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Short communication

Evaluation of a sectoral scaling approach for bubbling fluidized beds with vertical internals

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HIGHLIGHTS

▶ Modified scale-up approach of fluidized beds with vertical tubes.
▶ Scale-independent autonomous sector of vertical tubes as characteristic length scale.
▶ Scale-up verification with dimensionless pressure fluctuation signal and spectral analysis.
▶ Agreement of modified scale-up approach in terms of incoherent hydrodynamic phenomena.

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ABSTRACT

In this paper, an alternative scale-up approach for fluidized beds with vertical heat exchanger tubes is presented. This sectoral scaling approach is based on the hydraulic diameter of a sector of vertical tubes in the fluidized bed. In this way, scale-up becomes independent of the total column diameter of the large-scale unit, and consequently any fluidized bed with the corresponding sector of vertical tubes can be scaled. In the same way, more stringent scaling laws can be applied. As a result, it is shown that in the mid-section of an industrial-scale and a lab-scale fluidized bed, similarity in terms of the incoherent output power spectral density (IOP) of pressure fluctuation measurements is achieved.

1. Introduction

Fluidized bed reactors are nowadays used in many chemical and physical processes [1,2]. However, the scale-up of fluidized beds to commercial sizes is still a complicated and troublesome procedure [3–5]. In particular, the proper scale-up of hydrodynamic phenomena such as bubble growth is of utmost importance to obtain the anticipated performance and profitability of the reactor.

Since gas–solid interactions in a bubbling fluidized bed (BFB) are complex, it is usually impossible to precisely predict the hydrodynamics in an industrial-scale reactor solely based on computations. Therefore, in practice, a lab-scale cold flow model with similar hydrodynamics as the industrial-scale reactor is built to inexpensively and safely mimic hydrodynamic phenomena. Over the past decades, several scaled cold flow models have been constructed and successfully operated (e.g., [6–10]). However, there are still major challenges associated with the proper design of an appropriate cold flow model.

Traditionally, fluidized beds are scaled based on sets of dimensionless numbers which are kept constant for both scales. The most widely used set of these dimensionless numbers is the so-called full set of scaling relationships by Glicksman [11]

$$\frac{u_0 \rho_g L}{\eta}, \frac{u_0^2}{gL}, \frac{\rho_g}{\rho_p}, \frac{L}{H}, \frac{d_p}{L}, \phi, \ \text{psd} \tag{1}$$

In words, Eq. (1) includes (from left to right): Reynolds number, Froude number, gas–solid density ratio, bed geometry ratio, particle-bed diameter ratio, particle sphericity, and particle size distribution (psd). As the characteristic length scale L in Eq. (1), the entire bed diameter D of the full-scale reactor is taken (cf. Fig. 1). However, for large reactors this approach is limited in its applicability. In particular, if the large reactor is pressurized and the scaled cold flow model is supposed to be operated at ambient pressure, the cold flow model is often as large as the full-scale unit [5].

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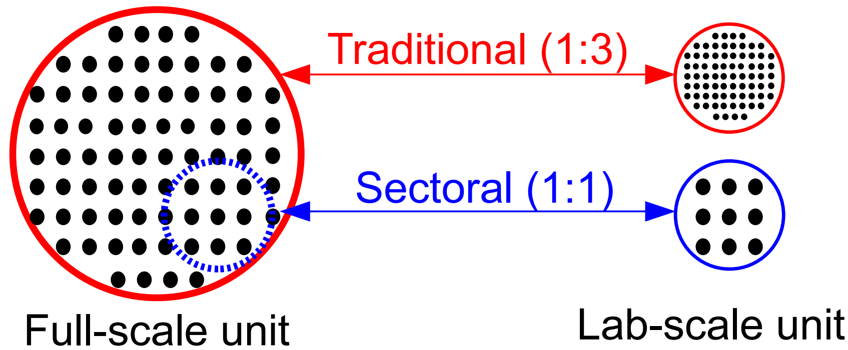

Fig. 1. Schematic principle of the traditional and the sectoral approach for the scale-up of fluidized beds with vertical tubes (=black dots).

While in earlier studies (e.g., [12,13]) this traditional scale-up approach has successfully been applied for low Reynolds numbers and small scale changes, more recent studies (e.g., [10,14–16] more and more question the accuracy of this approach. A critical discussion in this respect is given in a recently published review article of Rüdisüli et al. [5] on the scale-up of bubbling fluidized beds. Moreover, with large scale changes between the full-scale and the lab-scale unit and with changes in the Geldart type [17] of particles, the traditional scaling approach with dimensionless numbers based on the entire bed diameter D is even more problematic [4,5,14].

