast bubbles, which have a low surface to volume ratio and residence time within the reactor, are critical to the breakthrough of educt gases [2]. Particularly, because of these large and fast bubbles, the bubble size and rise velocity distribution have to be known to enable reliable design and scale-up [3–5].

The literature includes several reports about the distribution of the bubble size, chord-length, and rise velocity in fluidized beds e.g. [6–9], a review summarizing different works is provided by [10]. Interesting are investigations based on X-ray tomography or similar non-invasive techniques, which are capable to detect both the bubble size and rise velocity to the same time [11].

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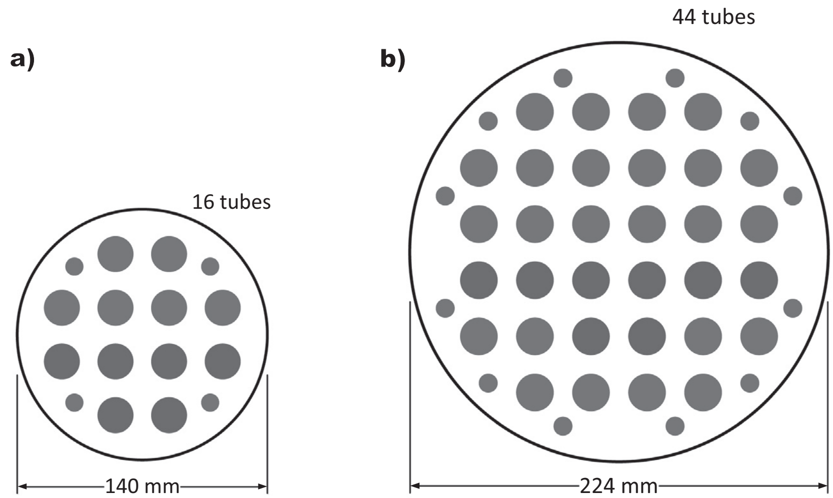

Fig. 1. Cross-sections of columns showing their vertical internal tubes: (a) lab-scale column adapted from [23], (b) pilot-scale column.

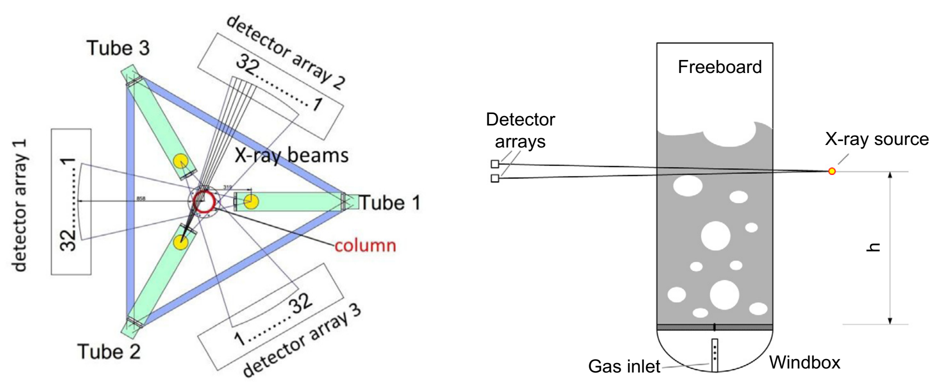

Fig. 2. Top- and side-views of the X-ray tomographic scanner with the column in the center, adapted from [25].

Some researchers have derived a dependency between the bubble size distribution and the chord-length distribution [12–14], others have derived a dependency between the average bubble size and the average bubble rise velocity [15,16], while still others have developed correlations for the bubble size- or bubble rise velocity distribution by relying on the Gamma, the Rayleigh distribution, or lognormal functions [17–23]. However, to the best of the authors' knowledge, none of these studies has developed a dependency between the bubble size distribution and the bubble rise velocity distribution.

In this study, the authors set out to simulate a bubble sample based on a new correlation type, which includes the bubble size distribution and the bubble rise velocity distribution. For the development of the correlation published X-ray measurement data from a lab-scale column equipped with vertical heat exchanger tubes [24,25] and unpublished data from a pilot-scale column equipped with similar tubes (see Section 2.1) were used. Different superficial gas velocities and measurement heights were studied using both columns. The columns were filled with Geldart A/B particles. Details about the X-ray measurement technique and its accuracy are provided in [26] as well as in the experimental section.

The use of the X-ray data provides the needed dependency between the rise velocities of individual bubbles, and their size. In contrast to earlier X-ray investigation, which correlated averaged values of the bubble size and rise velocity to the height – a nice comparison is for instance provided in [11], the authors connected the rise velocity and the size of individual bubbles rising in a bubble swarm.

Two different definitions of bubble diameter have been applied: the volume equivalent spherical bubble diameter as well as the hydraulic bubble diameter ($d_{b,hyd}$) the latter being calculated as four times the cross-sectional area (S) of a bubble at its center of mass, divided by the perimeter (P_{tot}) of the bubble, including the perimeter of the enclosed internals.

$$d_{b,hyd} = \frac{4S}{P_{tot}} \quad (1)$$

The derived method for bubble simulation, applicable for lab- and pilot-scale fluidized bed columns with vertical internals such as heat exchanger tubes, could be used to validate advanced bubbling fluidized bed models, or as input data for obtaining better predictions.

2. Material and methods

2.1. Experimental

The hydrodynamic properties of two different fluidized bed columns with vertical internal tubes were studied applying X-ray tomography. The type of tube bundles are e.g. used in acrylonitrile production, the aniline production and the synthetic natural gas production, a summary including different process examples is