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Experimental and computational study on the bubble behavior in a 3-D fluidized bed

A. Acosta-Iborra *, C. Sobrino, F. Hernández-Jiménez, M. de Vega

Departamento de Ingeniería Térmica y de Fluidos, Universidad Carlos III de Madrid, ISE Research Group, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain

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ABSTRACT

The results from a two-fluid Eulerian–Eulerian three-dimensional (3-D) simulation of a cylindrical bed, filled with Geldart-B particles and fluidized with air in the bubbling regime, are compared with experimental data obtained from pressure and optical probe measurements in a real bed of similar dimensions and operative conditions. The main objectives of this comparison are to test the validity of the simulation results and to characterize the bubble behavior and bed dynamics. The fluidized bed is 0.193 m internal diameter and 0.8 m height, and it is filled with silica sand particles, reaching a settle height of 0.22 m. A frequency domain analysis of absolute and differential pressure signals in both the measured and the simulated cases shows that the same principal phenomena are reproduced with similar distributions of peak frequencies in the power spectral density (PSD) and width of the spectrum. The local dynamic behavior is also studied in the present work by means of the PSD of the simulated particle fraction and the PSD of the measured optical signal, which reveals as well good agreement between both the spectra. This work also presents, for the first time, comparative results of the measured and the simulated bubble size and velocity in a fully 3-D bed configuration. The values of bubble pierced length and velocity retrieved from the experimental optical signals and from the simulated particle fraction compare fairly well in different radial and axial positions. Very similar values are obtained when these bubble parameters are deduced from either simulated pressure signals or simulated particle volume fraction. In addition, applying the maximum entropy method technique, bubble size probability density functions are also calculated. All these results indicate that the two-fluid model is able to reproduce the essential dynamics and interaction between bubbles and dense phase in the 3-D bed studied.

1. Introduction

Fluidized bed technology is widely used in process industry and energy production. Gas–solid fluidized beds operating in the bubbling regime, for which high contact efficiency between the gaseous and the solid phases leads to high conversion and heat transfer rates, are now broadly commercialized. In this regime, the bubble flow is of main importance to obtain a good mixing between gaseous and solid phases, while the dynamic characteristics of the fluidized bed, given by other properties such as pressure and pressure fluctuations, are relevant for the operation of the bed under stable conditions. Thus, both bubble flow and pressure dynamics can be considered major parameters during the design, operation and scale-up of these systems. However, most of the work is still dependent on expensive pilot-scale experiments along with empirical or semi-empirical models obtained from laboratory studies. Therefore in the last years, modeling and numerical simulations of fluidized beds have increased interest on them as a complementary tool to experiments.

Presently, simulation of small- and medium-scale gas fluidized beds is commonly undertaken by means of two-fluid computational fluid dynamic (CFD) models, also known as Eulerian–Eulerian two-fluid models, which are primarily based on the representation of the gas phase and the particulate phase as two interpenetrating continua (Gidaspow, 1994; van Wachem and Almstedt, 2003). Two-fluid models provide information about the macroscopic hydrodynamics (i.e. velocity and volume fraction) of the two phases, including the bubble formation and motion. Therefore, these models are especially suitable for the understanding of fluidized beds regarding dense phase bulk motion, and gas phase flow including bubbles. Although two-fluid models have been applied in the literature with satisfactory results to predict the behavior of bubbles in fluidized beds, there are numerous questions that need further validation (Grace and Taghipour, 2004). For example, the closure equations for the particle drag, viscosity and pressure rely on the granular temperature theory, which is based on the assumption of

* Corresponding author: Tel.: +34 916248465.
E-mail address: aacosta@ing.uc3m.es (A. Acosta-Iborra).

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isotropy in rapid granular flows (Gidaspow, 1994). The consideration of particles as perfectly spherical is also a simplification that may deteriorate the accuracy of the simulated interparticle and interphase stresses. Besides, to make affordable the simulation, boundary conditions are simplifications of what actually occurs in beds. For example, the commonly employed boundary condition of uniform velocity (i.e. spatially homogeneous) for the air inlet at the bed distributor is a realistic assumption of beds under bubbling regime. However, small time fluctuations of the air entering the bed at the distributor might influence the bed dynamics as a result of the bed sensitivity to small perturbations (Peirano et al., 2002). A problem always present in fluidized bed simulations is the influence of the mesh resolution on the accuracy of the large gradients appearing at the bubble boundary. As bubbles can cross any point in the bed, the use of very fine meshes covering all the bed volume is unaffordable in three-dimensional simulations. Owing to all these questions, there is a need of practical validation of two-fluid models, which should be carried out for each particular bed geometry and regime.

A greater detail in the description of the particle phase can be obtained using Lagrangian models such as discrete particle models (Deen et al., 2007) and lattice Boltmann models (Ladd and Verberg, 2001), which allow the simulation of the individual motion of each particle. Although great progress has been done in the last few years in the field of Lagrangian models, their use is still restricted to a number of particles far below the amount encountered in fluidized beds of industrial interest.

