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Bubble formation at a central orifice in a gas–solid fluidized bed predicted by three-dimensional two-fluid model simulations

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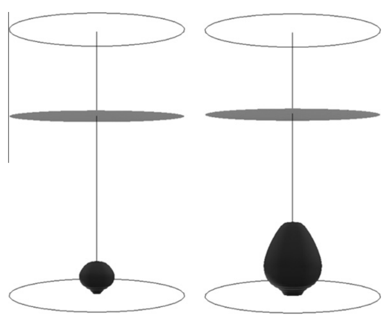
HIGHLIGHTS

- We present an extensive study of bubble formation at an orifice in a fluidized bed.
- We use a highly efficient two-fluid model based on kinetic theory of granular flow.
- We quantify the effects of particle properties, flow rate and bed size.
- We compare our results with experimental results and approximate theoretical models.

GRAPHICAL ABSTRACT



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ABSTRACT

We apply a recently developed two-fluid continuum model (TFM) based on kinetic theory of granular flow (KTGF) in three dimensional cylindrical coordinates, to investigate bubble formation through a single central orifice in a gas–solid fluidized bed. A comprehensive study for Geldart D type particles, revealing the influence of particle diameter, jet injection flow rate, and bed size on bubble characteristics have been investigated. At a given gas injection flow rate, the bubble diameter continuously increases while gas leakage from the bubble to the emulsion phase decreases with time. With increasing particle diameter, leakage fraction increases and hence a smaller bubble diameter is predicted. These results are consistent with DPM simulations, experimental results and approximate bubble formation models reported previously in the literature.

1. Introduction

Gas–solid fluidized beds are extensively used in process industries because of their excellent mixing and heat and mass transfer characteristics. They are currently used in separation, classification, drying and mixing of particles, chemical reactions and regeneration processes. The performance of a fluidized bed in relation to solids motions, gas–solids contacting are majorly governed by its bubble characteristics [1], so understanding the formation and propagation of bubbles is of great practical interest. The bubbles are formed at the gas distributor plate; thereafter these bubbles propagate throughout the bed with different characteristics such as bubble size distribution, bubble rise velocity and the bubble frequency distribution. Bubble formation in gas-fluidized beds is a fairly complicated process influenced by many factors, including properties of the gas and particulate phases, orifice geometry, and gas flow rate. Many theories have been developed and validated for bubble formation, both experimentally and numerically. However, most of the theories were limited to, or validated for, 2D or pseudo 2D systems. 2D simulations have been performed and compared with experimental data gathered from pseudo 2D beds [2–4]. Simulations with 2D cylindrical coordinates have also been used to predict bubble formation in 3D

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Nomenclature

C	fluctuation particle velocity, m s^{-1}
g	gravitational acceleration, m s^{-2}
I	unit tensor, –
p	pressure, Pa
q	kinetic fluctuation energy, kg s^{-1}
u	velocity, m s^{-1}
t	time, s
e	coefficient of restitution, –
d_p	diameter of particle, m
g_0	radial distribution function, –
D	diameter, m
V	volume of the bubble, m^3
Q	volumetric flow rate, m^3 s^{-1}

Greek symbols

β	interphase momentum transfer coefficient, kg m^{-3} s^{-1}
γ	dissipation due to inelastic particles collisions, kg m^{-1} s^{-3}
ε	volume fraction, –
ρ	density, kg m^{-3}
μ	shear viscosity, kg m^{-1} s^{-1}
Θ	pseudo particles temperature, m^2 s^{-2}
τ	stress tensor, Pa
Ψ	leakage fraction, –

