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Compressible-gas two-fluid modeling of isolated bubbles in a vertically vibrated fluidized bed and comparison with experiments

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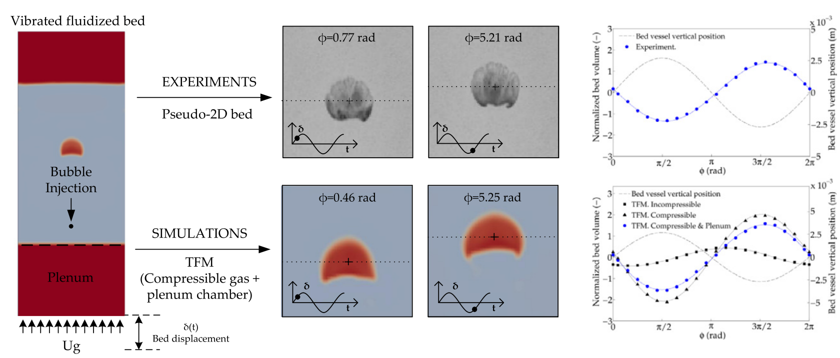
HIGHLIGHTS

- Isolated bubbles in a vibrated pseudo-2D bed are simulated with two-fluid models.
- Oscillations and phase delays of bubble diameter and velocity are obtained.
- The use of incompressible gas model yields unrealistic oscillations and delays.
- Simulations with compressible gas and plenum compare well with experiments.
- The phase delay of oscillations in vibrated beds is caused by the gas compressibility.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work the size and motion of isolated bubbles in a vertically vibrated fluidized bed are numerically investigated by means of two-fluid model simulations. The oscillations of the bed bulk and the bubble diameter and velocity are compared with experimental results of a pseudo-2D bed using an averaging of cycles method to account for the intrinsic unsteadiness caused by vibration. The effects of gas compressibility and the air plenum of the vibrated bed are also numerically investigated. The results show that the two-fluid model simulations resorting to a compressible gas model are able to reproduce both the cyclic compression and expansion of the bed bulk and the bubble oscillations observed in the experiments. In contrast, the simulations with the incompressible gas model fail to reproduce these effects. The presence of the air plenum in the numerical model diminishes the amplitude of the bed and bubble oscillations and improves their resemblance to the experiments. In the simulations with compressible gas, a phase delay is found between the bed displacement and the oscillation of bubble characteristics. In harmony with experiments, the phase delay is smaller in the lower half of the bed (i.e. close to the distributor) than in the upper half. This effect is not reproduced by the simulations with incompressible gas-phase. These results suggest that the phase delay in vibrated beds is caused by the compression of the gas phase, which leads to compression-expansion waves traveling through the bed. The simulations also confirm that the amplitude of vibration influences the magnitude of the bubble diameter and velocity oscillations, whereas the delay of the bubble characteristics is mainly affected by the bed vibration frequency.

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Nomenclature

$\boldsymbol{a}(t)$	instantaneous acceleration (m/s^2)
A	vibration amplitude (mm)
A_{ap}	bed cross-sectional area, WK (m^2)
D_b	bubble equivalent diameter (m)
$\overline{D}_b$	moving average of D_b (m)
d_p	particle diameter (μm)
e	restitution coefficient (–)
f	vibration frequency (Hz)
$\boldsymbol{f}_{eq}$	equivalent mass force (m/s^2)
g	gravity acceleration constant (m/s^2)
g_0	radial distribution function (–)
h_0	settled bed height (m)
H	bed vessel height (m)
H_{eq}	equivalent plenum height (m)
$\boldsymbol{I}$	unit tensor (–)
$\boldsymbol{I}_{gp}$	inter-phase momentum exchange (kg/m^{2}s^2)
I_{2Dg}	second order deviatory tensor (s^{-2})
K	bed thickness (m)
N_{tot}	total number of phase intervals (–)
N_ϕ	number of cycles (–)
R_g	ideal gas constant (J/K Kg)
t	time (s)
T	oscillation period, $1/f$ (s)
T_g	gas temperature (K)
U	velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
V_b	bubble velocity (m/s)
$\overline{V}_b$	moving average of V_b (m/s)
V_{ap}	plenum chamber volume (m^3)
V_{prop}	propagation velocity of oscillations (m/s)
W	bed width (m)
$y(t)$	instantaneous value of a variable
$\bar{y}(t)$	moving average of y
z	vertical distance to the distributor (m)
z_b	bubble centroid vertical coordinate (m)

