Measurement 117 (2018) 226–240

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Bubble size and bubble rise velocity estimation by means of electrical capacitance tomography within gas-solids fluidized beds

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ARTICLE INFO

Keywords:
Gas-solids fluidized beds
Electrical capacitance tomography
Bubble diameter
Bubble rise velocity
Numerical simulation

ABSTRACT

Electrical capacitance tomography (ECT) has been developed as a non-invasive and non-intrusive measurement technique to investigate the internal hydrodynamic characteristics of gas-solids systems in fluidized beds. This paper describes an investigation, in which a customized twin-plane ECT sensor was designed and constructed to study the fluid flow processes within a bench-scale gas-solids fluidized bed. A detailed calibration process was conducted using hollow plastic balls of different diameters to derive the reference grey level cut-off values for determining the bubble diameter. In addition, numerical simulations were carried out to investigate the plastic ball wall effect on measured capacitance values. Bubble diameters were estimated by means of the individual reference cut-off values and their linear and second-order fitted curves. Linear back-projection (LBP) and iterative LBP image reconstruction algorithms were compared with respect to estimating the bubble diameter. A number of approaches were investigated to estimate the bubble rise velocity including three methods based on cross-correlation techniques and the detailed signal analysis. Bubble diameters were also obtained using a new approach based on "back-calculation" of the bubble rise velocity through widely accepted empirical correlations from the existing literature.

1. Introduction

Gas-solids fluidized beds have been playing a vital role in many industrial applications, such as chemical reactions, energy conversions, and physical contacting [16,33,34]. The reasons for their extensive utilization are twofold: the rapid and extensive solids mixing and high rates of heat and mass transfer between solid particles and gas phase [9]. Amongst different types of gas-solids fluidized beds, bubbling regime beds exhibit a high dynamic complexity and are attractive in a wide range of applications, especially in drying and food processing industry; it is believed that the variation of bubble properties contributes to their widespread usage [23].

Therefore, numerous researchers have studied the characteristics of the bubbling beds, especially in regard to bubble properties by means of several point-wise measurement techniques. Capacitance probes [10,38] were applied to derive bubble size (pierced length) and bubble frequency, and cross correlation techniques were utilized to detect the rise velocity of a single bubble with two separated probes [39]. Fibre optic probes were employed to not only determine local solid particle movements and the particle concentration [27] but also to characterize bubble features such as bubble size, bubble frequency, bubble rise velocity and bubble size distribution [20,32]. Pressure transducers inserted into the bed body were employed to determine the expanded bed height and bubble travelling time which was ultimately used to extract the bubble rise velocity [3,38].

Although useful conclusions have been drawn with respect to some fundamentals of gas-solids fluid flow processes, all the aforementioned point-wise measurement techniques are not able to effectively map the whole cross sectional area. In addition, they are intrusive in nature, which inevitably introduces disturbances to and interference with the internal fluid flow within the gas-solids fluidized beds [17,30]. Owing to the rapid developments in computing and instrumentation technology, tomographic measurement techniques – traditionally associated with medical imaging – have become a popular tool in multiphase flow measurements [7]. Among these, electrical capacitance tomography (ECT) has evolved into an inexpensive, non-intrusive, non-invasive, and easy to handle and operate measurement technique. Additionally, it poses no radiation hazard and can withstand a harsh industrial environment, including high pressure and high temperature [40].

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https://doi.org/10.1016/j.measurement.2017.12.017
Received 8 September 2017; Received in revised form 7 December 2017; Accepted 12 December 2017
Available online 13 December 2017
0263-2241/

Nomenclature

Abbreviations/acronyms

CMU	capacitance measurement unit
ECT	electrical capacitance tomography
Fps	frames per second
LBP	linear back-projection algorithm
LBP10	10-step iteration with linear back-projection algorithm

