Chemical Engineering Science 172 (2017) 395–406

Contents lists available at ScienceDirect

Chemical Engineering Science

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

On the internal solids circulation rates in freely-bubbling gas-solid fluidized beds

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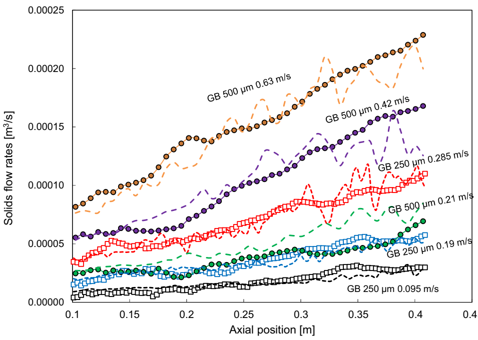
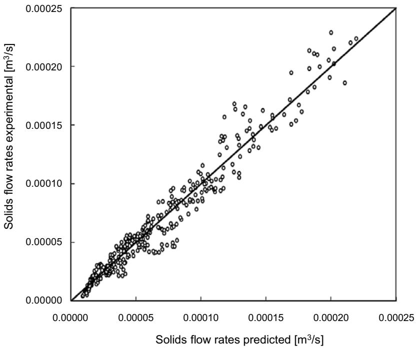
HIGHLIGHTS

- The amount of solids inside bubbles has been quantified for different conditions.
- Bubble fraction measured differs from theoretical correlations.
- A novel method to determine the wake parameter has been developed.
- The internal solids circulation has been quantified by solving the mass balance.
- A sensitivity analysis confirms the need to correct for the assumptions.

GRAPHICAL ABSTRACT





ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 21 May 2017
Accepted 29 June 2017
Available online 30 June 2017

Keywords:
Fluidized bed
Assumptions
Hydrodynamics
PIV/DIA

ABSTRACT

The solids mass flux distribution and internal solids circulation rates in freely-bubbling gas-solid fluidized beds has been studied in detail in a pseudo-2D column. A non-invasive Particle Image Velocimetry (PIV) combined with Digital Image Analysis (DIA) technique has been further extended to investigate and quantify the gas and solids phase properties simultaneously for different particle types and sizes (all Geldart B type) at different fluidization velocities. It is found that the solids fluxes increase strongly, practically linearly, as a function of the vertical position and depend on the excess gas velocity but not on the particle size, while the most often used phenomenological two-phase fluidized bed models assume the vertical solids fluxes to be constant. To further investigate this important discrepancy, the underlying assumptions of the phenomenological models have been validated, especially concerning the average solids fraction inside the bubbles, the laterally and time-averaged axial bubble fraction profile (or visual bubble flow rate) and the wake parameter (the amount of solids carried along a bubble relative to the bubble volume). To this end, the PIV/DIA technique was further extended and a new method for the determination of the wake parameter is proposed. From the experimental results, it was concluded that i) the average solids fraction inside the bubbles is about 2.5–3% for glass beads and alumina particles and is practically independent of the excess gas velocity and particle size; ii) the measured laterally and time-averaged bubble fractions are considerably lower compared to often used correlations from literature, which would lead to a significant over-prediction of the visual bubble flow rate and iii) the wake parameter depends strongly on the bubble size and with the developed correlation the axial solids mass fluxes as a function of the vertical position can be well described. Finally, the influence of these findings was evaluated by performing a sensitivity analysis with an existing phenomenological model for fluidized beds with the new values and closures considering the case of the heterogeneously catalyzed steam methane reforming. With the developed findings and correlations the predictions with

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http://dx.doi.org/10.1016/j.ces.2017.06.046

Nomenclature

Acronyms

CARPT	computed automated radioactive particle tracking
DIA	digital image analysis
ECT	electrical capacitance tomography
FCC	fluid catalytic cracking
MPT	magnetic particle tracking
MRI	magnetic resonance imaging
PEPT	positron emission particle tracking
PIV	particle image velocimetry
PTV	particle tracking velocimetry
Ar	Archimedes number
A_r	surface area of the column m^2
d_b	bubble diameter m
d_p	particle diameter m
SF	solids fluxes kg m^{-2} s^{-1}
u_0	superficial gas velocity m/s
u_{mf}	minimum fluidization velocity m/s
V_b	volume of the bubble cm^3
V_s	volume of the sphere cm^3

Greek letters

α	wake parameter
δ	bubble fraction in the bed
$\varepsilon_{bs,avg}$	average bubble solids holdup
ε_{mf}	emulsion phase porosity
ρ_g	gas density kg/m^3
ρ_p	particle density kg/m^3

the two-phase phenomenological models can be further improved, especially concerning the hydrodynamics of the solids phase.

