MULTIPHASE SCIENCE
AND
TECHNOLOGY

EDITORS-IN-CHIEF

G. F. HEWITT

J. M. DELHAYE

VOLUME 21 ISSUES 1- 2 2009

MULTIPHASE SCIENCE AND (ISSN 0276-1459) is published quarterly and is owned by Begell House Inc., 50 Cross Highway, Redding, Connecticut 06896, telephone (203) 938-1300. USA subscription rate for 2009 is $749.00. Add $10.00 per issue for foreign airmail shipping and handling fees for all orders shipped outside the United State or Canada. All subscriptions are payable in advance. Subscriptions are entered on an annual basis – i.e. January to December. Payments should be made either by check (drawn on a U.S. bank) or by credit card (Visa, MasterCard, American Express, Discover Card, or Diners Card) with the following information: name of cardholder, card number, expiration date, telephone/fax number, and signature of card holder. For immediate service and charge card sales, please call (203) 938-1300 Monday through Friday 9 AM – 5 PM EST. Orders can be faxed to 203-938-1304 or mailed to Subscriptions Department, Begell House, Inc. 50 Cross Highway, Redding, Connecticut 06896.

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Multiphase Science and Technology, Vol. 21, No. 1–2, pp. 13–24, 2009

CFD PREDICTION OF BUBBLE BEHAVIOR IN TWO-DIMENSIONAL GAS–SOLID FLUIDIZED BEDS

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Abstract. This work focuses on the computational fluid dynamics (CFD) simulation of a laboratory-scale, two-dimensional fluidized bed and the relevant experiments in order to validate the prediction capability of the adopted codes and models. Both experimental and computational quantitative data were analyzed by means of an original digital image analysis technique, allowing for coherent comparison of computational and experimental results. In particular, this work analyzes the capability of the CFD simulations in predicting the fluctuating behavior of bubbling fluidized beds by means of frequency analysis of bubble-related phenomena.

1. INTRODUCTION

Many of the characteristic features of gas-fluidized beds, like the excellent solid mixing, and heat and mass-transfer properties, can be related to the presence of bubbles and their behavior. A deeper knowledge of the fluidized bed hydrodynamics would provide the base for the development of a fully predictive model describing the fluidized bed hydrodynamics.

The development of mathematical modelling of particulate solid behavior together with the increased computing power enables researchers to simulate the fluidized powder dynamics and to link fundamental particle properties directly to the powder behavior. In this regard, computational fluid dynamics (CFD) provides a fundamental tool to support engineering design and research in multiphase systems. Many authors recognize that computational modelling in multiphase systems has the potential to increase process efficiency and reduce the number of scale-up steps in the design of reliable commercial plants. It is invariably emphasized that a necessary step toward the development of reliable, fully predictive CFD models is an extensive experimental validation of the simulation results. The experimental validation will come to assess the suitability of the CFD model chosen to simulate the investigated regimes.

On the above basis, the present work focuses on the simulation of a two-dimensional (2-D) fluidized bed operating under bubbling and slugging conditions carried out with the use of the commercial CFD code Ansys CFX-10.0. Computational results are first postprocessed by a digital image analysis technique (DIAT), fully described in the paper by Busciglio *et al.* (2008), to measure fundamental quantities such as bed height, bubble hold up, bubble diameter evolution and distribution, and bubble velocity, and subsequently compared with experimental data. Among all quantities available by DIAT, some are presented in terms of time series, i.e., bed height and global bubble hold up. In this work, a frequency domain analysis was performed, starting from data obtained by CFD simulation and relevant experiments, in order to fully validate CFD reliability in predicting the evolution of time-dependent quantity.

2. LITERATURE REVIEW

Dynamics of fluidized beds may be studied on the basis of time-averaged properties such as voidage and velocity profiles, bubble properties, and/or on the basis of time-dependent quantities (e.g., fluctuations in voidage and pressure), globally or locally in the bed. Both types of information are significant for choice of the appropriate conditions for stable operation and control of the fluidized system. In the literature, there is a number of parameters whose evolution in time and space is chosen to characterize the dynamics of the fluidized bed. Frequently, pressure fluctuation measurements are chosen to investigate the hydrodynamic behavior of fluidized beds.

