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CHARACTERIZATION OF THE BUBBLE BEHAVIOR IN VIBRATED FLUIDIZED BEDS BY MEANS OF TWO-FLUID CFD SIMULATIONS COUPLED WITH ACCELEROMETRY DATA

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ABSTRACT

In the present contribution a set of accelerometer measurements, taken from a real vibrated fluidized bed, is used to define the vessel displacement that is incorporated as an input to two-fluid (Euler-Euler) CFD simulations. The bubble behavior, i.e. bubble size and velocity, obtained from these simulations under different vibration amplitudes and frequencies is analyzed and qualitatively compared with experimental evidences. Very similar results are obtained using the real accelerometry data and the perfect sinusoidal displacement, indicating that the bubble dynamics is principally affected by the main vibration frequency and less by other secondary vibration frequencies of the bed vessel. Using the simulations results, a novel correlation is proposed for predicting the rising velocity of bubbles in the vibrated fluidized bed as a function of the bubble equivalent diameter and the vibration strength parameter.

INTRODUCTION

Fluidization is a process widely used in industry owing to the good performance in solid mixing and the high gas-solid contact efficiencies it provides (1). Nevertheless, agglomeration and channeling may occur, causing the fluidization to be poor. Mechanical vibration of fluidized beds, i.e. vibrated fluidized beds, is a technology consisting in introducing a vibration to a conventional fluidized bed. This can be done by applying an oscillatory displacement to the bed-containing vessel. Vibration of the bed 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, drying of granular material and agglomeration control. Vibration can be also used to control particle segregation in a fluidized bed. In all these processes the presence of voids (i.e. bubbles) in the bed plays an important role. However, the effects of vibration on the behavior of the bubbles are far from being completely understood.

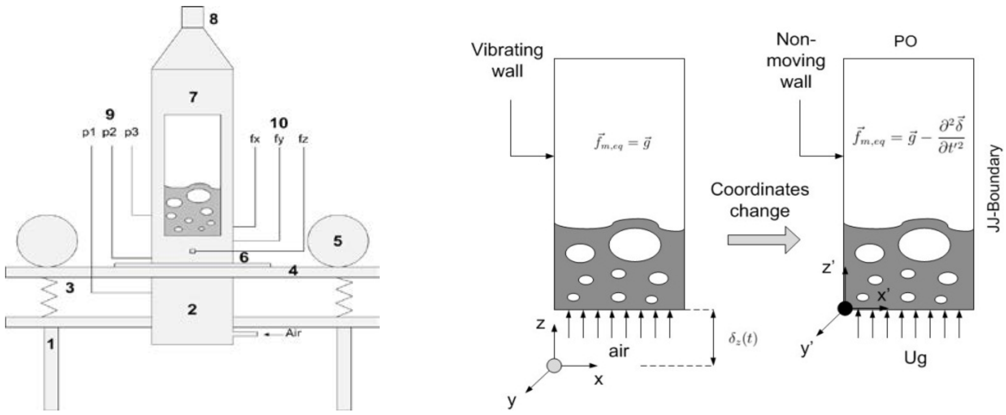
Numerical simulation of fluidized beds can be employed as a tool to understand the behavior of bubbles during vibration. The simulation of vibrated fluidized bed has been typically performed in the literature using a Lagrangian-Eulerian approach also known as discrete element method, DEM. In this approach, the gas-flow field is described as a continuum medium and the movement of each particle is calculated individually. This makes the method highly computationally demanding and restricted to beds of small dimensions (i.e. small number of particles), (2).

As a less computationally demanding alternative, Acosta-Iborra et al. (3) proposed the simulation of vibrated fluidized beds by solving the two-fluid (Euler-Euler) model CFD equations (4) in a coordinate system that moves with the bed. In this methodology, vibration is transformed into acceleration terms that are introduced in the simulations as body forces in both the gas and particle phases. The advantage of this Euler-Euler approach is that particles are not defined individually but grouped as an equivalent continuous fluid that is interpenetrated by the gas phase. Virtually all the previous simulations studies have considered an ideal sinusoidal vibration of the bed vessel (2-3). Thus, it would be interesting to check whether more realistic vibrations have an impact on the bubble behavior.