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1. Introduction

Fluidization technology is currently applied worldwide for many widely varying applications, ranging from chemical conversions, to polymer synthesis, adsorption, drying and many other processes (Kunii and Levenspiel, 1991). When the fluid flow is increased until the pressure gradient is overcome to suspend the particles, the solids phase assumes a fluid-like behaviour. In such conditions, the fluidized bed is considered at its minimum fluidization (u_{mf}) and with a further increase in the gas velocity bubbles start to appear. The behaviour of these rising bubbles are responsible for the main advantages of fluidized beds over other systems, as they induce the movement of particles creating efficient contact between the fluid and solid phases and vigorous mixing, which in its turn provides enhanced heat and mass transfer and thermal homogeneity.

A large-scale description of such a complex system has been proposed through phenomenological models that can be distinguished into different levels depending on the complexity and main underlying assumptions and correlations used (Horio and Wen, 1977; Kato and Wen, 1969; van Deemter, 1961; Kunii and Levenspiel, 1968). In general, the bubble phase refers to the voids rising in the bed, while the dense phase is referred to as emulsion phase. These models combine information on the hydrodynamics and bubble-to-emulsion mass transfer and describe the properties of the two phases along the bed height. Many of these properties have been studied, often separately, using various different experimental techniques, such as X-ray (Maurer et al., 2015), Particle Image Velocimetry (PIV) Bokkers et al., 2004, Digital Image Analysis (DIA) Lim and Agarwal, 1990, Particle Tracking Velocimetry (PTV) Chaouki et al., 1997, Magnetic Resonance Imaging (MRI) Boyce et al., 2014, Positron Emission Particle Tracking (PEPT) Laverman et al., 2012, Computed Automated Radioactive Particle tracking (CARPT) Fraguío et al., 2007, Electrical Capacitance Tomography (ECT) Weber and Mei, 2013, Magnetic Particle Tracking (MPT) Buist et al., 2014, electrostatic probes (He et al., 2015), or pressure sensors (van Ommen et al., 2011). Although the mass exchange between the gas in the bubbles and the emulsion phase has been investigated with different experimental techniques, the theoretical simplified approach described by Davidson and Harrison (1963) in the early 60's is still generally employed, with the improvement proposed by Kunii and Levenspiel (1991). To close the phenomenological models several assumptions have to be made, which have not all been validated by detailed experimental work. For instance, it is still often assumed that all excess gas above u_{mf} goes to the bubble phase and that the gas velocity in the emulsion phase remains constant at u_{mf} (i.e. assuming the visual bubble flow rate parameter to be equal to unity), that the solids are moving upwards in the wake of the bubbles at the corresponding bubble velocity and emulsion porosity with a constant wake fraction compared to the bubble volume, and that the bubble phase is free of particles. In this work some of these assumptions are revisited with new experimental data using a modern non-intrusive optical technique, in particular focusing on the amount of solids inside bubbles, and the bubble hold-up and wake fraction along the bed height.

Based on the postulate by Davidson and Harrison, a gas bubble is often assumed devoid of particles (Davidson and Harrison, 1963). Even though the solids volume fraction inside bubbles might be small, they could enormously influence practical operations where rapid kinetic operations are carried out. For instance, for mass transfer limited systems, and/or in case of highly exothermic catalytic reactions, where the catalytic particles may ignite inside bubbles of fresh reactant, resulting in changed selectivity or progressive deterioration of the catalyst. The solids content in the bubble phase has been investigated by different researchers using different techniques. Toei et al. (1965) photographed bubbles using a lens with an extremely shallow depth of field, while Hiraki et al. (1965) used the Tyndall effect of dispersed particles illuminated by a thin beam of light and Kobayashi et al. (1965) measured the bulk density of rising bubbles with a sensitive micro phototransistor. In average, a solids content of 0.2–1.0% in the bubble phase was measured. More recently, Aoyagi and Kunii (1974) used a rapid combustion technique of dispersed particles by injected bubbles of air into a very hot bed of carbon particles fluidized at u_{mf} by air or nitrogen, using the fact that any particle finding itself in the air bubble ignites and becomes white hot and visible. Cui et al. (2000) investigated using a single cross-optical fiber probe the influence of different particle types (FCC catalyst and irregular sand) on the solids content inside the bubbles. They found that the