Xu *et al.* (2004) studied time series signals by means of statistical analysis, frequency analysis (e.g., fast Fourier transform, FFT), and chaotic analysis, by which the behavior of fluidized systems can be characterized and scaling-up relationships may be validated. Power spectrum densities of different flow regimes have different characteristics and thus they can be used to identify the flow regimes. The influence of sampling locations was also discussed.

Johnsson *et al.* (2000) compared time, frequency, and state-space analyses of pressure measurements of fluidized beds. The results from the frequency domain (power spectra) and state-space analyses of the pressure fluctuations are generally in agreement and can be used complementary. The power spectra can be divided into three regions, a region corresponding to the macrostructure (due to the bubble flow) and, at higher frequencies, two regions representing finer structures that are not predominantly governed by the macrostructure of the flow. In all fluidization regimes, the measured pressure fluctuations exhibited an intermittent structure which is not revealed by the power spectral analysis of the original signals.

Zhong and Zhang (2005) investigated pressure fluctuation frequency characteristics in a 2-D spouted bed. A multichannel differential pressure sampling system was adopted to obtain pressure fluctuations, and the modern ARM (auto-regressive model) power spectrum was developed to estimate the pressure fluctuation major frequency. Effects of spouting gas velocity, fluidizing gas flow rate, and static bed height on the pressure fluctuation major frequency were systematically examined. In addition, digital image analysis was used to investigate the gas–solid interactions in the bed. The analysis of pressure fluctuations so far performed allowed further studies of the complex gas–solid interactions and flow pattern transitions in spouted beds.

Lu and Li (1999) studied pressure fluctuations of bubbling fluidized beds to evaluate the fluidization quality. Information collected from pressure fluctuations can be used to analyze the bubbling behavior. Signals representing bubbling characteristics can be separated from raw signal through discrete Wavelet analysis.

3. EXPERIMENTAL SETUP

The fluid-bed reactor purposely designed and built for the present investigation is made of Perspex® with dimensions equal to 800 (height) $\times$ 180 (width) $\times$ 15 (depth) mm. The reactor is therefore almost 2-D, thus allowing visual observation of bubble dynamics within the bed. A plastic porous distributor, whose thickness is equal to 10 mm, is placed at the bottom of the particle bed. Below the distributor a wind box allows equalization of the gas flow. Glass ballotini in the size range 212–250 μm were used for the experimental runs with density equal to 2500 kg/m^3. The particles were filled to a settled bed height of 360 mm, i.e., twice the bed width. The value of u_{mf} was experimentally determined and found equal to 5.24 cm/s. The average value of gas voidage has been experimentally determined by knowledge of the loaded particle mass and the bed volume. The void fraction at minimum fluidization conditions was thus found equal to 0.385. Under these conditions the fluidized bed had a typical Geldart group B system behavior. The investigated powder was fluidized at different inlet gas velocities by ambient air, i.e., 1.7, 3.4, 5.0, and 7.0 u_{mf}.

The bubble-related flow structures were visualized with the aid of a backlighting device and recorded by a commercial digital camcorder (Sony, model DCRTRV530E PAL) placed opposite to the bed at a distance of 270 cm, as shown in Fig. 1. Continuous high-intensity, uniform illumination was obtained by placing at the back side of the bed six fluorescent lamps. The digital acquisition system allowed collection of images of the bed at a frequency of 25 Hz. Each acquisition lasts for 20 seconds, thus providing 500 frames.

Preliminarily, the measurement device was accurately calibrated by means of a purposely generated set of still images that included horizontal and vertical scales, with rectangular, circular, and ellipsoidal objects. The image processing routine was developed on Matlab 7.0 (MathWorks, Inc.) using the Image Processing Toolbox.

Thanks to the flexibility of the Matlab environment, almost all steps in image processing, data acquiring, and elaboration could be easily automated. The reader is referred to the paper by Busciglio *et al.* (2008) for full details on the experimental setup adopted and measurement techniques.

