Measurement and Modelling of Local Phase Holdup and Flow Structure in Three-phase Bubble Columns

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1 Abstract

As part of an ongoing project in the field of three-phase flow, the local disperse phase holdup in a pilot-plant size bubble column was investigated under technically relevant operating conditions by measurement and simulation. A measurement probe was developed comprised of a combination of time domain reflectometry respectively conductivity and differential pressure measurement. The probe design was such that measurements could be performed at axial and radial positions covering most of the reactor interior thus delivering a detailed impression of local gas and solid holdups from sparger to degassing zone and from center to reactor edge. Investigations were carried out in a 6 m-high, 0.6 m-diameter bubble column using a model system of deionized water, air and plastic particles (particle diameter approximately 3 mm). System variations ranged from sparger type (jet ring, single injection nozzle, multi-hole plate) to superficial gas velocity (0.02 to 0.09 m/s), integral solids loading (0, 5 and 10 Vol.-%) and solids density (1200 kg/m^3 and 1400 kg/m^3). Measurements were extended by implementation of electrodiffusion technique for determination of local liquid flow structures. Measurement results strongly show the dependencies of local phase holdup on geometry and flow parameters thus indicating possible improvements in future reactor designs. Simulation using a 2D dispersion model and a commercial CFD Code (CFX-4) showed reasonable accordance with measurement results thus hinting a way to improved reactor design methods.

Keywords: Bubble Column, Three-Phase Flow, Local Phase Holdup, Liquid Flow Structure, CFD

2 Introduction and Literature Survey

Due to its immediate relevance to parameters like mass transfer coefficient and specific surface area, the local holdup of gaseous and solid phase in multiphase reactors has been of crucial importance in past research in the field of enhanced-performance reactors for chemical and biological process applications [1]. For reason of lacking experimental methods, investigations carried out so far have been constrained to either two-phase (gas-liquid) systems or (as for example with tomographic methods [2]) three-phase systems at extremely low loadings of particles very small in size. Most methods reported in the literature do not really deliver the 2D or 3D phase distributions but rather simplified axial or radial profiles [3]. The measurement technique presented here overcomes these drawbacks by applying a combined-probe method [4]. The developed method was used to determine local phase holdup structures for various parameter variations in a pilot-plant size bubble column. Furthermore, investigations into the liquid flow structure were carried out by means of electrodiffusivity measurements [5]. This method has been selected because of its applicability even at very high gas and solid holdups where other techniques like noninvasive optical methods (Laser-Doppler Anemometry [6] or Particle Tracking Velocimetry [7]) would fail. Experimental work was complemented by simulations of phase holdup and flow structures using a 2D dispersion model in analogy to [8] and CFD techniques.

3 Experimental Setup

Measurements were performed in a plexiglass bubble column of 0.63 m inner diameter at liquid heights of 5 m. The model system consisted of deionized water with 0.01 M/L K_2SO_4 added, air and plastic granules as solid phase. The plastic granules were chosen for their density to represent that of common biocatalysts, e. g. immobilisation particles like glass beads overgrown by microorganisms. Plexiglass (PMMA, density 1200 kg/m^3) and polyoxymethylene (POM, density 1400 kg/m^3) particles were found to best suit that purpose; the particles were almost monodisperse at an average particle diameter of 3 mm. The three most common sparger types were considered, namely a jet ring sparger, a single injection nozzle and a multi-hole plate sparger. Superficial gas velocity was varied from 0.02 m/s to 0.09 m/s covering the homogeneous and heterogeneous flow regime.

The measurement probe consisted of a combination of either time domain reflectometry (TDR) or conductivity and differential pressure measurement. Time domain reflectometry was initially conceived as a method for detecting errors in electric circuits but has proved useful in soil moisture and two-phase flow holdup measurements as well [9]. TDR has been shown to be accurate and reliable but was also rather slow in data acquisition and processing thus the faster combination of conductivity and differential pressure measurement was chosen for most of the measurements described below.

The local liquid flow structure inside the reactor was determined by electrodiffusion measurement (EDM). EDM is based on the influence of the flow velocity on the mass transfer boundary layer thickness in the diffusion-limited regime. Three-segment silver needle probes deliver two-dimensional information on the local liquid flow velocities including turbulent velocity oscillations. The method was developed at the Universities of Dortmund and Bremen (Germany) and has now reached a status where it can be considered ready for widespread applications in multiphase flows.