The aim of present work is the characterization of the bubble diameter and velocity in a vibrated fluidized bed using the mentioned two-fluid approach. A special feature of the simulation performed is that the accelerations terms of the equations come from accelerometers installed in a real bed of similar dimensions and operative conditions.

EXPERIMENTAL SETUP

Fig. 1. shows the vibrating fluidized bed apparatus from which the real vibration displacement of the bed vessel was obtained. This displacement will be imposed to the simulations by means of the acceleration terms in the momentum equations of the gas and particle phases. The experimental bed is a prismatic column of 0.2mx0.2m horizontal section and 0.512m height. To prevent particles to escape from the bed during vibration, the upper part of the vessel has a 45º narrowing, ending on a circular section of 0.05m diameter. In the front wall of the bed there exists a visualization window of 0.128m x 0.28m (width x height) whose lower edge is separated 0.106m from the distributor. The bed was filled with ballotini glass spheres whose minimum fluidization velocity without vibration, obtained experimentally, was 110 l/min (U_{mf}=0.0458 m/s). Table-1 describes the particle properties and experimental conditions of the bed.



(a) **(b)**

Fig. 1. (a) Experimental setup: (1) supporting structure, (2) plenum, (3) springs, (4) vibrating structure, (5) vibro-motors, (6) distributor, (7) vessel, (8) air output, (9) pressure probes, (10) accelerometers. (b) Simulation procedure: change of coordinates and boundary conditions.

Property	***Value***	***Property***	***Value***
Particle diameter	200 μm	Superficial velocity	0.0521-0.0833 m/s
Particle density	2500 kg/m³	Vibration frequency	15.62 Hz
Static bed height	0.177 m	Vibration amplitude	4.32 mm

Table-1. Particle properties and experimental conditions

To induce vibration on the bed, two vibro-motors (Italvibras MVSI 10/310 SO2) were symmetrically disposed at both sides of a horizontal structure on which the bed vessel was firmly attached. By adjusting the rotation velocity and position of the masses of the vibro-motors, the vibration of the bed vessel was set to a frequency close to 15Hz and amplitude close to 4mm (i.e. peak to valley displacement of 8mm).

Data acquisition

As Fig.1 indicates, three piezoelectric accelerometers were attached to the external surface of the bed vessel to measure its displacement acceleration in the three spatial directions. These accelerometers were connected to an acquisition card NI 9233 and stored for later data examination. The data acquisition frequency was set to 10 kHz, which is large enough in comparison with the vibrating frequency of the vessel. By analyzing the data given by the accelerometers during the experiments for a time period of 240 seconds, it was found that the principal frequency of the vibration was 15.62Hz and the mean amplitude 4.32mm regardless of the gas superficial velocity of the bed.

NUMERICAL MODELLING

Simulation of vibration in the two-fluid model

The vibrated fluidized bed described in the previous section was simulated using a two-fluid model approach. The computational domain was a two-dimensional (2D) rectangular reproduction of the central section of the experimental bed (0.2mx0.5m). The MFIX code was employed for the solution of the governing equations that describe the gas and particle phases in the two-fluid model. In addition, the granular energy transport equation (partial differential equation) was chosen for the formulation of the granular temperature to be included in the closure models (5). Each of the performed simulations comprised 30 seconds of physical time. The last 25 seconds were used for the data analysis to avoid the transient effects during the simulation start-up.

Vibration was introduced in the simulation equations by means of vertical body forces for both the gas and the solid phases governing equations (3):

$$f_{m,eq} = -g - a(t) \qquad (1) \qquad\qquad f_{m,eq} = -g - \frac{d^2\delta(t)}{dt^2} = -g + 4\pi^2 f^2 A\sin(2\pi t) \qquad (2)$$

Where $g = 9.81 m/s^2$ is the gravity constant and $a(t)$ is the instantaneous acceleration taken from the accelerometry data. Another option is to follow previous studies (2-3) that assume that the vibration displacement is purely sinusoidal, $\delta(t) = A \cdot \sin(2\pi ft)$, so that the equation (2) is the one utilized.