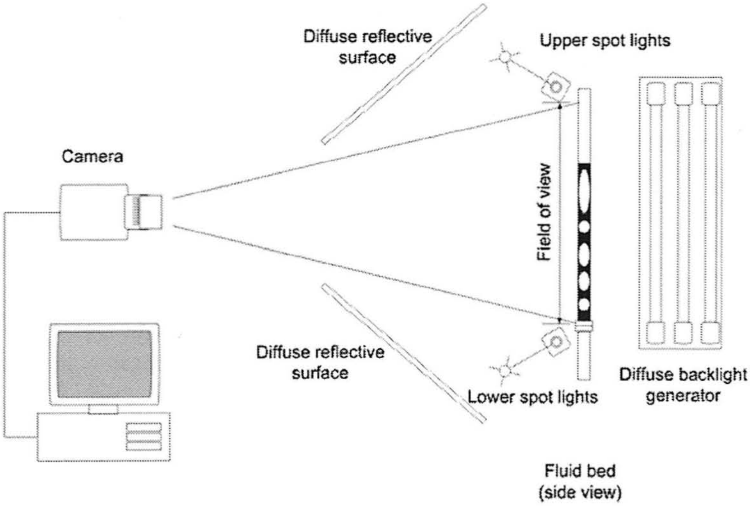


Figure 1 Experimental setup.

4. COMPUTATIONAL MODELS AND METHODS

In this study the Eulerian–Eulerian multiphase flow model (MFM) coupled with the granular kinetic theory (GKT) as presented in Gidaspow (1994) was adopted. This choice is a standard option of the CFD code Ansys CFX-10, purposely selected for this work.

For the present case of two-phase flow, the model has to solve essentially nine partial differential equations (one scalar continuity balance equation and three scalar momentum balance equations for each phase involved, plus a volumetric fractions balance equation) in as many unknowns: the two volumetric fractions, the six velocity components, and the pressure P (equal for both phases).

Volume fractions balance

$$\varepsilon_g + \varepsilon_s = 1 \tag{1}$$

Mass conservation equation of gas and solid phases

$$\frac{\partial}{\partial t}(\varepsilon_g \rho_g) + \nabla \bullet (\varepsilon_g \rho_g \vec{v_g}) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{v_s}) = 0 \tag{3}$$

Momentum conservation equation of gas and solid phases

$$\frac{\partial}{\partial t}(\varepsilon_g \rho_g \vec{v_g}) + \nabla \cdot (\varepsilon_g \rho_g \vec{v_g}\vec{v_g}) = \nabla \cdot \overline{\overline{S_g}} + \varepsilon_g \rho_g \vec{g} - \vec{I_g} \tag{4}$$

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_s \vec{v_s}) + \nabla \cdot (\varepsilon_s \rho_s \vec{v_s} \vec{v_s}) = \nabla \cdot \overline{\overline{S_s}} + \varepsilon_s \rho_s \vec{g} + \vec{I_g} \tag{5}$$

Of course, closure relations are also needed. To this end, the standard GKT model is adopted for estimating rheological properties of fluidized solid phase, and the Wen and Yu (1966) drag model is adopted to estimate the momentum exchange between phases. Because of the similarities between particle–particle interactions and molecular interactions in a gas, the concepts from gas kinetic theory can be used to develop a model for the solid phase stress tensor. Particle–particle interactions are described as binary instantaneous collisions, resembling those between gas molecules. Complete details on the derivations and applications to granular flow can be found in Gidaspow (1994).

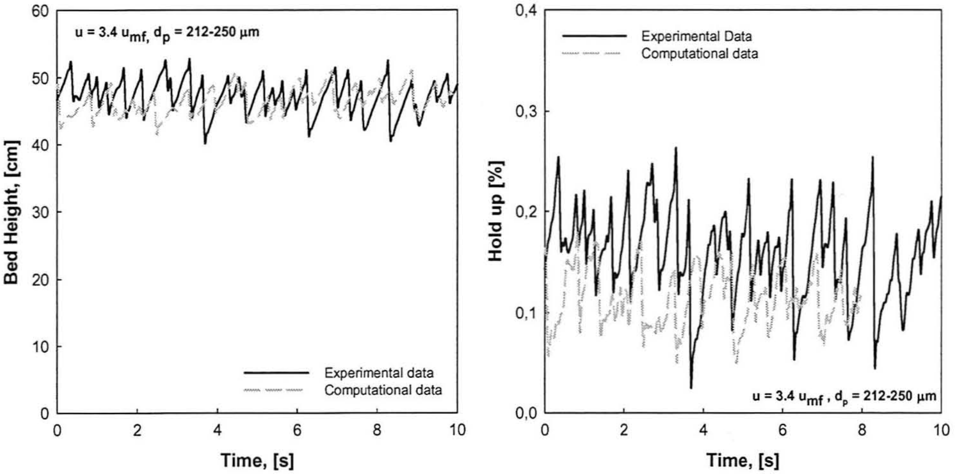
As far as the numerical aspects are concerned, CFD simulations were performed in 2-D mode choosing a computational grid consisting of 5 mm square cells with 288 (height) × 36 (width) subdivision. The lateral walls were modelled using the standard no-slip boundary condition. The upper section of the simulated geometry, or freeboard, was considered to be occupied by gas only. A simple pressure boundary condition was imposed at the top of the freeboard (i.e., fully developed flow condition). A Dirichlet boundary condition was employed at the bottom of the bed to specify a uniform vertical gas inlet velocity throughout the distributor. Symmetry planes were imposed on the front and rear faces of the simulated bed. The initial conditions specify only the distribution of solid volume fraction within the bed of solids which was set equal to 0.65. Typical running CPU times for CFX10 simulations were equal to about 100 hours for 10 seconds of real-time, simulated with a fixed time step interval $\Delta t = 10^{-3}$ s on a Dell Dimension 8300 personal computer. All the physical and geometrical parameters of the simulated cases are identical to that experimentally investigated.