4 Results of Measurement and Modelling

Measurement results are comprised of local phase distribution for several parameter variations and corresponding local liquid flow structure in the three-phase bubble column. Phase distribution measurements have been completed, but liquid flow structure measurements are still in progress. Axial symmetry is assumed during all measurements. The immense wealth of information gained from local phase distribution measurement allows only for a few representative examples to be addressed here. Fig. 1 shows the dependency of local gas distribution in the three-phase bubble column on superficial gas velocity $u_{G,0}$; the column was operated with 10 Vol.-% loading of plexiglass granules and equipped with a ring sparger. At low superficial gas velocities, change in gas holdup mainly takes place in axial direction and can be attributed to gas expansion. With increasing gas velocity, a radial gradient becomes apparent developing into the well-known parabolic profile in the upper third of the reactor. In the lower part, the sparger influence is clearly visible in a crest structure showing a distinct gas holdup maximum at the radial position of the sparger outlet ($r = 0.23$ m) which shifts to column center with increasing height. Fig. 2

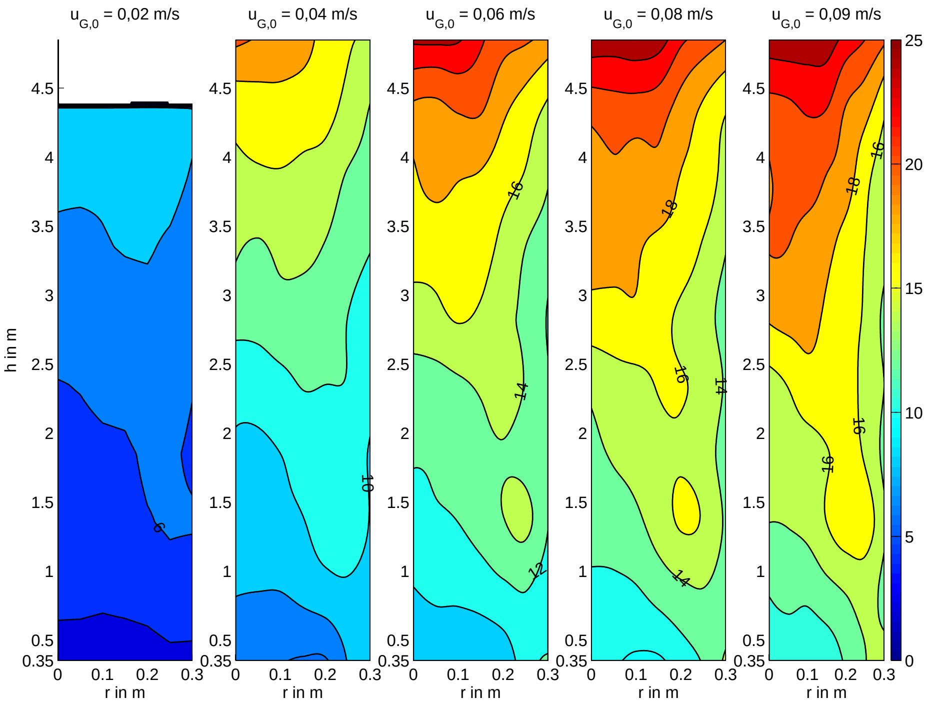

Figure 1: Gas phase distribution in the three-phase bubble column; ring sparger, sparger radius 0.23 m, solids plexiglass, integral solids loading 10 Vol.-%

shows the corresponding solid phase distributions. It is evident that due to the small density difference between liquid and solid, even at the lowest superficial gas velocity of 0.02 m/s complete and almost homogeneous fluidization can be achieved. With increasing gas

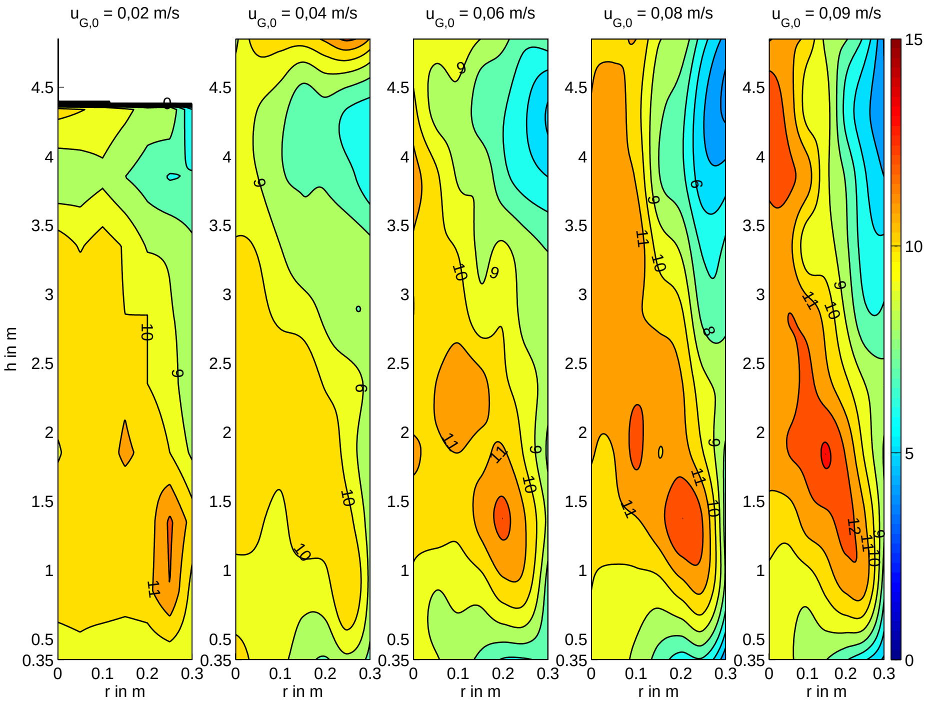

Figure 2: Solid phase distribution in the three-phase bubble column; ring sparger, sparger radius 0.23 m, solids plexiglass, integral solids loading 10 Vol.-%