Alternatively, in industry, when fluidized bed reactors are equipped with vertical heat exchanger tubes, rather a sector of vertical tubes, which is operated at (more or less) the same operation conditions as the commercial unit, is investigated. This alternative concept of sectoral scaling is based on the idea of vertical tube banks constituting autonomous "sectors" of the entire reactor (cf. Fig. 1). That is, the influence of adjacent internals on the hydrodynamics in a fluidized bed is much stronger than that of internals further away or of the reactor wall. In other words, it is assumed that hydrodynamic phenomena such as bubble growth are confined to a certain zone (=sector) of the fluidized bed and interactions with other sectors are minimized by the vertical tubes. Thus, each sector is independent of the entire bed diameter and can consequently be scaled to any size. The scaled characteristic length scale L of the scaling laws in Eq. (1) is therefore not the entire bed diameter D, but the hydraulic diameter D_{hyd} of the sector

$$D_{hyd} = \frac{4A}{P} \tag{2}$$

with A as the cross-sectional area and P as the total wetted perimeter of the tubes within the sector. In this way, stricter scaling laws (e.g., the full set [11] instead of the simplified set [18]) can be employed and the cold flow model is still operated at atmospheric conditions. Although reportedly employed in industry, so far, this approach has not been discussed in the open literature.

Therefore, in this paper, an industrial-scale reactor is scaled in a lab-scale cold flow model according to this sectoral scaling approach. Since local and incoherent pressure fluctuations are associated with the passage of rising gas bubbles [19], which are again essential for the gas–solid mixing, heat and mass transfer as well as the overall conversion and selectivity of the reactor, the objective of this paper is to match the incoherent output power spectral density at both scales. To this end, pressure fluctuation measurements (PFMs) are taken at both the industrial-scale reactor and the cold flow model. In this respect, guidelines on how to properly measure PFM at an industrial-scale, pressurized, hot, and reactive fluidized bed are also provided.

2. Experimental

2.1. Lab-scale reactor

With the sectoral scaling approach, the industrial fluidized bed reactor is scaled down in a glass column fluidized bed ("Glas15") with internal diameter $D = 0.145$ m and total column height $H = 0.930$ m. At the wall of the glass column, several probe ports are located in order to take pressure fluctuation measurements (PFM). The porous distributor plate at the bottom of the glass column has a pore size of 10 μm. Beneath the distributor plate, there is a windbox with the gas inlet. For more information on the "Glas15", refer to Rüdisüli et al. [20]. For more information on how to take PFM in the "Glas15", refer to Rüdisüli et al. [21].

2.2. Full-scale reactor

The industrial-scale fluidized bed reactor used for this study is the pilot-scale methanation plant (PDU) in Güssing (Austria). A photograph of the PDU is shown in Fig. 2. The diameter of the reactor is less than 1 m, while its height is several meters. More detailed constructional features of the PDU cannot be given due to confidentiality terms. Therefore, confidential results in this paper are always displayed in dimensionless form and/or only discussed in a qualitative manner.

2.2.1. Pressure fluctuation measurement at PDU

In order to take pressure fluctuation measurements (PFM) at the PDU, six piezo-electric sensors by Kistler (type 7261) are used. A scheme of the setup of the PFM equipment is shown in Fig. 3. Since at the industrial-scale reactor pressure fluctuations are measured in a reactive environment, the sensors are separated from the reactor and the ambient air by pressurized "ex(plosion) protection boxes" (EPB). These EPB guarantee that the sensors do not become an ignition source in the unlikely event of reactive gas leaking out of the reactor. The overpressure inside the EPB is established with inert N_2, which is serially fed to the boxes (cf. Fig. 4). After the last EPB in the series, the inert gas is directed to a pressure switch which supplies the amplifier with electricity. The amplifier, in turn, is the electricity source of the sensors. If any of the EPB loses its overpressure, the pressure switch is switched off and the sensors can no longer be an ignition source.

Just outside the EPB, a stop valve is installed which enables easy removal. The coupling between the sensor and the (steel) tube is insulated with a short PTFE tube. Otherwise electric currents from electrostatics inside the fluidized bed or other poorly insulated electricity sources can be transferred to the sensor. These electric currents would corrupt the recorded pressure signal.

PFM probes at the industrial-scale reactor are located flush with the wall. Since it is not possible to measure PFM in the windbox of