5. RESULTS AND DISCUSSION

The analysis of parameters such as time-averaged bubble hold up and bed height, bubble size distribution, and bubble local velocity has been reported in a previous paper (Busciglio *et al.* 2008). The time-averaged quantification of such parameters, even if fundamental, is not sufficient for the correct assessment of bubbling behavior. In fact, the chaotic behavior of bubbles causes the fluidized bed to never reach steady-state conditions. On this basis, a helpful tool in data analysis is the power spectral analysis in the frequency domain of selected quantities. In particular, the analysis was focused on the time-dependent fluctuations of bed height (Fig. 2a) and bubble hold up (Fig. 2b).

Moreover, local information on bubbling behavior has been obtained through the analysis of time-dependent values of the local bubble hold up, computed in four regions of interest (ROI) in the bed. In particular, each ROI has the same width of the whole bed. The first ROI extends from the distributor to 0.25 H_0 (where H_0 is the settled bed height), the second extends from 0.25 to 0.50 H_0, the third extends from 0.50 to 0.75 H_0, and finally, the fourth extends from 0.75 to 1.00 H_0.

In order to characterize the frequency domain behavior of such time-dependent quantities for all the investigated cases, the well-known FFT algorithm has been adopted



(a) (b)

Figure 2 Comparison between experimental and computational data on instantaneous bed height (a) and bubble hold up (b) for the case at 3.4 u_{mf}.

(Duhamel and Vetterli, 1990; Matlab 7.0 User Guide). This algorithm allows for the detection of the frequency components of the fluctuating value of time-dependent quantities. Comparison of computational and experimental data in the frequency domain allows for the validation of the capability of the adopted CFD code in predicting the dynamic behavior of bubbling fluidized beds.

In Fig. 3 the computational and experimental power spectral densities of the Fourier transform of the signals relative to bed height at different inlet gas velocities are presented. The frequency domain data obtained by FFT have been smoothed by means of a standard moving average algorithm. Note that both experimental and simulated spectral density curves clearly increase their average values with increasing inlet gas velocity, as physically expected, due to the increasing intensity of bubble eruption. However, the simulated power spectra slightly underestimate the experimentally measured values of the power density.

For all investigated cases it is possible to observe a characteristic power law decay trend (i.e., a linear decay in logarithmic charts) for both simulated and experimental spectra, especially in the frequency range of 2–10 Hz. As reported in the following, this kind of decay has been used to characterize the bubbling behavior of the bed by means of the slopes and the intercepts of fitting straight lines. The linear fitting was applied only to the straight decaying part of the power spectra, adopting a standard squared error minimization algorithm. It is expected that fully developed slug flows will ideally give rise to a single frequency peak with pronounced decay rates. Conversely, the bubbling regime is expected to give rise to less pronounced power decay rates with frequency. The CFD predictions of the power decay slopes are highly satisfactory, being able to reproduce the bed surface dynamic in terms of decay rate.

