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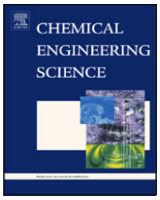

Local characteristics of hydrodynamics in draft tube airlift bioreactor

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ABSTRACT

Airlift column reactors have been widely used in bioprocesses. The design, scale-up, and performance evaluation of such reactors all require extensive and accurate information about the gas–liquid flow dynamics, particularly as computational fluid dynamics (CFD) has become more popular in the last decade. However, due to the limitation of most conventional techniques for gas–liquid flow dynamics measurement, only global hydrodynamic parameters (e.g., cross-sectionally averaged liquid circulation velocity, overall gas holdup, and overall mass transfer rate) have been extensively studied. The local flow characteristics (e.g., the macro-mixing and the turbulence intensity) remain unclear. In this study, we use the computer automated radioactive particle tracking (CARPT) technique to investigate the details of the multiphase flow dynamics in a draft tube airlift bioreactor, such as the liquid velocity field, turbulent kinetic energy field, distributions of shear stresses, etc. The flow structures in the whole reactor, as well as the structure in individual regions, i.e., the top, the bottom, the riser, and the downcorner are also characterized. We found significantly large turbulent kinetic energy in the top and the bottom regions, with spots of very high shear stress, which were also found in the vicinity of the sparger. The results also suggest that the top and bottom clearances have significant effects on the flow structures, which may have substantial effects on the bioreactor performance.

1. Introduction

Airlift reactors are pneumatically agitated reactors that have been widely used in chemical, petrochemical, and bioprocess industries, such as fermentation (Pollard et al., 1998) and wastewater treatment (Heijnen et al., 1990). Recently, many researchers (Merchuk et al., 2000; Sanchez Miron et al., 1999; Garcia Camacho et al., 1999; Chini Zettelli et al., 2003; Luo and Al-Dahhan, 2004) also recommended airlift column reactors as promising photobioreactors for culturing microalgae and cyanobacteria. Besides other advantages such as better scalability and operational flexibility, these reactors have the potential to significantly enhance the photosynthetic microorganisms' ability to use light energy more efficiently and thus improve the overall performance of the culturing system (Sanchez Miron et al., 1999; Janssen, 2002; Luo and Al-Dahhan, 2004).

The advantages of using airlift reactors in bioprocesses are obvious. These reactors have no moving parts, low power consumption, good solids suspending, high mass and heat transfer characteristics, and above all, provide rapid mixing while retaining homogeneous shear stress (Petersen and Margaritis, 2001; Chisti, 1998). The hydrodynamics of airlift column reactors are characterized by the buoyancy-driven flow due to the rising bubbles in the riser section of the reactor.

Such gas–liquid flow dynamics in airlift reactors have been studied extensively in the last decades (Chisti and Moo-Young, 1988; Joshi et al., 1990; Chisti, 1998; Petersen and Margaritis, 2001). However, as summarized in Table 1, most of these studies utilized conventional techniques (e.g., pulse response technique, differential pressure drop, Pitot tube, etc.) and focused on the gas–liquid velocity fields in the fully developed flow region in the reactor. Global hydrodynamic parameters, such as cross-sectionally averaged liquid circulation velocity, overall gas holdup, overall mass transfer rate, etc., were widely used to represent the flow dynamics in the these reactors. Only a few studies tried to investigate the local characteristics of hydrodynamics in the airlift column reactors by using recently developed measurement techniques like laser Doppler and optical fiber probe techniques (Vial et al., 2002).

Conventionally, bulk liquid circulation velocity can be measured by Pitot tube, magnetic tracer method, and liquid solution tracer techniques (Bello et al., 1984, 1985; Chisti and Moo-Young, 1988; Merchuk et al., 1998; Baten et al., 2003; Zhang et al., 2002). For example, the liquid solution tracer technique introduces a salt

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Table 1
Typical hydrodynamic measurements for airlift column reactors