Greek letters

$\delta(t)$	bed vessel vertical displacement (m)
Δt_{exp}	data export time-step (s)
Δy	oscillation of y
$\overline{\Delta y}$	average oscillation of Δy
ε	volume fraction (–)
ε_0	initial bed void fraction (–)
$\varepsilon_{p,th}$	threshold of solid volume fraction (–)
ε^*	packed bed void fraction (–)
ϕ	phase (rad)
ϕ_d	phase delay (rad)
Φ	specularity coefficient (–)
θ	angle of internal friction (°)
Θ	granular temperature (m^2/s^2)
κ_Θ	granular temperature diffusion coefficient (kg/m s)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
$\boldsymbol{\tau}$	stress tensor (Pa)
ω	angular velocity (rad/s)

Subscripts

exp	experiment
g	gas phase
i	frame index
p	particle (solid) phase
sim	simulation

1. Introduction

Fluidization is a process widely used in chemical reactors and materials processing due to the good efficiency it provides in solid–solid and gas–solid contacts [1]. Nevertheless, agglomeration or channeling of fine particles may occur, which can end up defluidizing the bed. Several strategies have been employed to improve fluidization homogeneity, e.g. the introduction of a mechanical stirrer or the pulsation of the gas flow [2]. Many efforts have been made to modify the particle and bubble behavior in a fluidized bed also by external means. For example, ferromagnetic particles subjected to magnetic fields can change the way the bed fluidizes, extending the bubble-free operation range in fluidization state [3] or diminishing the bubble size [4]. Acoustic fields have also been employed for the improvement of the fluidization quality of group C cohesive powders [5].

Mechanical vibration of fluidized beds, i.e. vibrating fluidized beds (VFB), is a fluidization technology consisting in introducing vibratory kinetic energy to a conventional fluidized bed [6–9]. Vibration of the bed reduces minimum fluidization velocity [10], and provides the necessary energy to break interparticle bonds, reduce agglomerates and avoid channeling. Thus, it is a very effective technique for the fluidization of cohesive particles [11,12], drying of granular material [13,14], agglomeration control [15] and control of particle segregation [16].

Existing experimental and simulation studies of bubbles in VFBs are mainly centered on beds working under bubbling regime [9,17–23]. Global indicators such as bubble mean diameter and velocity [9,24,17–19], air pressure and void fraction fluctuations [21,22] as well as solids circulation promoted by vibration [23] are included in these works, in which the presence of multiple interacting bubbles complicates the elucidation of the basic effects that vibration induces on each individual bubble. Eccles and Mujumdar [24] studied a train of bubbles in a vibrated thin bed. Zhou et al. [9] carried out experiments to study the particle flow pattern and its interaction with bubble paths, pressure drop and bed expansion ratio in a pseudo two-dimensional (2D) bed filled with spherical particles of 198 μm and subjected to horizontal and vertical vibration. Also, Mawatari et al. [17] and Zhou et al. [18] experimentally studied pseudo-2D beds under vertical vibration, using particles of 60 μm and 198 μm of average diameter, respectively. The vibrated bed conditions of [18] were reproduced by Acosta-Iborra et al. [19] using two-fluid models simulations. All these three studies [17–19] revealed that, once a fluidized bed is vibrated, the averaged bubble diameter increased with the amplitude or frequency of vibration, though a more complicated dependence was experienced by the averaged bubble velocity. In an attempt to better understand the intricate behavior of bubbles in vibrating fluidized beds, Cano-Pleite et al. [25] experimentally studied isolated bubbles in a pseudo-2D fluidized bed subjected to vertical vibration. Using digital image analysis (DIA) techniques, they captured the individual oscillation of the size and velocity of solitary bubbles and the oscillation of the bulk of the bed.

Numerical simulation of fluidized beds can be employed as a tool to improve the understanding the complex behavior of fluidized beds during vibration. Besides, once a simulation model is