Since the horizontal component of the accelerometry data was much smaller than the vertical component, only vertical acceleration terms were considered in this work. Three different conditions are studied here: (i) a non-vibrating bed, (ii) a vibrated bed whose vessel displacement is taken from the accelerometry data (equation (1)), and (iii) a vibrated bed whose vessel displacement is sinusoidal (equation (2)). Fig. 2. shows the accelerometry data $a(t)$ and the equivalent sinusoidal acceleration $-4\pi^2 f^2 A\sin(2\pi t)$ with the frequency f and amplitude A of vibration.

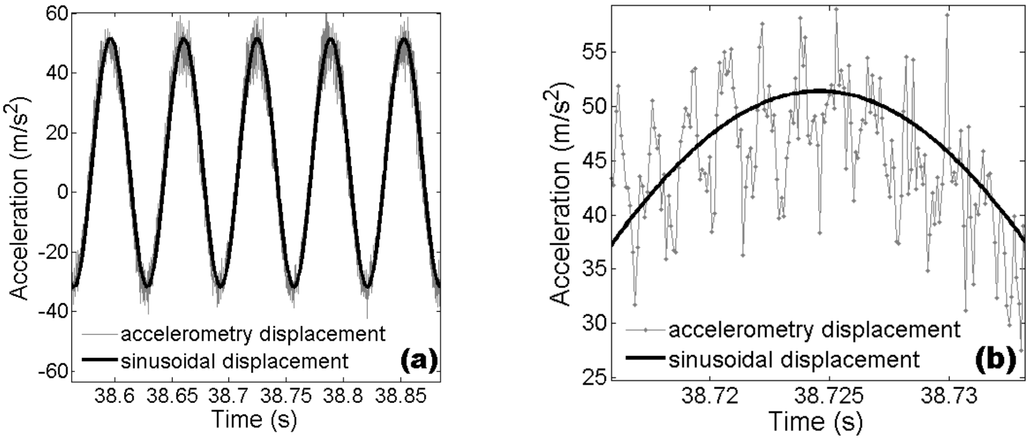


Fig. 2. (a) Vibration accelerations of the bed vessel used in the simulation (b) detail showing the differences between the accelerations given by the accelerometer and the sinusoidal displacement.

According to Fig. 2(a) the real acceleration of the bed in the experiment is close to a sinusoidal acceleration with small fluctuations superimposed. These small fluctuations of the accelerometry data (Fig. 2 (b)) follow a coherent pattern, indicating that they are caused by a real displacement of the vessel and not by signal noise.

Computational mesh, closure models and simulation conditions

A computational mesh of 50x105 rectangular cells in a 2D domain was used for the simulations. To solve the two-fluid equations, particles were considered spherical with properties given by Table-1. The gas-particle drag coefficient K_{gp} was modeled through the closure equation by Gidaspow et al. (4) which has been tested for two-dimensional vibrated beds in other works (3). The solids viscosity and pressure were calculated using the default closure models in MFIX (see Syamlal et al. (5)) that are function of the granular temperature following the kinetic theory of granular flows. For the particle-particle and particle-wall collisions, the restitution coefficient and angle of internal friction were set to 0.9 and 30º respectively.

	U_0/U_{mf}	*Vibration*		U_0/U_{mf}	*Vibration*
Case-1	1.14	None	Case-6	1.82	Sinusoidal
Case-2	1.14	Sinusoidal	Case-7	1.82	Filtered
Case-3	1.14	Filtered	Case-8	1.82	Accelerometry
Case-4	1.14	Accelerometry	Case-9	2.25	None
Case-5	1.82	None	Case-10	2.25	Sinusoidal

Table-2. List of simulated cases

Regarding the boundary condition at the bottom of the simulated bed, a constant and uniformly distributed vertical velocity, U_0, was chosen for the gas phase, and a null velocity was set for the particles to avoid them to cross the distributor. For the upper boundary, a pressure outlet condition with the static pressure set to one atmosphere was selected. At the walls, the non-slip condition was selected for the gas phase, and a partial-slip condition with specularity coefficient $\Phi = 0.6$ was chosen for the particle phase and the granular temperature (6). The simulation started with particles at rest having volume fraction 0.6 and settle bed height 0.177m, as the real bed.

