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Oscillatory behavior of the bed bulk and the bubbles in a vertically vibrated pseudo-2D bed in bubbling regime

E. Cano-Pleite [a,*], F. Hernández-Jiménez [a], A. Acosta-Iborra [a], Y. Mawatari [b]

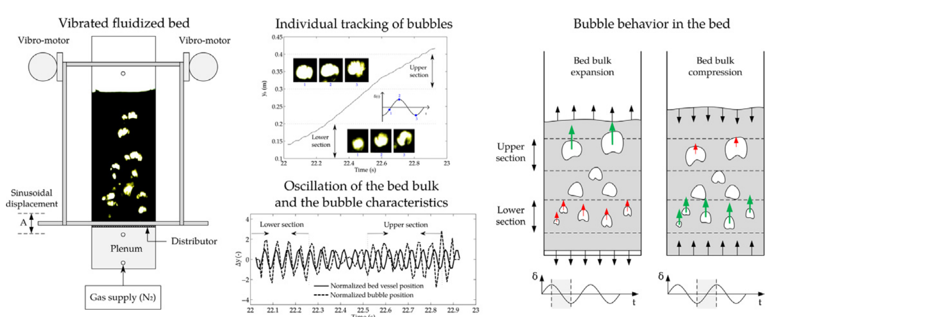
[a] *Department of Thermal and Fluid Engineering, Carlos III University of Madrid, Av. de la Universidad 30, 28911, Leganés, Madrid, Spain*

[b] *Department of Applied Chemistry, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata, Kitakyushu 804-8550, Japan*

HIGHLIGHTS

- DIA measurements of a bubbling fluidized bed subjected to vibration were performed.
- Bubbles were individually tracked and their oscillations were analyzed.
- Amplitude and phase of bubbles oscillations depend on the distance to the distributor.
- Bubbles present a phase delay between the upper and lower sections of the bed.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of the bed vessel vibration on the oscillatory behavior of the bed bulk and the bubbles is experimentally studied in the present work by means of Digital Image Analysis (DIA) in a pseudo-2D bed. The bed material was three different powders of Geldart A, B and A/B classifications and was operated in bubbling regime for different superficial gas velocities and vibration amplitudes and frequencies. A tracking methodology was developed in order to follow the oscillatory motion of the bed bulk and each individual bubble in the system. This allowed the analysis of the interaction of the dense phase of the bed with the oscillations of the bubble diameter, position and velocity. The results indicate that both the center of mass of the bed and the bubble characteristics follow the oscillation of the bed vessel with a similar frequency but with a phase delay. The amplitude and phase delay of the oscillation of the center of mass of the bed are more sensitive to variations of the vibration frequency than to variations of the vibration amplitude of the bed vessel. Both the amplitude and the frequency of the bed vessel vibration have a stronger impact on the bubble behavior of beds filled with small particles. The existence of a phase delay between the oscillations of bubble characteristics in the lower and upper sections of the bed indicates the existence of compression-expansion waves in the dense phase that modify the bubble behavior along the bed despite bubbles are interacting with each other. The presence of compression-expansion waves may shed light onto the different behaviors encountered for the mean bubble behavior in vibrated fluidized beds.

1. Introduction

Fluidization is a process that has several applications in chemical and process industries, such as fluid catalytic cracking (FCC), gasification, combustion of solid fuels, Fischer–Tropsch synthesis

* Corresponding author.
E-mail address: edcanop@ing.uc3m.es (E. Cano-Pleite).

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Nomenclature

A	vibration amplitude, peak-to-peak (mm)
A_b	bubble area (m^2)
$A_{\overline{\Delta z}}$	oscillation equivalent amplitude (–)
CM_y	center of mass vertical coordinate (m)
D_b	bubble equivalent diameter (m)
d_p	particle diameter (μm)
f	vibration frequency (Hz)
g	gravity acceleration constant (m/s^2)
H	bed vessel height (m)
K	bed thickness (m)
T	vibration period (s)
t	time (s)
u_s	equivalent sound velocity in the bed (m/s)
u_{s0}	gas velocity of sound (m/s)
U	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
V_b	bubble velocity (m/s)
V_{prop}	propagation velocity (m/s)
W	bed width (m)
y	vertical coordinate (m)
y_b	bubble centroid vertical coordinate (m)
$z(t)$	instantaneous variable value
$\bar{z}$	moving average of z

