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3-D face-masking detection and tracking algorithm for bubble dynamics: Method and validation for gas–solid fluidized beds

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ABSTRACT

The transient behavior of rising bubbles plays a critical role on the performance of fluidized bed reactors, but predicting bubble dynamics is difficult. CFD has been shown to be capable of reproducing bubbling phenomena, but data interpretation and visualization is challenging. In this study, a 3-D detection and tracking algorithm, called face-masking, is developed and validated by numerical simulations of lab-scale and pilot-scale gas–solid fluidized beds. This algorithm identifies discrete bubbles using the instantaneous whole-field void fraction data. Individual bubbles are characterized in detail, including size, shape and location. The algorithm tracks bubbles across successive time frames and computes axial and lateral bubble velocities. Bubble dynamics predicted by the face-masking algorithm are validated against four different published experimental measurements. The face-masking algorithm provides a new tool for post-processing large-scale three-dimensional fluidizedbed simulation data. The bubble surfaces found by this algorithm will enable computation of normal fluxes through the surface. This algorithm can also be applicable in other areas of multiphase flows where characterization of bubbles, droplets, and clusters is necessary.

1. Introduction

Fluidized beds are one of the most applied technologies in petroleum, chemical and energy industries [1]. They are challenging to design and scale up, primarily, due to the complex transient characteristics created by the formation of bubbles inside the bed. The performance of a fluidized bed is, therefore, significantly influenced by the formation of gas bubbles and their distribution, facilitating rapid solids mixing, impacting reaction rates, product selectivity, mass transfer, heat transfer rates to immersed surfaces, and elutriation of particles from the bed [2].

According to the classical two-phase theory by Toomey and Johnstone [3] and the Davidson theory for bubble movement [4], any fluid flow exceeding the minimum fluidization velocity passes through the fluidized bed as bubbles. Many studies including experimental and computational showed that rising bubbles in gas–solid fluidized bed has a significant impact on solids motion [5–12]. However, there is still no precise pattern that links solids movement and bubble dynamics due to the lack of experiments simultaneously measuring the solids and bubble motion, for a range of particle properties and operating conditions.

A sound understanding of bubble dynamics is, therefore, of primary importance for investigating behavior of fluidized beds. The formation and development of bubbles in gas–solid fluidized bed has been extensively studied employing different intrusive and non-intrusive techniques, like optical signals [13,14], pressure fluctuations [15–17] or electrical pulses [18,19], high speed cameras and digital image analysis [20–22], X-ray [23–26], electrical capacitance [23] and MRI [27]. From this range of measurement techniques, it is evident that the main difficulty in analyzing fluidization quality and bubble dynamics is concerned with the measurement of bubbles and their physical properties in the bed such as position, dimensions, axial and lateral velocities.

Advances in the theory and numerical techniques and the availability of fast affordable computing power have allowed researchers using the first-principles based computational fluid dynamics (CFD) towards a predictive tool to explore complex hydrodynamic behavior of gas–solid fluidized bed. CFD is capable of intrinsically capturing the complexity of bubble formation and the resulting non-linear interactions because of its fundamental basis in the conservation of mass, momentum, species, and energy. Many authors recognize the advantage of CFD as it can provide insight useful for scale-up, design, or process optimization for reliable commercial plants reducing economic risk, and potentially allowing for rapid scale-up [28–32]. In fact, CFD can allow for virtual experimental “measurement” that cannot be done in the physical world easily, or at all. However, the majority of bubble dynamics are restricted to pure two-dimensional (2-D) or slices of three-dimensional (3-D) cylindrical beds [12,25,28,33] or pseudo-2-D

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rectangular beds of small thickness [34,35]. Although 2-D bubble statistics provides valuable information on fluidization, many authors recognize the limitation of 2-D analysis [17,35–37]. Nevertheless, all practical gas–solid flows are three-dimensional, and studies of bubble statistics are limited in literature because of the difficulties associated with flow visualization and measurements — both experimentally and computationally [25].

Recently, Bakshi et al. [38] developed a 3-D bubble statistics algorithm that used void fraction data from a 3-D simulation to calculate bubble properties. In that algorithm, initially, a threshold was set to discard a large portion of void fraction data from computational cells, and then remaining data cells were interpolated using a fine grid (a cube with side of 2 mm, irrespective of CFD grid size) for resolving bubble boundaries. Verma et al. and Sobrino et al. used a reconstructive method that processed 2-D contours in consecutive horizontal sections at different axial locations and then stacking them to obtain bubble properties [25,37]. A sequence of target-grid and pending-grid method, known as flood-fill method, is developed by Lu et al. [33] to determine bubble properties from 2-D CFD data.

