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# Phase holdup measurement in a gas–liquid–solid circulating fluidized bed (GLSCFB) riser using electrical resistance tomography and optical fibre probe

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ABSTRACT

Phase holdups were measured in the riser section of a gas–liquid–solid circulating fluidized bed (GLSCFB). Electrical resistance tomography (ERT) as a non-invasive imaging technique, pressure transducers (PTs) and fibre optic probes were employed. Water was used as continuous and conductive phase, air as the gas phase and glass beads as solid nonconductive phases. ERT technique is based on conductivity measurement of the continuous phase (water in this study), which provides color-coded cross-sectional view of phases with a frequency of up to 250 images per second. The local conductivity measured by a number of electrodes located at the periphery of the plane was then further converted into a local phase concentration distribution based on Maxwell's relation. The results obtained by PTs, when combined with ERT results, were used to determine gas and solid holdups. Fibre optic probe was also employed to measure gas holdup independently. To measure gas and solid holdup, a model was introduced to exploit the fibre optic data in differentiating gas bubbles from solid particles in the riser. Radial profiles of the phase holdups were determined.



## 1. Introduction

Gas–liquid–solid circulating fluidized beds (GLSCFBs) have been widely used in chemical, petrochemical and biochemical and environmental processes, such as hydrogenation, desulfurization, fermentation, due to its efficient mixing, heat and mass transfer capabilities. Most of the studies on gas–liquid–solid fluidization systems have mainly focused on conventional expanded bed regime in the past decades [1]. Therefore a number of theoretical, empirical and semi-empirical models have been developed about hydrodynamics of such systems. The application of these models is limited in GLSCFB. Conventional fluidized beds also suffer from limitations such as liquid and gas velocities, solid particles size, density, etc. In GLSCFB, solid particles are circulated between the riser and the downer at higher velocities compared to conventional fluidized beds, which leads to formation of smaller bubbles and a better contact between phases. GLSCFB also offers great flexibility in terms of solid particles or catalyst regeneration in the downer. In spite of substantial work the hydrodynamics of GLSCFB is not completely understood yet.

Different methods have been employed in the study of hydrodynamics such as direct sampling, optical fibre, electric conductive probe, process tomography, static-pressure, ultrasound and isokinetic separation. Phase holdups as a main parameter was of major concern. Warsito and Fan [2] used electrical capacitance tomography (ECT) to distinguish the three phases qualitatively. Due to the complexity of the systems, different techniques should be applied simultaneously for quantitative measurement of phase holdups.

In this study, electrical resistance tomography (ERT), a newly developed method for the measurement phase holdups, is presented. However ERT cannot measure phase holdups for all the phases, therefore an optical fibre probe and pressure transducers (PTs) are used simultaneously to measure phase holdups for all three phases. In the experiments, water was used as the liquid (continuous and conductive) phase, air as the gas phase and glass beads with 500 μm range as the solid phase. Combination of these measurement techniques provided valuable information about the hydrodynamics of GLSCFB riser. Average phase holdups, and local distribution of phases were obtained and compared with published data wherever applicable.

## 2. Available measurement techniques

Different measurement techniques have been developed to measure phase holdups such as; optical fibre technique, ultrasound

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area |
| $P$ | pressure (psia) |
| $r$ | radial position (m) |
| $R$ | radius of the riser (m) |
| $S$ | standard deviation |
| $U_a$ | auxiliary liquid velocity (m/s) |
| $U_l$ | superficial liquid velocity (m/s) |
| $U_g$ | superficial gas velocity (m/s) |
| $\bar{V}$ | average voltage of the signals |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | holdup |
| $\rho$ | density (kg/m$^3$) |
| $\sigma$ | conductivity (μSi/cm) |
| $\sigma_i$ | local conductivity for single phase (μSi/cm) |
| $\sigma_m$ | estimated local conductivity (μSi/cm) |
| $\sigma_0$ | local conductivity for mix phases (μSi/cm) |

*Subscripts*

| | |
|---|---|
| g | gas phase |
| l | liquid phase |
| s | solid phase |
| ls | liquid–solid phase |
| gls | gas–liquid–solid phase |
| bed | fluidized bed |

technique, electric conductive probe technique, and process tomographic technique.

