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Profiles of solid fraction and heterogeneous phase structure in a gas–solid airlift loop reactor

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ABSTRACT

The time-averaged and transient local solid fractions in a gas–solid airlift loop reactor (ALR) were investigated systematically by experiments and CFD simulations. To demonstrate the macro-flow pattern, the time-averaged local solid fractions in four regions of the ALR were measured by optical fiber probe under the conditions of different superficial gas velocities and particle circulation fluxes. The experimental results show that the lateral distribution of time-averaged local solid fraction is a core-annulus or heterogeneous structure in the three regions (draft tube, bottom region, particle diffluence region), but a uniform lateral distribution in the annulus. The operating conditions have different effects on the lateral distribution of time-averaged local solid fraction in each region. In the CFD simulation, a modified Gidaspow drag model considering the formation of particle clusters was incorporated into the Eulerian–Eulerian CFD model with particulate phase kinetic theory to simulate and analyze the transient local solid fraction and the two-phase micro-structures in the gas–solid ALR. The predicted values of solid fraction were compared with the experimental results, validating the drag model. The contours of transient flow field indicate that the flow field of the ALR should be divided into five flow regions, i.e., draft tube, annulus, bottom region, particle diffluence region and constrained back-mixing region, which further improves the understanding of the airlift reactor where only four divisions were determined from the experiments. The transient local solid fraction and its probability density function profoundly reveal the two-phase micro-structures (dilute phase and emulsion phase or cluster phase in the constrained back-mixing region) and explain the heterogeneous phenomenon of solid fraction in the ALR. The dilute phase tends to exist in the center of bed, while the emulsion phase mainly appears in the wall region. The results also indicate that the gas–solid ALR has the common characteristic of aggregative fluidization similar to that in normal fluidized beds. The simulated two-phase transient micro-structures provide the appropriate explanations for the experimental core-annulus macro-structures of time-averaged local solid fraction.

1. Introduction

Airlift loop reactor (ALR) is widely used in many industrial processes due to its many advantages, such as high gas holdup, high mass and heat transfer rates, efficient mixing, and simplicity in structure. At present, ALR is mainly running in gas–liquid (Kemblowski et al., 1993), liquid–solid (Wang et al., 2003) or gas–liquid–solid systems (Hwang and Cheng, 1997). According to literature reviews, experimental and numerical simulation studies on ALR are mainly focused on three aspects: (1) hydrodynamics, including gas holdup, liquid circulation velocity, mass transfer (Korpijarvi et al., 1999; Chia and Lii, 2001; Guo et al., 1997; Blažej et al., 2004a; Cockx et al., 1997, 2001; Oey et al., 2001), and residence time distribution of gas or liquid phase (PrmHamo et al., 2001; Pareek et al., 2001; Gavrilescu and Tudose, 1999; Sivashanmugam and Sundaram, 2000; Sahle-Demessie et al., 2003); (2) mathematical models to predict gas holdup and liquid circulation velocity based on several principles, such as energy conservation (Kundakovic and Vunjak-Novakovic, 1995; Heijnen et al., 1997; Garcia-Calvo et al., 1999; Lu et al., 1995), and drift flux (Zuber and Findlay, 1965); (3) structural development and optimization, mainly focusing on the square or rectangular ALRs (Couvert et al., 1999; Lu et al., 2000), the dimension optimizations including configuration of draft tube (Blažej et al., 2004b; Bado, 1990; Fu et al., 2004; Du et al., 1994), gas distributor and bottom structure (Lin et al., 2004; Luan et al.,1994; Mudde and Van Den Akker, 2001), and configuration of the gas–liquid separation region (Freitas and Teixeira, 1997; Zhang et al., 2005).

However, the relevant literatures about ALR of gas–solid system are few. In recent years, only several researchers have

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developed a type of dense gas–solid ALR system of Geldart A particle on the basis of theories of gas–liquid ALR and conducted a series of experiments on gas–solid flow (Liu et al., 2002, 2004; Liu and Lu, 2001; Zhang et al., 2004). This gas–solid ALR has been successfully used as catalyst stripper in fluid catalytic cracking unit (FCCU) to remove oil gas from deactivated catalyst or non-condensible flue gas from regenerated catalyst (Lu et al., 2002). The gas–solid ALR system has some similar hydrodynamic characteristics of gas–liquid ALR, as well as those of a usual gas–solid fluidized bed. Therefore, the gas–solid ALR system has gradually become a research branch and evolved into a broadened application of conventional ALR. In addition, some researchers (Chu and Hwang, 2002; Shih et al., 2003; Song et al., 1997; Kim et al., 1997a, 1997b, 2000; Lee et al., 1998; Mukadi et al., 1999, 2000; Mine et al., 1999) developed a type of gas–solid internally circulating fluidized bed (ICFB) with a draft tube which was mainly used to the combustion and gasification of Geldart B or D particle, such as coal and industrial solid wastes, and as well as the recycling process of waste plastics by ultra-pyrolysis. Although ICFB shows some resemblances to the conventional ALR in structure and particles loop flow pattern, ICFB is also distinct in operation pattern from gas–solid ALR. The superficial gas velocity in draft tube of ICFB is relatively higher than in gas–solid ALR. The operation status in draft tube of ICFB exhibits a gas–solid dilute mixture, but a dense mixture in gas–solid ALR. Therefore, ICFB belongs to one type of spouted beds.