Latin symbols

A_t	the cross-sectional area of the bed
C_i	a new cut-off value obtained in the iteration loop
C_0	assumed step reduction of cut-off value
D	the bed diameter
D_B	the diameter of the sphere having the same volume as the bubble
D_{BM}	maximum possible bubble diameter
D_e	the equivalent ball diameter or bubble diameter
D_i	the initial bubble diameter
D_t	the tentative bubble diameter
d_0	initial bubble diameter
g	acceleration due to gravity
h	height in the bed
h_0	a constant characterizing the distributor
j	number of elementary steps of the time lag
k	row index for the location of pixels
K	the maximum value of row index for the location of pixels
l	column index for the location of pixels
L	the maximum value of column index for the location of pixels
N	number of samples in the discretised signal
n	element index of the signal sample
n_d	total number of orifices on the distributor plate
P	the time series of 32 × 32 pixel images for plane 1
Q	the time series of 32 × 32 pixel images for plane 2
$\hat{R}_{xy}$	cross-correlation function value
t_{b1}	time instant when a bubble appears at plane 1
t_{b2}	time instant when a bubble appears at plane 2
U	the superficial gas velocity
U_b	bubble rise velocity
U_{br}	single bubble rise velocity
U_{mf}	superficial gas velocity at incipient fluidization
$x(n)$	discretised ECT signal from plane 1
$y(n)$	discretised ECT signal from plane 2

Greek symbols

φ	constant parameter in Werther [37] correlation for bubble rise velocity
$\nabla\cdot$	divergence operator
$\varepsilon(\boldsymbol{r})$	spatial permittivity distribution
$\varphi(\boldsymbol{r})$	electrical potential distribution
ε_{eff}	effective relative dielectric permittivity of the medium
ε_i	permittivity of the inclusions
ε_m	permittivity of the matrix
δ_i	volume fraction of the inclusions
ε_A	permittivity of the material A
ε_B	permittivity of the material B
$(\partial\varphi/\partial n)_A$	gradient of the electrical potential in the normal direction (from material A side)
$(\partial\varphi/\partial n)_B$	gradient of the electrical potential in the normal direction (from material B side)
δ	percentage error between D_t and D_i
δ_0	assumed percentage error
σ_N	the normalized two-dimensional cross-correlation coefficient
σ_{max}	the maximum value of two-dimensional cross-correlation coefficient
σ_{min}	the minimum value of two-dimensional cross-correlation coefficient
σ_{PQ}	the two-dimensional cross-correlation coefficient
Δx	the distance between the centres of the two measuring planes
Δt	elementary time step
Δt_i	the bubble time delay between plane 1 and 2

2. Literature review

ECT is a tomographic measurement technique which can give reconstructed images containing the information about concentration of one phase in a two-phase mixture by utilizing certain image reconstruction algorithms [35]. During the past few decades, ECT has been developed and applied in many industrial applications, e.g. pneumatic and hydraulic conveying systems, bubbling columns and hydrocyclones [7]. More importantly, many previous researchers investigated important bubble characteristics including the bubble size and bubble rise velocity within gas-solids fluidized beds by capitalising on unique capabilities of ECT.

One of the earliest studies related to bubble sizes was conducted by the Morgantown Energy Technology Centre [11,12] who observed bubble coalescence phenomenon in a 15.24 cm diameter fluidized bed using capacitance imaging system which contained 193 individual pixels. The frontal diameter of bubbles was estimated by assuming that they are hemispherical in shape, which was not always practically consistent with previous findings [13]. Due to the limited number of pixels, bubble boundary was not provided on a pixel basis, and only an average cross-sectional voidage (between 0.7 and 0.75) was utilized in deriving the bubble diameter. However, the obtained bubble diameter results were not compared with or validated against the existing empirical correlations. Wang [35] and his co-workers [36] utilized an ECT system to investigate the flow pattern in the vicinity of an air distributor. The ECT system they used had 812 pixels distributed within the circular cross-section area of the 150 mm diameter bed vessel. Thus clearer boundaries between bubbles and emulsion phase were obtained; in addition, bubbling and slugging regimes were identified. It was concluded that bubble diameter for a bubbling fluidization was in the range of 0.5–1.5 cm. These values were compared with some empirical correlations, which indicated that the ECT system typically under-predicted the bubble diameter with an increase of the gas superficial velocity. Unfortunately, no deeper discussion was provided on the methods of estimating the bubble diameter, and in particular on identification of bubble boundaries which are normally defined based on a grey level "cut-off" value in a 32 by 32 pixel ECT image. Thus distinguishing between the gas bubble and emulsion phases was not clearly addressed.

In order to discover the influence of permittivity models on ECT image boundary sharpness (normally three models: parallel, in-series and Maxwell are available for a conventional ECT system), McKeen and Pugsley [25] performed "phantom tests" using tubes made out of paper with 3.2 and 4.2 cm diameter. Linear back-projection (LBP) image reconstruction algorithm has been compared with iterative LBP reconstruction algorithm with the maximum number of iterations chosen as 500. Estimated equivalent tube diameters were compared with the expected values, which give different but relatively small errors for the