Greek letters

γ	heat capacity ratio (–)
Δz	oscillation of a variable (–)
$\overline{\Delta z}$	normalized oscillation of a variable (-)
Δz_f	fitting of a variable (–)
$\delta(t)$	bed vessel vertical displacement (m)
ε	bed void fraction (–)
Λ	vibration strength parameter (–)
ρ_g	gas density (kg/m^3)
ρ_p	particle density (kg/m^3)
σ	standard deviation
ϕ	phase (rad)
ϕ_d	phase delay (rad)

or drying and coating [1]. Despite the fact that fluidized beds have been widely used for these processes since the 1920s and great progress has been made, some aspects of fluidized bed dynamics are still far from being fully understood and, hence, they constitute active fields of research. In particular, when using particles of type A and C according to Geldart's classification [2], effects such as channeling, formation of bubble preferential paths inside the bed and agglomeration may occur, which can dramatically decrease the fluidization quality. Several strategies have been followed in order to avoid such effects, as for example the use of mechanical stirrers, pulsation of the gas flow [3], the use of ferromagnetic particles subjected to magnetic fields [4], perturbation by acoustic fields [5], rotatory distributors [6,7], inclined injection of gas [8] and vibration of the bed [9–18].

In particular, mechanical vibration of fluidized beds (i.e. vibrated fluidized beds, VFBs) is a promising technology consisting in introducing vibratory kinetic energy to a gas fluidized bed [9–11]. This is done by applying vibration to the bed vessel, in form of an oscillatory displacement, which transmits the vibration to the rest of the bed. The first noticeable effect of the vibration is the reduction of the minimum fluidization velocity, as reported in [12]. Besides, vibration is a very effective technique for fluidizing cohesive particles, drying granular material and controlling agglomeration and particle segregation [13–18].

Besides, it is worth noticing that vibration of the bed substantially increases the complexity of dynamics of the fluidized bed. It has been reported that vibration modifies the dynamic behavior of the bed by introducing oscillations in the local voidage [19], the particle average kinetic energy and the pressure of the fluidizing gas [20]. Vibration also affects the general and oscillatory behavior of bubbles in the bed. Cano-Pleite et al. [21,22] studied both experimental and numerically the effect of vibration on isolated bubbles rising in a bed aerated at minimum fluidization conditions. However, if the bed is operated in bubbling regime, it is expected that the interaction between multiple bubbles may affect their oscillatory behavior. In a previous study, Cano-Pleite et al. [23] analyzed the mean values of diameter, velocity, fraction and number density of bubbles in a vibrated fluidized bed. They observed that the mean behavior of bubbles changes when they are far from the distributor. In this region, the interaction between bubbles becomes greater compared to that of bubbles in the lower section of the bed due to their bigger size and the confinement of bubbles induced by vibration.

It is clear that the interaction of bubbles with other bubbles and the bed bulk is an intrinsically transient phenomenon. Besides, vibration creates oscillations in the bed bulk and in the bubble characteristics, as evidenced in [21] for isolated bubbles. Thus, a fundamental study of the oscillatory behavior of a vertically vibrated bed operated in bubbling regime is paramount to identify the different phenomena affecting the oscillation of the bed bulk and the bubbles, which may have a direct impact on the mean behavior of bubbles in the bed.

Pseudo two-dimensional (pseudo–2D) beds, which are lab–scale beds of simplified geometry, have been crucial for the understanding of the dynamics of gas-particle systems [24–27]. Pseudo-2D fluidized bed systems typically have a transparent front wall in order to allow optical access to the system. The back wall of the bed is separated to the front wall by a narrow distance to ensure that the visualization is representative of the whole system. The optical access to the bed allows the use of measurement techniques aimed to understand the bed and bubble dynamics such as Particle Image Velocimetry (PIV) [26] or Digital Image Analysis (DIA) [24,25,27]. The use of pseudo-2D beds has been successfully applied to VFBs. For example, Mawatari et al. [28] studied how vibration affects the bubble distribution in the bed and Zhou et al. [29,30] analyzed the bubble position and diameter in the bed. The DIA has been also proven to be a useful technique to investigate the behavior of VFBs [11,21,28–31] including the characterization of the average oscillatory behavior of isolated bubbles in a VFB.

Existing experimental and numerical studies of VFBs operating in bubbling regime, analyze the effect of vibration on global indicators such as bubble mean diameter and velocity [10,28–32], air pressure, bed height and void fraction fluctuations [20,33,34], aggregate diameters [35] as well as solids circulation promoted by vibration [36]. However, to the authors' best knowledge, experimental studies analyzing the oscillatory behavior of the bed bulk and bubbles in a vertically vibrated fluidized bed are still scarce [19,21,22,34]. Wang et al. [19] studied the energy transfer mechanism in a vertically vibrated cylindrical bed of 200 mm inner