Table-2 lists the cases simulated. They comprise three different superficial velocities and the acceleration term in equation (1), which was obtained from the experiments without any signal filtering (Accelerometry), with smoothing by a moving mean comprising 10 data (Filtered), and with a perfect sinusoidal vibration (equation (2)).

RESULTS AND DISCUSSIONS

General bubble behavior

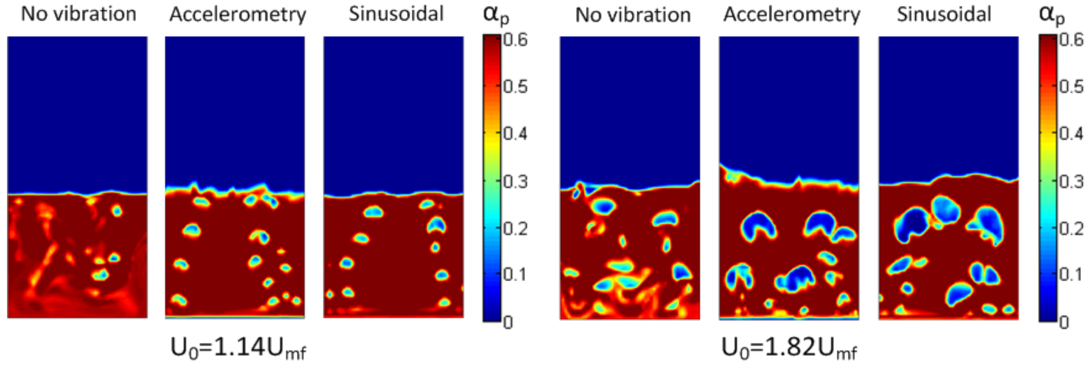
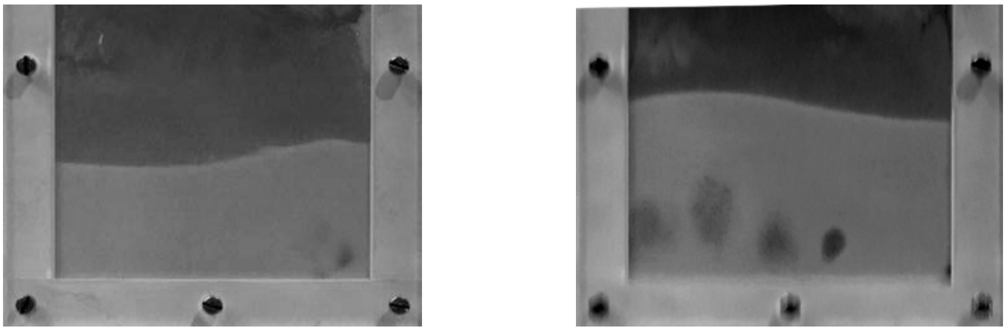


Fig. 3. Snapshots of solids volume fraction obtained from the simulated fluidized bed without vibration and with vibration (f=15.62Hz and A=4.32mm).



(a) **(b)**

Fig.4. Grey scale photographs of the observation window in the experimental bed showing the particle distribution at U_0/U_{mf}=1.14: (a) without vibration and (b) with vibration (main harmonic with f=15.62Hz and A=4.32mm)

The effect of vibration on the bubble size and distribution can be qualitatively seen in Fig. 3. As revealed by the simulations, vibration promotes the formation of larger bubbles. In the case of superficial velocities close to minimum fluidization, Fig. 3(a), bubbles are scarce when the system is not vibrating whereas they are observable when vibration in introduced. This effect is corroborated by the experiments shown in Fig. 4. For a higher superficial velocity, Fig. 3(b), vibration increases the size of the bubbles while keeping them well distributed in the bed. Qualitative differences in the bubble size and distribution are not observed between the simulation cases with real accelerometry data (equation (1)) and the ideal sinusoidal vibration (equation (2)).