Lee and de Lasa [3], de Lasa et al. [4] and Yong and Sang [5] used fibre optic probe to measure the gas holdup directly in a three phase system. A single core silica optical fibre of 400 μm U-shape probe was employed to detect gas bubbles. The gas holdup was determined by measuring the time elapsed by the gas bubbles travelling inside the bed. Air was introduced through large nozzles (0.94 cm) producing large bubbles compared to particles average size (250 μm). Wang et al. [6] studied bubble behaviour in a fluidized bed using 62.5 μm diameter optical fibre probe. Pipe type distributor was employed to produce large bubbles. Single emitted light beam is sent into the fibre through the fibre coupler and then each beam is reflected at the end of the fibre. Although the application of fibre optic sensor in detection of gas bubbles in a fluidized bed is simple, it is limited by the size of bubbles and not capable of detecting fine bubbles in a dispersed flow regime.

Uchida et al. [7] developed a new technique for solids holdup measurement in a three phase fluidized bed using ultrasonic sound wave. Later, Vatanakul et al. [8,9] used similar concept for flow detection. This technique is based on the change in speed and amplitude of ultrasonic wave incident on a surface. Similar to light beams, when ultrasonic waves strike at the interface between two media, they may be partially/totally reflected, scattered or transmitted. Vatanakul et al. [9] reported that the effects of gas bubbles on sound velocity were contradictory. Some believe that sound velocity is independent of gas holdup whereas others argued that the bubbles could affect sound velocity due to great distortion of ultrasound waves around bubbles [18]. Vatanakul et al. [8] reported that that temperature sensitivity and complicated data analysis were major disadvantages of commercially available ultrasonic instruments.

A dual electrical resistivity probe system was developed by Matsuura and Fan [10] to measure phase holdup and bubble rise velocity in a fluidized bed. The probe was capable of detecting the difference in conductivity of gas and liquid. The dual conductivity probe consisted of two 0.4 mm diameter stainless steel syringe needles coated with epoxy resin. The vertical distance between the tips was 0.3 mm. The striking bubbles generated signals which were recorded digitally. The average lag time of signals (due to the passing bubbles) were used for calculation of average bubble rise velocity. The technique was claimed to be effective in detecting bubbles as small as 1 mm in size. The method is more applicable to larger bubbles compared to solid particles. The experiments were carried out where the bubbles average size was about 5 mm which was 10–15 times larger than the solids particles used in the experiments. Liang et al. [11,12] used similar setup for gas holdup measurement and a horizontal probe for the measurement of solid holdup in the bubble wake and the emulsion phase. They also measured the solids holdup from the same signals by using the conductivity of the pure liquid as the base line.

Process tomography is an area which has experienced a significant growth over the last 10 years in the study of multiphase flow due to its non-intrusive technique [13]. There are many tomographic techniques, which have been developed in the past 5–10 years and employed in the study of three phase systems such as slurry bubble columns and three phase fluidized beds. However, there are no imaging techniques available for the study of three phase systems in real time [2]. Most of the tomographic techniques such as electrical capacitance tomography, electrical impedance tomography (EIT) or ERT are suitable for two phase systems. George et al. [14] developed a combined system of EIT and gamma-densitometry tomography (GDT) to measure distribution of phases in a vertical three phase flow system simultaneously. Razzak et al. [15] measured phase holdups and velocities in a GLSCFB system by combining ERT and PTs. Warsito and Fan [2] successfully developed a new reconstruction technique for electrical capacitance tomography based on the Hop-field neural network multi-criteria optimization technique (neural network multi-criteria image reconstruction technique, NN-MOIRT). However this imaging technique was useful only in qualitative determination of phases. The application of tomographic technique in the study of multiphase flow systems continues to grow due to its qualitative and quantitative advantages.

## 3. Experimental setup

Schematic diagram of the experimental setup of GLSCFB is shown in Fig. 1. The GLSCFB consists of two main sections, riser and downer, both made of Plexiglas. The riser is 5.97 m tall and 0.0762 m in diameter and the downer is 5.05 m and 0.2 m in diameter. A gas–liquid–solid separator is located at the top of the riser to separate out the solids from the gas and liquid flow and a solids circulation rate measurement device is located near the top of the downer to measure the solids circulation rate.

There are two liquid distributors at the bottom of the riser shown in Fig. 2, the main liquid distributor, made of seven stainless tubes occupying 19.5% of the total riser cross-section and extending 0.2 m into the riser, and the auxiliary liquid distributor, a porous plate with 4.8% opening area at the base of the riser.

The gas distributor shown in Fig. 2 is a tube of 19 mm in diameter and bent in a ring shape of approximately 0.0413 m in diameter, located at 0.34 m above the bottom of the riser. There are 460 small holes of 0.5 mm in diameter on the ring, giving a total opening area of 361 mm$^2$, pointing downwards for gas flow. There is also a ring-type liquid distributor in the conical area near the bottom of the downer, which is a tube of 25.4 mm in diameter and bent in a ring shape of approximately 0.114 m in diameter, with 96 small