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Estimation and experimental validation of the circulation time in a 2D gas–solid fluidized beds

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ABSTRACT

The circulation time is defined as the time required for a group of particles to reach the freeboard from the bottom of a fluidized bed and return to their original height. This work presents an estimation and validation of the circulation time in a 2D gas–solid bubbling fluidized bed under different operating conditions. The circulation time is based on the concept of the turnover time, which was previously defined by Geldart [1] as the time required to turn the bed over once. The equation $t_{c,est} = 2Ah'/Q_b$ is used to calculate the circulation time, where A is the cross-section of the fluidized bed, h' is the effective fluidized bed height and Q_b is the visible bubble flow. The estimation of the circulation time is based on the operating parameters and the bubble phase properties, including the bubble diameter, bubble velocity and bed expansion.

The experiments for the validation were carried out in a 2D bubbling fluidized bed. The dense phase velocity was measured with a high-speed camera and non intrusive techniques such as particle image velocimetry (PIV) and digital image analysis (DIA), and the experimental circulation time was calculated for all cases.

The agreement between the theoretical and experimental circulation times was satisfactory, and hence, the proposed estimation can be used to reliably predict the circulation time.

1. Introduction

A high reaction-rate per unit reactor volume is the deciding factor in the selection of a fluidized bed in many gas–solid reactions processes (e.g., drying, combustion, chemical processes). Therefore, depending on the process, the design and scale-up of the fluidized bed is currently an important factor to take into account. In particular, the scientific community has paid special attention to the movement of the particles because their movement has a great influence on the mixing and performance of the fluidized bed. The studies of solids movement can be divided into two categories: those in which the dense phase in studied and those in which the bubble phase is analyzed.

Several authors have focused on studying the solid phase movement using tracking techniques. Tomography tracking techniques have been employed to characterize the motion of objects in a 3-D fluidized bed. Positron emission was used by Stein et al. [2] to observe and quantify the particle trajectory as well as the flow pattern, velocity and circulation frequency of the solids. The authors observed in deep beds (cylindrical columns, group B particles) that the particles move upward in the central region and downward near the wall. Other authors, such as Grassler and Wirth [3] have used X-ray computer tomography to determinate the solids concentration with high spatial resolution to characterize the gas–solid flow inside a circulating fluidized bed, especially in vertical tubes. Du et al. [4] used electrical capacitance technology to describe quantitatively and qualitatively the gas and solid mixing in a quasi 3-D fluidized bed under turbulent and bubbling regimes using helium and phosphor tracer techniques. In addition, optical and non intrusive tracking techniques, such as particle image velocimetry (PIV), have been applied to characterize the solids movement in a 2-D fluidized bed [5,6] to study the movement, mixing and particle segregation.

On the other hand, several studies have investigated the bubble spatial distribution and bubble properties in fluidized beds to characterize the fluidized bed behavior, since the performance of the fluidized reactors depends strongly on the bubble behavior [7]. Kunii and Levenspiel [8] used pressure and optical probes to measure the fluidized bed dynamics (bubble size and bubble velocity) in a 3-D (three dimensional) bubbling fluidized bed. Their experimental results were compared with the results from a two-fluid Eulerian–Eulerian 3-D simulation of a cylindrical bed, filled with Geldart-B particles and fluidized with air in the bubbling regime. The values of the bubble pierced length and velocity retrieved from the experimental optical signals compare well in different radial and axial positions to the values obtained from the simulated particle fraction. These results indicate that the two-fluid model is able to reproduce the essential dynamics and interaction between the bubbles and the dense phase in the studied 3-D bed. Shen et al. [9] developed a new method of digital image analysis technique to study the 2-D hydrodynamics of a bubbling fluidized bed with a digital video camera. The authors studied the size and the velocity of the gas bubbles, as well as the axial and radial distribution of bubble voidage, to relate these

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properties to the visible bubble flow and the gas throughflow, which is of great importance for combustion applications. Busciglio et al. [10] presented a DIA technique to study the 2-D fluidization dynamics in a lab-scale bubbling fluidized bed. They obtained different bubble properties including the bubble size and bubble velocity distribution. The results agree well with the literature, thus confirming the potential of this technique. Asegehegn et al. [11] also used DIA technique to characterize the bubbles in a bubbling fluidized bed with and without immersed tubes. The technique developed by the authors and implemented in the study allowed for the simultaneous measurement of various bubble properties, such as the bubble diameter, rise velocity, aspect ratio and shape factor. The experimental results were found to be in good agreement with available literature correlations. To properly design a process in a fluidized bed, a comparison between the circulation time of the reactor and the characteristic reaction time for a specific application is needed. This comparison is also useful for the modeling of fluidized beds to verify the assumption made in the model for different purposes (countercurrent, back-mixing, well-mixing, plug-flow). To ensure that the fluidized bed is well mixed, the characteristic circulation time of the specific application needs to be similar to the circulation time. Besides, the circulation time obtained with the estimation can be useful to validate Dynamic Numerical Simulation models.