Subscripts

s	solid phase
g	gas phase
e	equivalent
mf	minimum fluidization

Operator

∇	gradient
$\nabla\cdot$	divergence

beds, but the validity of these simulations is questioned. Geldart [5] reported that in a 2D bed bubbles are restrained by the walls in one dimension, transforming to slugs when viewed from the side of the bed, contributing to a greater bed expansion and considerable difference between particle and bubble characteristics. Three-dimensional studies are rarely found in the literature as they still pose a challenge: numerically because of high computational costs, and experimentally because flow visualization and measurements are difficult to perform. Nevertheless, the most commonly used geometry in industry is the cylindrical one. Therefore, in this work we consider a full three dimensional domain with cylindrical grid structure to study realistic bubble formation at a central circular orifice in a cylindrical fluidized bed. We investigate the influence of particle diameter, gas injection velocity, bed size, orifice size and computational grid size on the bubble characteristics. Previous studies [2–4] on bubble formation in 2D reported that bubble formation is sensitive to the background gas velocity, i.e. U_{mf}. The most pronounced gas leakage effects take place for particles having relatively high U_{mf} values, which is why in this study we focus on particles falling in the Geldart D classification. Comparison is made with experimental data reported by Nieuwland [4] and approximate bubble formation models [6,7].

These models have been proposed based on different assumptions to describe bubble formation in a gas–solid fluidized bed at a single orifice. Davidson and Schuler [8] were the first to provide a theoretical solution to a single bubble formation in a viscous liquid. On the same basis, with the assumption of no gas exchange from the bubble to the surrounding emulsion phase, Harrison and Leung [7] provided a formula for the bubble volume at detachment and the time of bubble detachment. Nguyen and Leung [9] performed experiments on a 2D fluidized bed of alumina particles and concluded that a considerable (47%) amount of gas leakage takes place from the bubble to the emulsion phase. Later, Rowe et al. [10] came to the same conclusion after observations in cylindrical fluidized beds using X-ray cine-photography. Yang et al. [11] accounted for gas leakage from the bubble surface to the surrounding emulsion phase, from evidence of their own experimental work on a large-scale (3 m diameter semicylindrical) cold flow construction. They assumed that the gas leaks from the bubble at a rate equal to the minimum fluidization velocity, as was suggested by Zenz [12]. However, this model is semi-empirical because it requires the bubble frequency as an input obtained from experiments. Caram and Hsu [6] applied Darcy's law to obtain the expression for the superficial gas leakage velocity at the bubble boundary. They reported satisfactory agreement of their model prediction with available experimental data.

In recent years, powerful computational resources have enabled the use of detailed computational models to investigate bubble formation on a feasible time span and in three-dimensional space. Two of the most common modeling approaches for dense gas-fluidized beds are the two-fluid model (Euler–Euler) and the Discrete Particle Model (Euler–Lagrange). In the latter, particle trajectories are obtained by integrating Newton's equations of motion. Particle–particle and particle–wall interactions are explicitly taken into account using various physical models such as the soft sphere model. To study large three dimensional systems a Lagrangian approach becomes computationally too expensive, particularly for small particles. Therefore Euler–Euler approaches have been adopted by several authors, where the gas and solid phase are treated as fully interpenetrating continua. Incorporating the kinetic theory of granular flow is used to account for particle–particle interaction. Kuipers et al. [2] used a two-fluid model (TFM) to satisfactorily predict the formation of a bubble at a single orifice in a two dimensional (2D) bed. Pierrat and Caram [13] solved reduced two fluid model equations, for solid phase mass and momentum conservation in one dimension. Their model does not take into account the equation of motion of the bubble so it can not predict bubble detachment time. Huttenhuis et al. [14] used TFM to study the effect of gas-phase density on bubble formation at a single orifice in the 2D gas–solid fluidized bed. Nieuwland et al. [15] studied experimentally and numerically the effect of particle properties on the bubble formation at a single orifice in a 2D bed and a semi-circular bed. They compared results of a semi-circular bed with a 2D axisymmetric simulation and found some discrepancy with the experimental results due to absence of front wall in their simulation. Olaofe et al. [16] used an earlier developed discrete element model to study Geldart D type particles and investigate the influence of particle diameter and injection velocity on bubble formation at a single orifice in 2D gas–solid fluidized beds. Rong et al. [17] used a soft sphere Discrete Particle Model to study the effect of various parameters on bubble formation due to a single jet pulse in a 2D coarse-particle fluidized bed. Other researchers [18,19] studied bubble formation in a 3D domain to assess certain numerical aspects of the TFM. However studies on the influence