Most of the comparisons between experiments and two-fluid models presented in the literature account for two-dimensional or quasi two-dimensional (2-D) beds. van Wachem et al. (1998) compared with existing correlations the time-averaged bubble size and velocity obtained with an Eulerian–Eulerian multiphase CFD model of a 2-D square column filled with Geldart-B particles in free bubbling regime. This study was completed in van Wachem et al. (1999), where the authors presented the dynamic characteristics of the gas–solid behavior and compared it with published experimental data and correlations. The comparison included the velocity of pressure and voidage waves, the power spectra of pressure and voidage fluctuations and the Kolmogorov entropy, among other results. Taghipour et al. (2005) tested their model predictions of time-averaged solid volume fraction, bed expansion ratio, pressure drop and qualitative gas–solid flow pattern against experimentally obtained pressure drop data and local voidage calculations using a reflective optical fiber probe in a 2-D Plexiglas column. The size distribution, rise velocity and visible flow of bubbles in a freely bubbling fluidized bed for Geldart-B and D particles predicted by the constant viscosity model and the kinetic theory of granular flow models were compared by Patil et al. (2005) with correlations and experimental data taken from other authors. Wang et al. (2008) used a two-fluid model in a 2-D domain to study the flow behavior of particles in a riser; the computed results were compared with experimental particle distributions, velocities and bed expansion ratio measurements reported in literature for 2-D systems. Passalacqua and Marmo (2009) performed a two-fluid model simulation of a 2-D bubbling fluidized bed with and without a central jet using different frictional stress models. They compared the equivalent diameter obtained from the area of their simulated bubbles, with experimental data present in the literature. Most of these studies show a reasonable agreement between experiments and simulations regarding the bed dynamics (e.g. pressure signals) and bubble behavior, but they are restricted to 2-D bubbling beds.

There are also studies on the bed dynamics and bubble characteristics that use two-dimensional numerical domains to represent three-dimensional (3-D) systems. That is the case of McKeen and Pugsley (2003), who used a 2-D two-fluid CFD model to simulate a 3-D freely bubbling bed of FCC particles. Their simulations results of time-averaged radial voidage profiles, radially averaged solids volume fraction and bed expansion were compared to experimental data, extracted from electrical capacitance tomography. Johansson et al. (2006) simulated a fluidized bed operating in the slugging regime. As a validation, they evaluated their results with the power spectral density distribution of the fluctuating pressure signal and with local bubble parameters obtained experimentally with capacitance probes signals provided by other authors. Ahuja and Patwardhan (2008) compared their simulation and experimental results of solids hold-up in a bubbling fluidized bed and studied the effect of geometrical parameters such as internals and gas distributor configuration. In that study, experiments were carried out in a cylindrical column using gamma ray tomography, whereas the simulation of the bed was done in a 2-D domain. A cylindrical laboratory reactor was modeled in two dimensions by Hulme et al. (2005). These authors conducted a parametric study to determine the effect of time step, differencing scheme, closing equations and frictional stress in the simulation. The bubble properties, such as the average bubble diameter, were determined from maps of solids fraction using different cut-off voidages (0.3, 0.2 and 0.15), which showed that the definition of the cut-off is important to determine the bubble boundary.

However, it is not clear if two-dimensional simulations can always be used as a reliable tool to reproduce the bed dynamics and bubble behavior in 3-D beds. At this regard, the limit of the use of 2-D models to study particular implementations of 3-D systems has been subject of analysis in several works. Peirano et al. (2001) studied, in a statistically stationary bubbling fluidized bed of rectangular section (one lateral length much shorter than the other), the differences between 2-D and 3-D simulations by comparing their numerical simulations to experimental data concerning the power spectra of pressure fluctuations, the bed height and the probability distribution function of the particle volume fraction. They concluded that there may be significant differences between 2-D and 3-D simulations, pointing out that 2-D simulations can only be used for sensitivity analysis, and that quantitative validation must be done in 3-D. Moreover, they found that only 3-D simulations can predict the bed height and the pressure spectra of the bed, because of the natural three-dimensionality of the flow. More recently, Xie et al. (2008) presented the range of validity of 2-D simulations to approximate both cylindrical and rectangular fluidized beds. The comparison with full 3-D simulations was focused on the bed height, and the time-averaged values of void fraction and velocity of gas and solids at different heights in bubbling, slugging and turbulent regimes, showing that discrepancies can be significant when the gas superficial velocity is sufficiently high (i.e. $U \geq 1.85 U_{mf}$) to produce bubbles of final size comparable to the bed width.

Despite the above commented differences between 2-D and 3-D simulations, two-fluid 3-D simulations are comparatively scarce in the literature, probably because of their computational cost. Peirano et al. (2002) studied the influence of the air supply system in a freely bubbling fluidized bed of rectangular section. They simultaneously used pressure and optical probes at the same location and capacitance probes. Nevertheless, owing to the high noise level present in their optical signals, only the results from the capacitance probes were used for comparison with a two-fluid simulation. In particular, results from the numerical simulation were validated against measurements of the bed height, the spatial distribution of solids and the pressure spectra. Peirano et al. (2002) found some significant differences between their numerical predictions and these measurements. According to their results, the probability density function of particle volume fraction leads to a peak value shifted towards a volume