Bubble diameter and velocity

In Fig. 5. the local mean diameter and velocity of bubbles at different distances, z, from the distributor are depicted. The mean magnitudes are the sampling average of the values of the bubbles collected within vertical intervals of 2cm in the bed. Here, the bubble equivalent diameter is calculated as the diameter of a circle having the same area of the bubble. The bubble rising velocity is obtained from the vertical displacement of the bubble centroid in two consecutive time steps divided by Δt. According to Fig. 5(a,b), bubbles are bigger in vibrated fluidized beds and their growth with the distance to the distributor is slightly higher than in beds without vibration. No significant differences are detected among the different vibrations tested (accelerometry, filtered and sinusoidal).

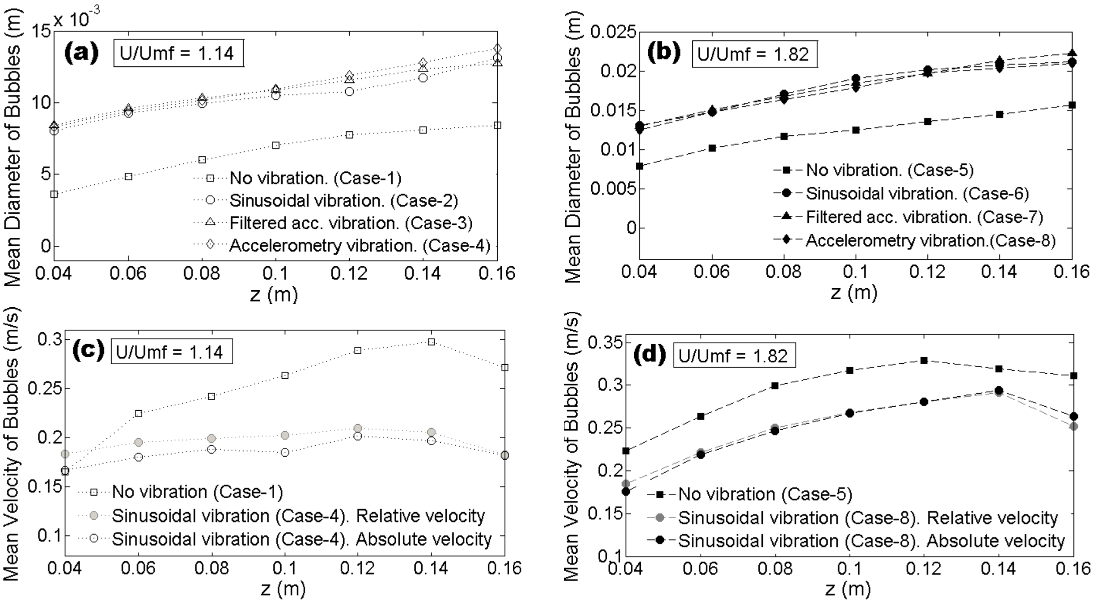


Fig. 5. Mean diameter of bubbles, (a) and (b), and mean bubble rising velocity, (c) and (d), as a function of the distance to the distributor z in the simulated fluidized bed without and with vibration (f=15,62Hz, A=4,32mm) at two different superficial velocities.

The simulation results in Fig. 5(c,d) clearly shows that the mean rising velocity of bubbles in a vibrated fluidized is smaller than without vibration, in harmony with A. Acosta et al. (3). Expressing the mean velocity in a relative coordinate system moving with the distributor (relative velocity) or in an absolute coordinate system (absolute velocity) does not greatly change the mean values in Fig. 5(c,d), since differences are compensated after calculating the mean. An increase of the superficial velocity produces a growth of the bubble size and velocity regardless the bed is vibrated or not.