The above observations suggest that whichever the method employed, these approaches, except Bakshi et al. [38], may be inefficient when applied to large volumes of simulation data from pilot/commercial-scale three-dimensional beds. Nonetheless, most of the previously developed methods are unable to capture surface properties such as gas flux, local stresses at the bubble surfaces as they compute bubble statistics by aggregating the volume of computational grid cells. In the present work, a new 3-D algorithm, called “face-masking”, is developed that will enable processing large volume of 3-D numerical simulations data for determining bubble properties. This algorithm uses the instantaneous whole-field of void fraction data of 3-D fluidized bed simulation, and extracts the bubble surface by triangulating it. The algorithm identifies discrete bubbles, characterizes the size and shape of those bubbles, and tracks the bubbles as they rise through a bed, including splitting and coalescence. This algorithm is verified using predefined shapes and validated by computing bubble properties using data from 2-D and 3-D fluidized bed simulations and comparing them with experimental measurements for a wide range of particle sizes and for different bed geometries (lab- and pilot-scale). In addition, bubble properties computed by this algorithm are also compared with commonly used semi-empirical correlations from literature. This is a complete algorithm and can be easily applied for identifying bubbles, droplets, clusters, etc. in multiphase flow [38] and validating 3-D numerical simulations.

2. Experimental studies

Bubble dynamics characterized by face-masking algorithm from simulation data are compared with four different experimental measurements by Velarde et al. [39], Rüdisüli et al. [15], Verma et al. [25], and Geldart [40]. Velarde et al. [39] used glass beads as bed material in a pseudo-2-D quartz column with bed width, depth and height of 0.25, 0.015 and 0.7 m respectively. Bubble sizes are measured from images captured by a Dantec Flowsense 16 M camera coupled with an optical endoscopic laser. Rüdisüli et al. [15] carried out experiments using γ-Al_2O_3 as bed materials in a glass column with internal diameter of 14.5 cm. Bubble sizes were measured using reflective-type optical probes at a sampling frequency of 400 Hz. A bubble linking algorithm that used the measured response from two probes placed 1 cm apart was used to determine bubble rise velocity. Verma et al. [25] conducted their experiments in a polycarbonate cylindrical column with inner diameter of 0.1 m using glass as bed material. An ultrafast electron beam X-ray scanner acquiring data at 1000 Hz with a high spatial resolution of about 1 mm was placed at three cross-sections of the bed. Images from experiments were reconstructed using an algorithm to determine bubble properties. In Geldart's experiment [40], sand particle was used as bed material in a perspex column with inner diameter of 30.8 cm. A standard meter-rule marked in millimeters, still 35-mm photographs, and 16-mm high speed cine pictures were used to analyze bubble sizes.

All of these experiments described above were operated in the regime of bubbling fluidization using Geldart B and D particles. A summary of all the experimental conditions and particle properties is presented in Tables 1 and 2, respectively.

3. Simulation setup

3.1. Two-fluid model (TFM)

In this study, the TFM is used which treats each phase (fluid and solid) as an interpenetrating continuum, and therefore to construct integral balances of continuity, momentum, and energy for both phases, with appropriate boundary and leap conditions for phase interfaces. TFM applies averaging techniques and assumptions to obtain momentum balance for the solids phases since the resultant continuum approximation for the solid phase has no equation of state and lacks variables such as viscosity and normal stress [41]. The evaluation of the solid phase stress tensor is based on the flow regimes - the viscous regime where the stress tensor is evaluated using the Kinetic Theory of Granular Flow (KTGF) and the plastic flow regime where the theory of Schaeffer [42] is employed to account for the frictional effects [43]. The TFM equations are coupled with constitutive relations derived from data or analysis of nearly homogeneous systems. The interphase momentum transfer between gas and solid phases is coupled by drag force. Numerous correlations for calculating the drag coefficient of gas–solid systems have been reported in the literature, including those of Syamlal and O'Brien [44], Gidaspow [43], and Wen and Yu [45]. Syamlal-O'Brien drag model that bridges the results of Wen and Yu [45] for dilute systems and the Ergun approach for dense systems, is used in this work. The detailed description of the conservation of mass, momentum, and energy equation and drag model of the TFM are described somewhere else [46].

3.2. Initial and boundary conditions

The standard initial conditions were used to describe both 2-D and 3-D simulations. The bed was assumed to be under minimum fluidization with superficial gas velocity equal to u_{mf} initially. Lateral gas velocities were set to zero for initial conditions. A constant pressure was defined in all horizontal planes up through the bed of particles depending upon static pressure. The upper section of the simulated geometry, or freeboard, was considered to be occupied by gas only at time zero. For both 2-D and 3-D simulations, the lateral walls were modeled using partial-slip boundaries, with no-slip for gas and free-slip for solid phase. The particle-wall interactions are modeled using the Johnson-Jackson model [47], which evaluates the solids slip velocity at the walls by considering momentum and granular energy balance. Dirichlet boundary conditions were employed at the distributor to specify a uniform gas inlet velocity, U_0. Pressure boundary conditions were employed at the top of the freeboard.

Table 1
Experimental conditions.

Physical properties	Velarde et al. [39]	Rüdisüli et al. [15]	Verma et al. [25]	Geldart [40]
Bed width/diameter, m	0.25	0.145	0.10	0.308
Static bed height, m	0.375	0.50	0.20	0.20
Measuring height, m	0.2–0.35	0.23, 0.45	0.05–0.20	0.05–0.20
U/U_{mf}	3.0	2.3–6.8	1.25–3.0	1.0–3.0
Type of geometry	Pseudo-2-D	3-D	3-D	3-D