Reference	Reactor type	Variables measured	Techniques used for the measurements
Merchuk and Stein (1981)	External loop column	Liquid circulation velocity Gas holdup	Magnetic flow meter Differential pressure
Weiland and Onken (1981)	External loop column	Liquid circulation velocity Mixing time Dispersion coefficient Gas holdup	Magnetic flow Conductivity method Pulse tracer technique Differential pressure
Bello et al. (1984, 1985)	External loop column Internal loop column	Liquid circulation velocity Gas holdup	Tracer technique Differential pressure
Chisti and Moo-Young (1988)	Internal loop column Split cylinder	Liquid Circulation velocity	Tracer technique
Young et al. (1991)	External loop column	Local liquid velocity Local gas velocity Local gas holdup	Hot-film anemometry Resistivity probe Gamma densitometry
Merchuk et al. (1998)	Internal loop column	Liquid circulation velocity Overall gas holdup	Pulse injection–response Differential pressure
Vial et al. (2002)	External loop column	Liquid circulation velocity Overall gas holdup Local liquid velocity rms velocity Local gas velocity Local gas holdup	Pulse injection–response Differential pressure Laser Doppler Anemometer Aerometric Ultrasound Doppler Optical fiber probe
Zhang et al. (2002)	Internal loop column	Gas holdup (overall, riser, and downcomer) Liquid circulation velocity	Volume expansion and differential pressure Pulse injection–response
Baten et al. (2003)	Internal loop column	Gas holdup Liquid circulation velocity	Differential pressure Pulse injection–response
Klein et al. (2003)	Internal loop column	Gas holdup (riser and downcomer) Liquid circulation velocity	Differential pressure Magnetic tracer method
Nakao et al. (2003)	External loop column	Liquid circulation velocity	Pitot tube
Lo and Hwang (2003)	Internal loop column	Bubble dynamics (gas holdup, gas velocity, and bubble size distribution)	Dual electrical resistivity probes
Wu and Merchuk (2003)	Internal loop column	Liquid circulation velocity	PIV technique

solution (or an acid solution) from the bottom of the column and measures the liquid conductivity (or pH for acid tracer) at the top by a conductivity (or pH) probe. Thus, the bulk circulation velocity can be calculated from the peak pulses detected by the probe and the distance from the probe to the tracer injection location. However, this technique's accuracy is usually low because the tracer's concentration usually reaches equilibrium shortly after the tracer is injected. Only a few peak tracer concentrations were usually detected by a probe installed in the reactor. Moreover, Pitot tube measurements (Soderberg, 1980; Nakao et al., 2003) could disturb the flow considerably, and the magnetic tracer method (Weiland and Onken, 1981; Klein et al., 2003) could not detect the turbulence flow because of the large size of the tracer particles used (the particle used by Klein et al., 2003 is 11 mm in diameter). Therefore, it is fair to say that these conventional measurement techniques can hardly provide sufficient hydrodynamic information for reactor design.

Due to the limitations of these conventional measurement techniques, no information can be extracted from the experimental data to estimate the Reynolds shear stress in an airlift reactor. As a result, researchers (Contreras et al., 1999; Vial et al., 2002) have used purely dimensional considerations based on energy input and the total area of bubbles or the mixing length scale. These studies are rather primitive, and can provide only a qualitative analysis.

Young et al. (1991) are among the first investigators to study the local two-phase hydrodynamics in an external loop airlift column reactor. They measured the local liquid velocity by the hot-film technique (and thus calculated the liquid turbulence intensity), the local gas velocity by the resistivity probe technique, and the overall and radial gas holdups by the gamma densitometry technique. Thus the slip velocity between gas and liquid phases could be calculated.

Vial et al. (2002) investigated the global and local hydrodynamics in the riser of an external airlift column. They measured the overall gas holdup and bulk liquid circulation by conventional techniques, the bubble size distribution by photographic techniques, the local gas holdup by the optical fiber probe technique, the local gas velocity by the ultrasound Doppler technique, and the local liquid velocity and thus root mean square (RMS) velocities by the laser Doppler anemometer aerometric technique.

Lo and Hwang (2003) further investigated the bubble dynamics in an internal loop airlift column, i.e., local and overall gas holdups, local gas velocity, bubble size distribution, by using the dual electrical resistivity probe technique.

Wu and Merchuk (2003) used the PIV (Particle Image Velocimetry) technique to measure the liquid flow map in the wall vicinity of the downcomer in an internal loop reactor.

Although these studies have considerably enhanced our understanding of the gas–liquid flow dynamics in airlift column reactors, the local flow characteristics, such as the turbulence intensity and the Reynolds shear stress, remain unclear. Moreover, the flow structures in the top and the bottom regions in airlift reactors have rarely been studied. In these regions, the gas phase separates from the liquid phase, and the liquid flow changes direction. Both phenomena have significant effects on the driving force and the hydraulic resistance to the liquid flow in the reactor. Thus, changing the size and shape of these two regions will alter the gas–liquid separation efficiency, the gas holdup in different regions, and the liquid flow velocities, and will further affect the flow structures in the whole column.

For example, Luo and Al-Dahhan (2008) studied the macro-mixing in a draft tube airlift bioreactor using the computer automated radioactive particle tracking (CARPT) technique. It was found that the flow structures in the top and the bottom regions have significant effects on the macro-mixing in the reactor and are very different from the flow structure in the riser and the downcomer regions (definitions of the individual regions are illustrated in Fig. 1). Therefore, appropriate understanding of the flow phenomena in these regions is important for proper design and scale-up of airlift reactors.

Furthermore, there is an increasing trend in the literature to apply computational fluid dynamic (CFD) simulations to study the flow patterns in airlift column reactors (Sokolichin and Eigenberger, 1994; Jakobsen et al., 1997; Krishna et al., 1999; Mudde and Van Den Akker,