velocity, however, a radial gradient develops which leads to a characteristic crest structure similar to the gas distribution. At $u_{G,0} = 0.09$ m/s, highest solid holdups can be found immediately above the sparger with the maximum shifting to the center with increasing height; in turn, at the upper reactor edge an almost solid-free zone appears. This observation has immediate implications for future bubble column reactors' operating strategies by showing that an increased superficial gas velocity does not automatically lead to more homogeneous fluidization.

First results of liquid flow structure measurements in three-phase flow are shown in Fig. 3. The liquid circulation in the bubble column can be described from the upflow in the column interior and downflow at the edge. With increasing superficial gas velocity, liquid circulation velocity increases as well. Further investigations to be presented at the congress will show sparger and solids influence on liquid circulation as well as the interaction of local flow structure and phase holdup.

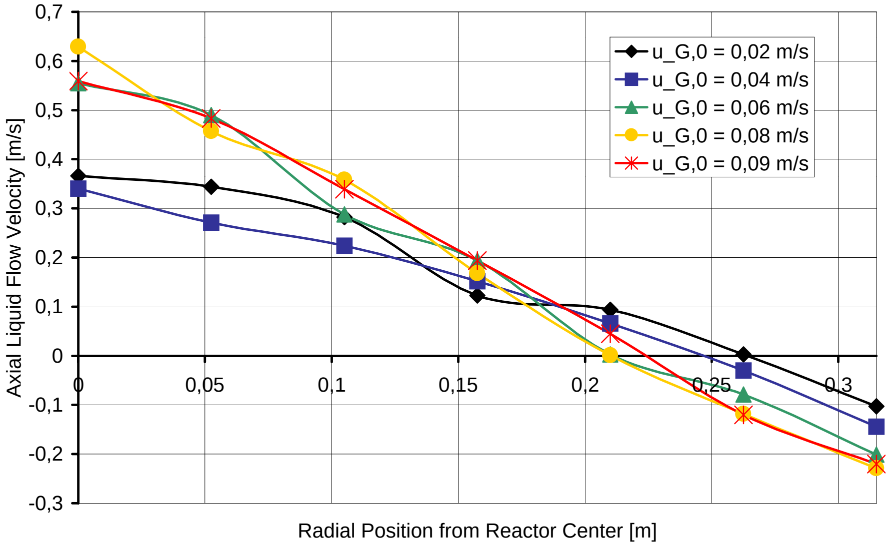

Figure 3: Local axial liquid flow velocities in the three-phase bubble column equipped with a plate sparger; vertical position 2.85 m above the sparger, integral solids loading 5 Vol.-% PMMA (Plexiglass)

Modelling was carried out using a simplified two-dimensional dispersion model as well as a commercial CFD code (CFX-4). The dispersion model equations were assembled according to Schlüter [8]:

$$\frac{\partial \varepsilon_i}{\partial t} = D_{ax,i} \cdot \frac{\partial^2 \varepsilon_i}{\partial x^2} - u_{i,k} \cdot \frac{\partial \varepsilon_i}{\partial x} + \frac{1}{r} \cdot D_{rad,i} \cdot \frac{\partial \varepsilon_i}{\partial r} + D_{rad,i} \cdot \frac{\partial^2 \varepsilon_i}{\partial r^2}$$

For each disperse phase i (gaseous or solid), an equation of the above kind can be set up. It includes convective and dispersive terms modelling deterministic and stochastic flow components. Dispersion coefficients were determined by numerically solving the system of linear equations resulting from discretization of the above partial differential equations and fitting the results to the measured phase distributions. Modelling results are in good accordance with measured values, though a firm scale-up criterion could not yet be developed due to numerical instability of the solution algorithm. CFD analysis of the problem setup is underway as well, aiming at developing a toolbox for design and scale-up of bubble columns and airlift loop reactors which can be applied on standard PC workstations.

5 Notation

Variable	**Units**	**Meaning**
$D_{ax,i}$	m^2/s	Axial dispersion coefficient of phase i
$D_{rad,i}$	m^2/s	Radial dispersion coefficient of phase i
i	1	Phase index (i = g, l, s)
r	m	Radial coordinate
t	s	Time
$u_{G,0}$	m/s	Superficial gas velocity
$u_{i,k}$	m/s	Convective axial velocity of phase i
u_l	m/s	Axial liquid flow velocity
x	m	Axial coordinate
ε_i	1, Vol.-%	Local holdup of phase i

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