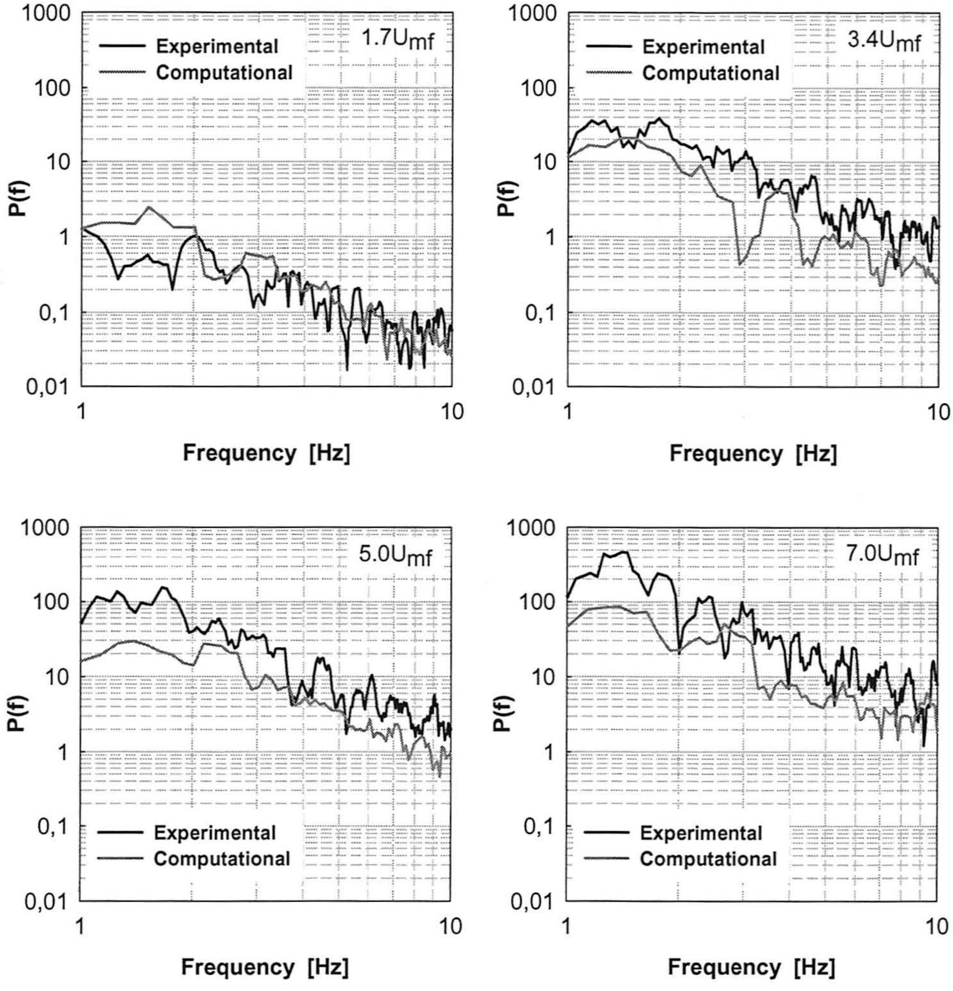


Figure 3 Comparison between experimental and computational power spectra of bed height at different inlet gas velocities.

In Fig. 4 the computational and experimental power spectra of the global bubble hold up are presented. Considerations quite similar to those made in the discussion of the bed height power spectra hold true to explain the physical role of such power spectra decay. The bubble hold up follows a similar trend with respect to that of bed height. In particular, it is supposed that the underestimation in computational power spectra with respect to relevant experimental cases is due to a difficulty of the adopted model in predicting the correct transition between the bubble phase and the emulsion phase, i.e., the thickness of the bubble boundary, as reported in a previous work (Busciglio *et al.*, 2009). In CFD codes such transition appears to be less sharp with respect to