Fig. 6 shows the probability density functions (PDF) for the bubble diameter and velocity from simulations at different superficial velocities. The higher the superficial velocity, the wider the distribution of bubble diameters in the bed is, Fig. 6(a). Vibration also promotes a more uniform PDF of bubbles diameters. For the case without vibration, there exist few negative velocities of bubbles in Fig. 6(b), which could be explained by instantaneous deformations of the bubbles. However, when introducing the vibration, Fig. 6(b) evinces a bimodal behavior of the bubble rising velocity. The PDF peak at negative velocities is due to the descending displacement of bubbles caused by the downward-motion of the bed vessel during vibration. Similarly, the PDF peak at positive velocities is produced by the upward-motion of the bed vessel. Very similar curves for the sinusoidal and filtered accelerometry cases were obtained and are not included here for simplicity.

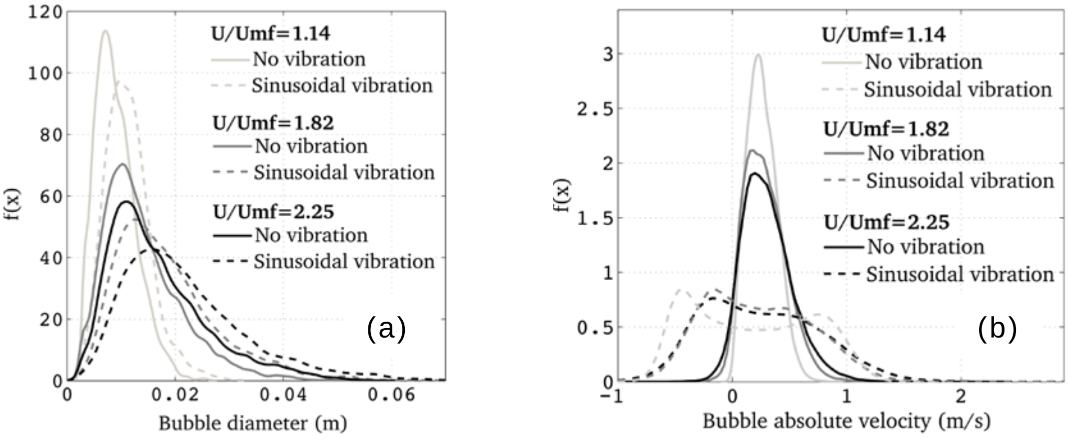
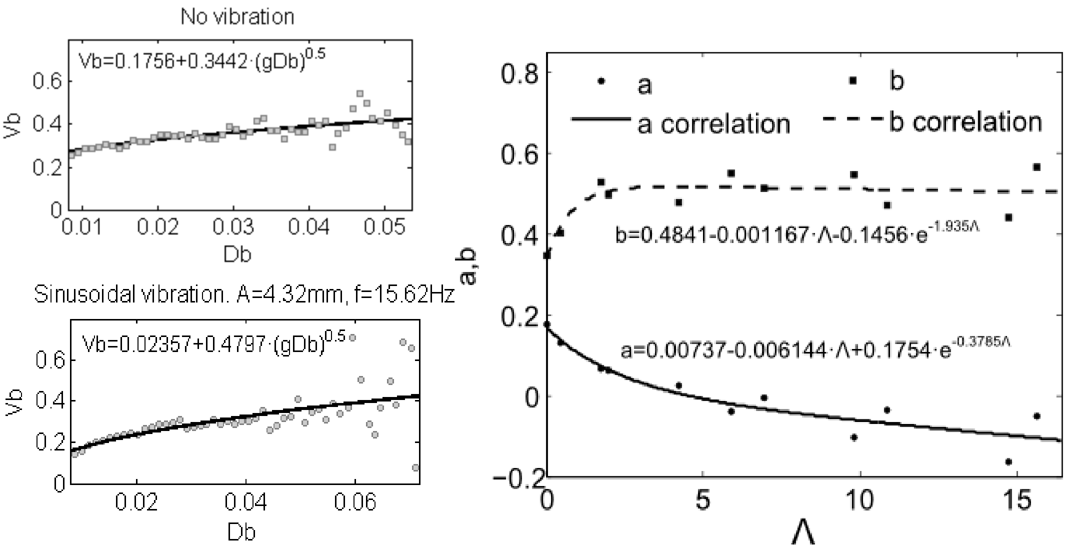


Fig. 6. Probability density functions of (a) bubble diameter and (b) bubble vertical velocity for non-vibrating and vibrating (f=15.62 Hz and A=4.32 mm) fluidized beds.