This work presents a combination of two non-intrusive techniques (PIV and DIA) applied in a 2-D bubbling fluidized bed to characterize the dense and bubble phases. The aim is to calculate the circulation time for a group of particles within the fluidized bed under different operating conditions. The results were compared with an estimation of the circulation time, based on the operating parameters and correlations of the bubble properties. The estimation of the circulation time reproduces is able to reproduce the experimental results.

2. Experimental setup

The experimental setup used in this work was similar to the one described by Sánchez-Delgado et al. [6]. A 2-D cold fluidized bed (50 cm width (W), 150 cm height (H) and 0.5 cm thickness (t)) with a glass front side and a rear wall made of aluminum and covered with a black card was used to improve the contrast during the images acquisition. The bed was illuminated by two *650W* spot-lights from the front of the bed. Fig. 1 shows a sketch of the experimental setup.

Spherical glass particles (Geldart-B [1]), which had been previously sieved, with a density, ρ_p, of 2500 kg/m^3 were fluidized with air. The diameter, d_p, of the particles ranged from 600 to 800 μm following a normal distribution, with a mean of 677.8 μm and standard deviation of 93.3 μm.

The gas pressure drop through the distributor was high enough to ensure that the bed and the air supply system were not coupled [12–14].

The experimental conditions were varied to test the effects of the bed aspect ratio and the excess air; four fixed bed heights (h = 30, 40, 50, 60 cm) and five excess-air ratios (U/U_{mf} = 1.5, 1.75, 2, 2.25, 2.5) were used. The minimum fluidization velocity U_{mf} was measured for the four bed height, h. The resulting values were U_{mf} = 43.17, 45.53,

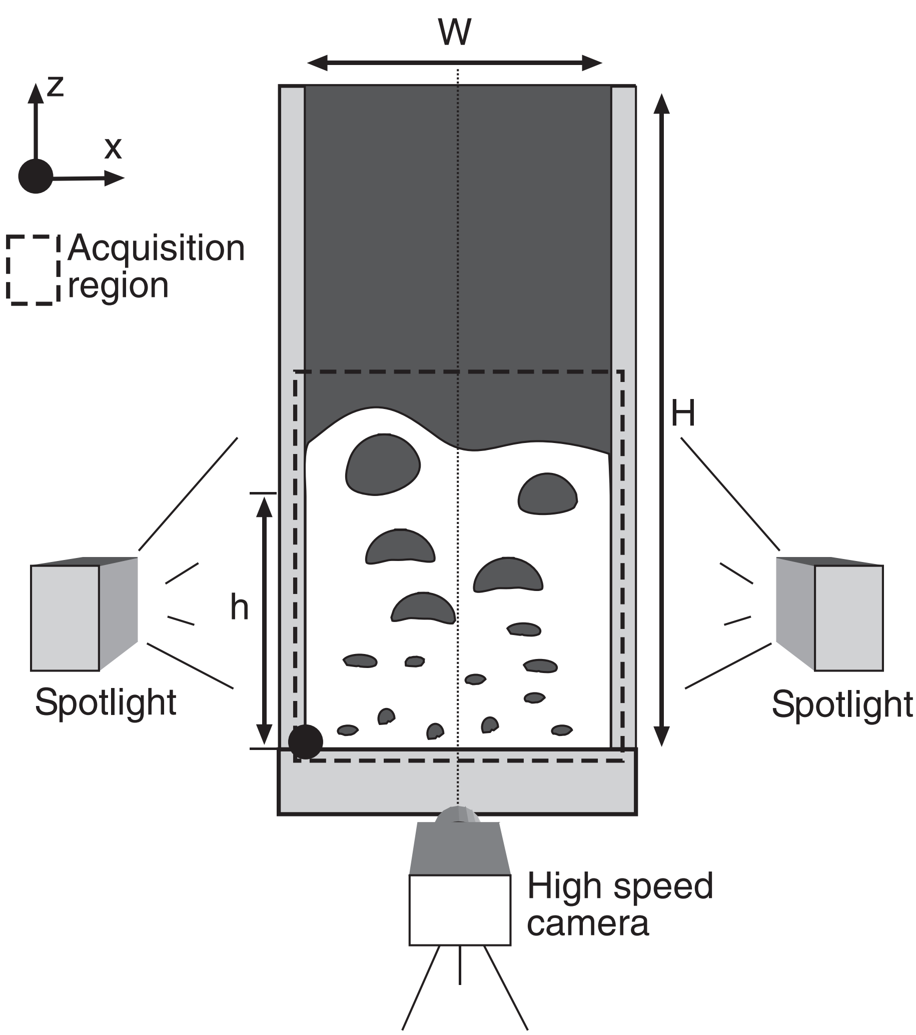

Fig. 1. Sketch of the experimental setup.