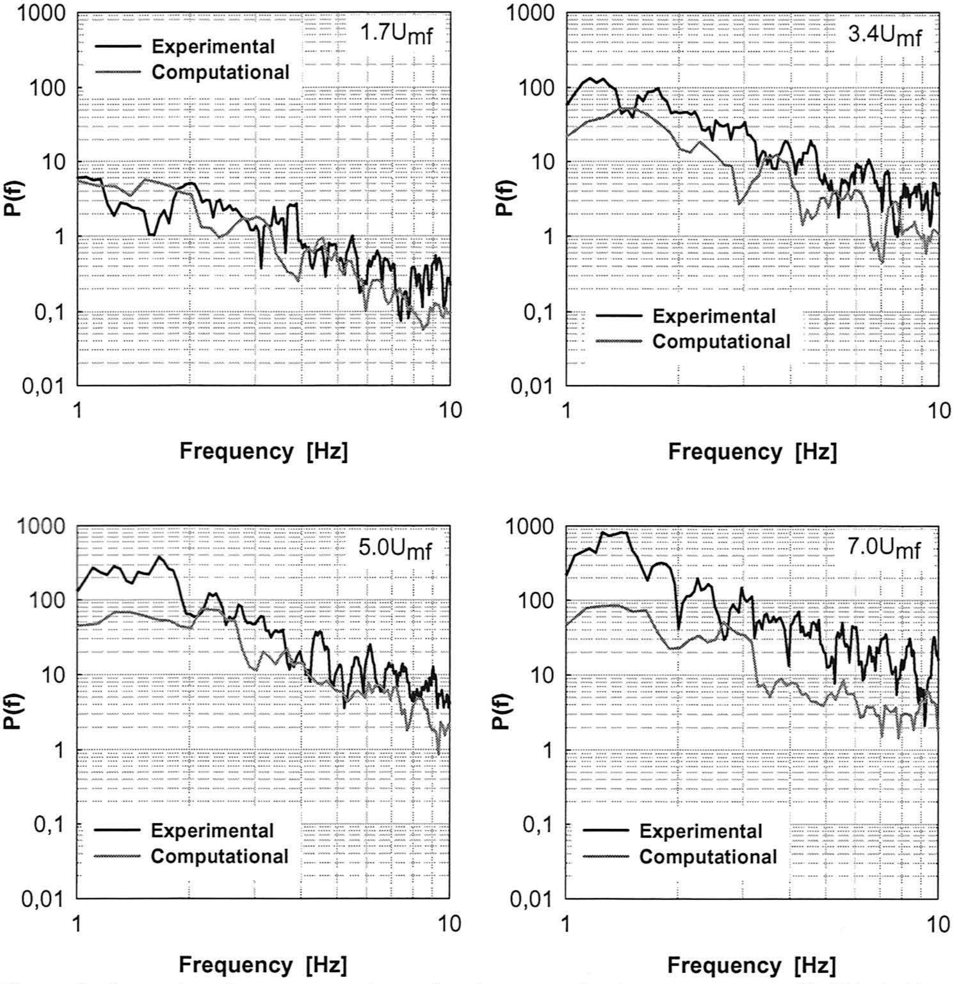


Figure 4 Comparison between experimental and computational power spectra of bubble hold up at different inlet gas velocities.

experiments: this leads to less-pronounced fluctuations in both bed height and bubble hold up, because part of the excess gas flowing through the bed is involved in such "expanded emulsion" near the bubble instead of inside the bubble.

The analysis of the experimental and computational power spectra of the local hold up at the four selected elevations, reported in Fig. 5 for the case at 3.4 u_{mf}, is useful to characterize the bubbling behavior evolution with increasing distance above the distributor. An increase of the slugging behavior with increasing distance above the distributor appears evident. Moreover, the slope variation appears to be less pronounced at higher elevations above the distributor, thus indicating the onset of a vigorous slugging behavior.