(a) **(b)**

Fig. 7 Fitting curves for: (a) the rising velocity versus the diameter of bubbles, and (b) the velocity coefficients. a and b as a function of the vibrating strength (Λ).

From a practical point of view, it is interesting to characterize how vibration affects the link between the bubble diameter, D_b, and velocity, V_b. A procedure to determine D_b as a function of V_b and the vibration strength, $\Lambda = (2\pi f)^2 A/g$, is proposed. Fig. 7(a) shows the bubble velocity and diameter obtained from the simulation at U_0=1.82U_{mf} without vibration (case-5) and with a sinusoidal vibration (case-6). A classical fitting curve of the form $V_b = a + b\sqrt{gD_b}$ (1) was included for each case, where a and b are the velocity coefficients determined by quadratic regression. The process was repeated for different values of vibration frequency (i.e. 5, 10, 15.62, 20, and 30Hz) and amplitude (2, 4.32, 6, 10 and 15mm). Fig. 7(b) shows the resulting values of a and b as a function of the vibration strength. As Fig. 7(b) demonstrates, the velocity coefficients depend basically on the vibration strength. In order to come up with an equation for the bubble rise velocity covering the whole range of vibration strengths, a relation between the a, b and Λ is to be found. After several tests, the linear-exponential relation included in Fig. 7(b) was selected, leading to:

$$V_b = 0.00737 - 0.006144\ \Lambda + 0.1754\ e^{-0.3785\ \Lambda} + \left(0.4841 - 0.001167\ \Lambda - 0.1456\ e^{-1.935\ \Lambda}\right)\sqrt{gD_b} \quad (3)$$

It can be concluded from Fig. 7(b) and equation (3) that, as the vibration strength increases, bubbles become slower (for a given diameter) in their rising velocity. A complete determination of the effect of vibration on the velocity versus the diameter of bubbles while covering a wide range of superficial velocities would require a vast number of simulations and is left to future studies.

CONCLUSIONS

The bubble behavior in a 2D vibrated fluidized bed was qualitatively and quantitatively analyzed by means of two-fluid CFD simulations. Accelerometry data, taken from experiments, were incorporated to define the vibratory displacement of the bed vessel more realistically. The simulation results indicate that the bubble mean diameter and velocity is affected by the main oscillatory displacement of the bed vessel, the secondary harmonics having little effect on the bubble behavior. The results also reveal that vibration increases the uniformity of the PDF for the diameter and velocity of bubbles, inducing a bimodal distribution in the case of bubble velocity. In average, vibration promotes bigger bubbles but slower in their rising velocity. The vibration strength seems to be a key parameter influencing the dependence of the bubble velocity on the bubble diameter in a vibrated fluidized bed. On the basis of this result, a procedure to correlate the bubble velocity as a function of its diameter and the vibration strength was proposed and exemplified for U_0=1.82U_{mf}.

ACKNOWLEDGEMENTS

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NOTATION

$a(t)$	instantaneous acceleration, m/s^2	U_{mf}	minimum fluidization velocity, m/s
A	vertical vibration amplitude, m	U_0	superficial gas velocity, m/s
D_b	bubble equivalent diameter, m	V_b	bubble vertical velocity, m/s
f	vertical vibration frequency, Hz	$\delta(t)$	vibration displacement, m
$f_{m,eq}$	equivalent mass force vector, m/s^2	Δt	time step, s
g	gravity acceleration, m/s^2	Φ	specularity coefficient, -
t	time, s	Λ	vibration strength, -

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