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Analysis of the bubbling behaviour of 2D gas solid fluidized beds Part I. Digital image analysis technique

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Abstract

Bubble characteristics are very important in the design of fluidized beds because they govern hydrodynamics and efficiency of the operation for which the bed is used. In this work, a digital image analysis technique has been developed to study the fluidization dynamics of a lab-scale two-dimensional bubbling bed. Digital image analysis may supply a great quantity of information; it is non-intrusive, capable of securing several properties simultaneously and cost effective. The image analysis method here developed allows for the simultaneous measurements of various significant bubble properties, i.e. bubble size and bubble velocity distributions, bed height and bubble-phase hold-up, by means of a purposely in-house developed software. Present results were compared with relevant literature correlations and resulted in sound agreement, thus confirming the large potential of the technique here developed.

Keywords: Image analysis; Bubbles; Fluidization

1. Introduction and literature review

In recent years, scientific research focused on industrial engineering issues has been largely benefiting from the huge increase of computing power made available by state of the art computers. Computational procedures which were considered, until a few years ago, not viable even on large mainframes, are now effortlessly run on commercial desktop computers.

Therefore, numerical simulations of more and more complex systems may today be successfully tackled. In particular, it is possible to run and validate complex models for the description of physico-chemical phenomena occurring into equipments operating under virtually any regime, for the case of single-phase or even multi-phase systems. Moreover, the possibility of devising more and more sophisticated mathematical models allows to analyze industrial equipments with higher modelling and computational requirements.

The above considerations allow to state the large potential to investigate complex fluidization dynamics, such as that of bubbling regimes, by means of mathematical modelling and numerical simulation.

However, in order to fully validate relevant models and methods it is necessary to get accurate and detailed quantitative experimental information, purposely collected for the task.

It is the aim of the present work to specifically develop a technique useful for the analysis of bubbling fluidization on the basis of digital image processing, which in fact may well perform a rigorous and highly detailed assessment of experimental data and may even be adopted for the analysis of computational results conveniently expressed into image graphics. Of course from stringent comparison between model and experimental results, it will then be possible to further develop and strengthen the modelling work.

The principal difficulty in analyzing fluidization quality and bubble dynamic is concerned with the possibility of measuring the physical and geometrical properties of the gas bubbles rising in a solid granular medium.

As a matter of fact, the gas flow in excess of that required to maintain the dense phase at minimum fluidization conditions flows through the bed in the form of bubbles and through flow [1]. Increasing the flow above the minimum bubbling velocity encourages more bubbles of larger size to nucleate in the bed,

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Nomenclature

A_0	catchment area of distributor (cm^2)
A_b	bubble area (cm^2)
$b(x,y)$	pixel luminance of a single object
d_b	bubble equivalent diameter (cm)
$f_n(x,y)$	matrix representation of frame nth
F	frame number
g	acceleration due to gravity (cm/s^2)
$g(x,y)$	pixel luminance in binary image
$G(x,y)$	bubble phase indicator
h	bubble height above the distributor (cm)
H_0	height of settled bed (cm)
k	constant value for second peak validation
k_b	first order constant for bubble density rate of change (1/cm^{3}s)
$l(x,y)$	pixel luminance in greyscale image
N_b	bubble density (no./cm^{2}s)
N_{b0}	bubble density at the distributor (no./cm^{2}s)
r_b	bubble density rate of change (no./cm^{3}s)
t	thickness of the two-dimensional bed (cm)
Th	threshold value
u	superficial gas velocity (cm/s)
u_b	bubble rise velocity (cm/s)
u_{mf}	minimum fluidization gas velocity (cm/s)
x,y	Cartesian coordinate (cm)
x_c, y_c	bubble centroid coordinates (cm)
X,Y	horizontal and vertical image dimensions in pixel
ΔX_m, ΔY_n	displacement vector (cm)

Greek letters

γ_1,γ_2	gamma distribution coefficients
$\Gamma(m)$	gamma function
ϕ	Davidson's coefficient
Φ	response matrix

making them to rise faster along the bed. The natural phenomena of bubbles break-up and coalescence potentially worsen the scenario. The fluidization quality of a bed is highly dependent on the distribution of bubbles and their physical properties in the bed such as position, dimensions, rise and lateral velocity. The spatial distribution of bubbles is determined by the temporal development of bubbles throughout the fluid bed. Ideally, for there to be good quality fluidization the population of bubbles in the bed should be large but the bubbles should be small in size, homogeneously occupy the bed and have low rise velocities.

To measure bubble parameters, different techniques have been employed which can be broadly classified into two categories, depending on the nature and position of the sensors used: (i) intrusive techniques, namely those based on resistance, inductance, impedance, piezoelectric or thermal probes, and (ii) non-intrusive techniques, among others those based on photographic, X-ray, light scattering and laser techniques.

The use of intrusive techniques implies an intrinsic source of error due to the presence of the measuring tool that creates some level of interference. On the contrary non-intrusive techniques provide good visual observation without interfering with the fluidization process. As an example, Rowe and Partridge [2] purposely developed an X-ray imaging technique to study bubbles in fluidized beds. The technique consisted of penetrating a gas-fluidized bed with X-ray beam to reveal the bubbles within it. Sung and Burgess [3] employed a laser, Glicksman et al. [4] took measurements with optic fibre probes, Atkinson and Clark [5] used pressure probes, while Halow et al. [6] used a high-speed three-dimensional capacitance imaging technique to measure voidage distributions.

In recent years, thanks to the continuous development of digital imaging systems and digital image processing, a great number of researchers have chosen digital visual methods to be applied in the field of experimental fluid dynamics [7–10]. These kinds of techniques play a fundamental role in analysis and data acquisition for multiphase flows such as gas–solid, gas–liquid, solid–liquid flows, where the observation of inter-phase boundaries is relatively simple.

Digital visual methods are limited of course to the case of bi-dimensional fluidized beds, as in this case bubbles can be easily observed.

Caicedo et al. [11] reported an experimental study of bubbling behaviour of gas-fluidized beds using digital image analysis. These authors investigated important parameters of bubbling dynamics such as bubble shape factor and aspect ratio. Experimental runs were conducted at several operation conditions. The results show that the investigated parameters obey to normal distribution across the operating fluid bed, and that statistical analysis must be performed when treating fluidized beds.

Goldschmidt et al. [12] developed an experimental technique based on digital analysis to measure bed expansion and segregation dynamics in dense gas-fluidized beds, in order to validate CFD simulation of mono-disperse and binary mixtures fluid beds. This technique allowed the authors to measure, through the use of differently coloured particles and RGB images decomposition, the extent of mixing and segregation. Extensive data on several systems investigated have been reported.

Shen et al. [13] developed a new method based on image analysis to study the hydrodynamics of two-dimensional bubbling fluidized beds by means of a digital video camera. Simultaneous measurements of size and velocity of gas bubbles were performed, as well as axial and radial distribution of bubble voidage. Equations for bubble diameter and bubble rise velocity prediction for two-dimensional beds were also proposed.

Bokkers et al. [14] studied the extent of mixing and segregation in a bidisperse gas–solid-fluidized bed induced by a single bubble injected in a monodisperse and bidisperse fluidized bed at incipient fluidization and in freely bubbling fluidized beds with both experiments and numerical simulation performed with the Discrete Particle Model. Experiments were run with a pseudo-2D fluidized bed, front-illuminated by halogen lamps. Fluid bed images were taken by means of a high-speed digital camera. The Particle Image Velocimetry (PIV) technique was applied for obtaining particles velocity fields of the experimental runs. The PIV technique adopted is the same widely used for single-