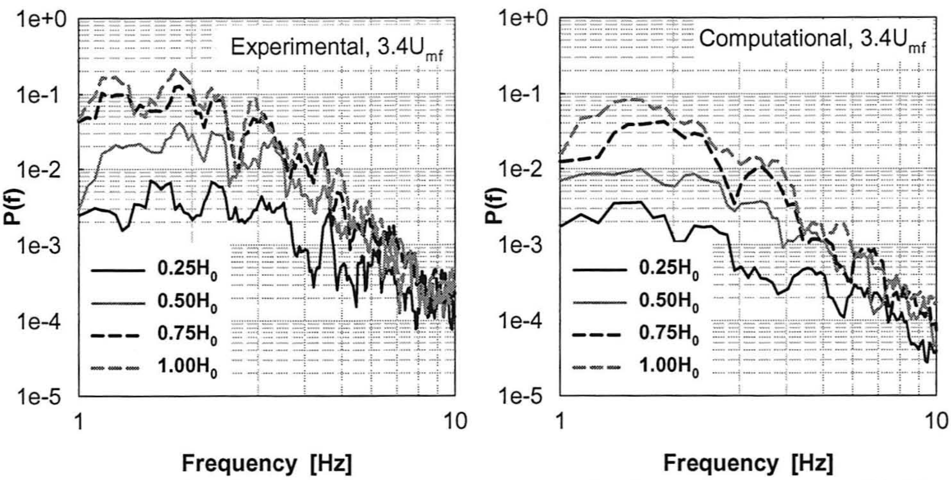


Figure 5 Comparison between experimental and computational power spectra of local hold up time series for the case at 3.4 u_{mf} at different elevations above the distributor.

In Fig. 6 the computed decay rates and intercepts of the fitting lines are reported. The analysis of the predicted decay rates highlights an articulate trend, with predictions giving rise to numerical values in acceptable agreement (within an order of magnitude) with experimental data. The overall decay rates of bed height fluctuation do not change appreciably with inlet gas velocity, while an increase in the intercept value is found. Conversely, a clear decrease of overall bubble hold up slope at increasing inlet gas velocities is observed. Such behavior can be explained by taking into account the different bubbling behaviors occurring at different inlet gas velocities. At low inlet gas velocities, fluctuations at all investigated frequencies are present, each one associated with the relevant bubble number in each size range. At high inlet gas velocities, the simultaneous presence of a bubbling region near the distributor (associated with high-frequency fluctuations) and a slugging region near the freeboard (associated with low-frequency fluctuations) gives rise to smaller overall decay rates. As far as the CFD predictions of intercept values are concerned, a substantial agreement with experimental data appears, although a slight underestimation is present.

The power spectra fitting parameters of local hold up at different elevations above the distributor are reported in Fig. 7. Both the experimental and the computational decay rates and intercept values show an increase with elevation above the distributor. This is due to bubble coalescence phenomena that lead to the formation of bubbles having a more pronounced slugging behavior in ROI at higher elevation. However, overall there is qualitative agreement between the experimental and computational data of Fig. 7.

6. CONCLUSIONS

CFD simulations of a 2-D bubbling fluidized bed were performed to evaluate their actual predictive capability. Relevant validation has been performed by means of a

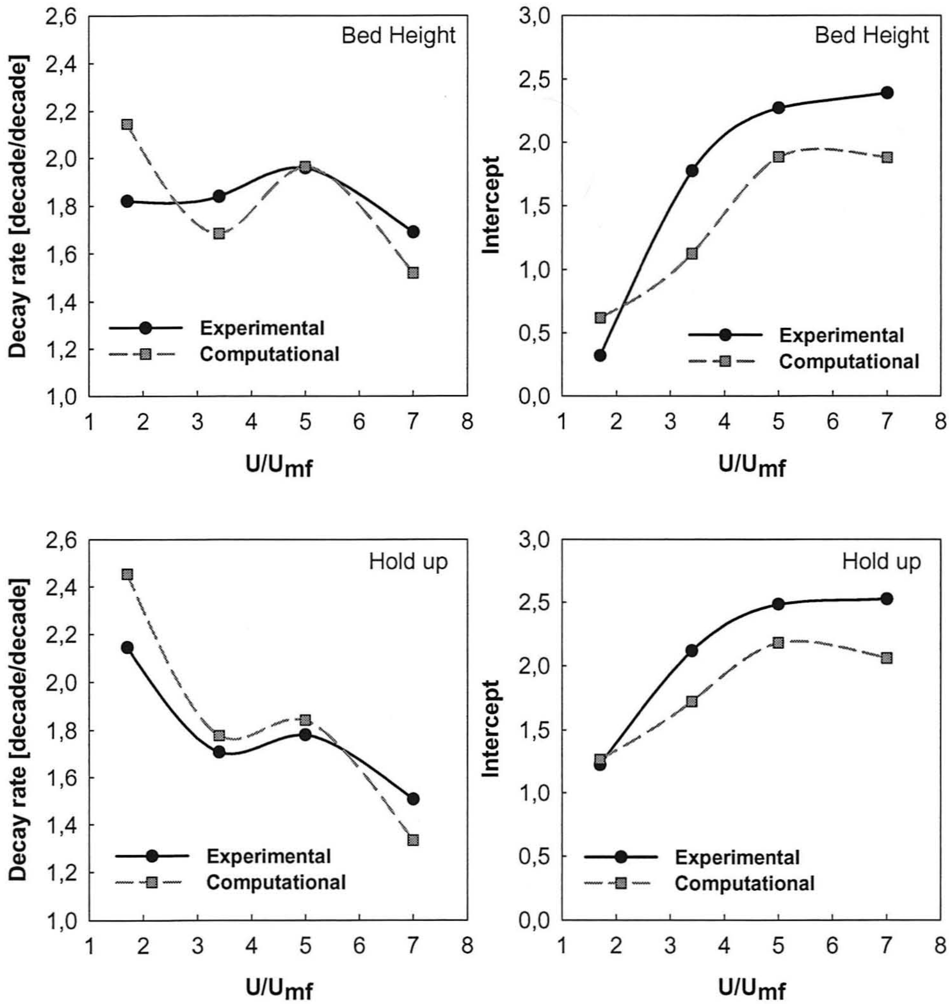


Figure 6 Comparison between experimental and computational power spectra fitting curve parameters for bed height and bubble hold up at different inlet gas velocities.

digital image analysis technique. Power spectral densities in the frequency domain of selected time-dependent quantities (i.e., bed height and global bubble hold up) obtained from both simulations and experiments were compared. The measured decay rates of power spectral densities characterize the bubbling intensity and even the local bubbling regime. The comparative analysis of results indicates that the adopted CFD code is able to correctly reproduce the bed height power spectral decays and intercepts at different inlet gas velocities, at least in a qualitative way. Moreover, the predicted power spectral decay rates and intercept for the local bubbling dynamic at a fixed inlet gas velocity are in fair agreement with experiments, confirming, in this respect, a good performance of

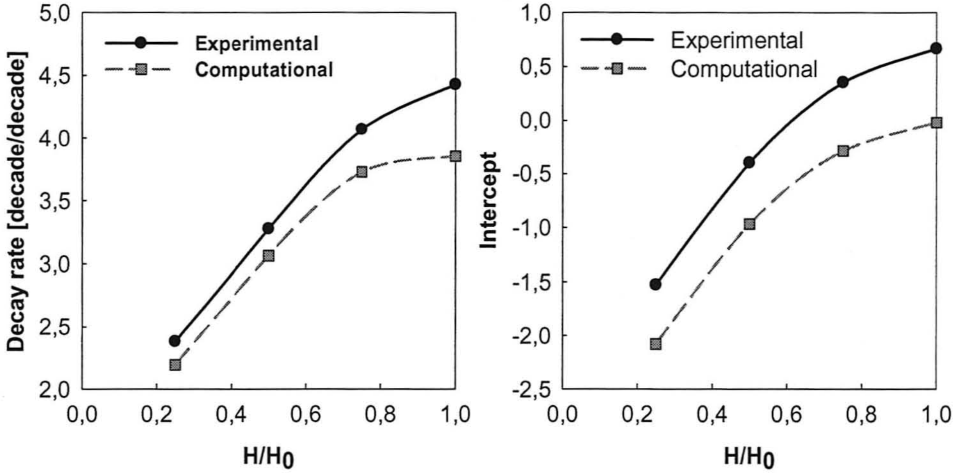


Figure 7 Measured values of experimental and computational decay rates for power spectra fitting curve parameters for local hold up at different elevations above the distributor for the case at 3.4 u_{mf}.

the CFD model here employed. Overall, the above findings provide valuable indications about future efforts toward fluidized bed modelling in order to improve the CFD code capability in predicting the transitions between fluidization regimes.

ACKNOWLEDGMENT

This work was carried out within the framework of the PRIN 2005 research program "Study of Fluidized Beds Stabilized by Means of Electric or Magnetic Fields," funded by the Italian Ministry of University.

NOMENCLATURE

d_p	particle diameter	m
g	acceleration due to gravity	m s^{-2}
I_i	interphase momentum exchange	kg m^{-2} s^{-2}
P	pressure	Pa
S_i	stress tensor	Pa
u	superficial gas velocity	cm s^{-1}
Greek letters		
ε_i	volume fraction	dimensionless
ρ_i	density	g m^{-3}
v_i	local velocity	m s^{-1}
Subscripts		
g	gas phase	
mf	minimum fluidization	
s	solid phase	

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