In this work, the study of gas–solid ALR system was mainly aimed for the application of the petroleum coke combustion system (Yan et al., 2009). Based on the combustion characteristics of petroleum coke, a coupled gas–solid fluidized bed combustor was proposed in this work. The overall circulation system of the fluidized bed combustor mainly consisted of a lower dense ALR section and an upper dilute riser section, as shown in Fig. 1. The ALR section is a key part of the coupled fluidized coke combustor. For its design and further structure, its hydrodynamics is required to be studied systematically to gain a better understanding.

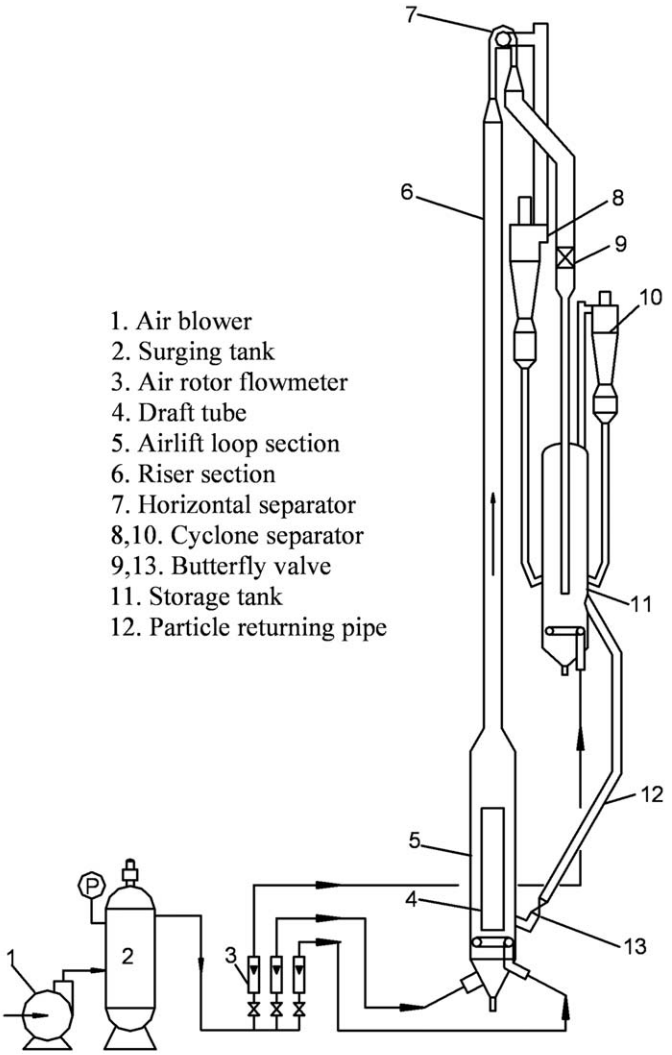

Fig. 1. Schematic of experimental apparatus.

The local solid fraction distribution is an important parameter describing the hydrodynamics of the gas–solid ALR. The study on local solid fraction in the gas–solid ALR can refer to fluidized beds. Many researchers (Rhode et al., 1998; Issangya et al., 2001; Zhang et al., 1991; Nieuwland et al., 1996; Miller and Gidaspow, 1992) have found out that the lateral distribution of time-averaged local solid fraction presents a core-annulus heterogeneous structure in fluidized beds. The gas–solid fluidization can be characterized by a nonlinear behavior or aggregation fluidization (Li et al., 1995). Gas–solid flow in fluidized beds is heterogeneous in both temporal and spatial domains. This embodies in strong local fluctuations of pressure and phase velocities and their non-uniform lateral distribution. Many studies have been carried out to characterize the temporal and spatial heterogeneity. Horio and Kuroki (1994) carried out the studies on the analysis of transient local solid density signal and cluster evolution by image. Yang et al. (1990), Bai et al. (1999), and Lin et al. (2001) measured the local solid fraction transient signal and obtained its time series in gas–solid fluidized beds. Many methods have been applied to analyze transient signals, such as statistical methods, chaos analysis (Bai et al., 1999; van den Bleek and Schouten, 1993; Kuhn et al., 1996), wavelet analysis and auto-correlation analysis. The transient density signal contains a large amount of information about the phase structures. Yang et al. (1990), Bai et al. (1999) found out that the local solid fraction transient signal exhibited a bimodal distribution for its probability density function (PDF). Lin et al. (2001) pointed out that there existed two kinds of stable phase structures in bubbling, turbulent, circulation, and pneumatic transport fluidized beds according to the probability density function (PDF) of the density signal. The dilute phase structure is termed as "void", characterized by a continuous gaseous phase with a log-normal solid fraction distribution. The dense structure is termed as "cluster", characterized by a continuous solid phase with a normal solid fraction distribution.

With the increase of computational power, the numerical simulation has become an additional tool to predict some microcosmic fluid dynamics and transport phenomena in multiphase flows which are difficult to be revealed by current experimental measurement techniques. Hence, the computational fluid dynamics (CFD) can offer a new approach to understand the complex phenomena of gas–solid flows. In recent years, many researchers (Cooper and Coronella, 2005; Pain et al., 2002; Witt et al., 1998; Zimmermann and Taghipour, 2005; Helland et al., 2002; Taghipour et al., 2005; Johansson et al., 2006; Peirano et al., 2001; van Wachem et al., 1999; Lu et al., 2007) have carried out the simulation studies on the hydrodynamics of gas–solid bubbling beds or turbulent beds by using standard Eulerian–Eulerian two-fluid model (TFM). Brandani and Zhang (2006) have proposed a new model for predicting the behavior of fluidized beds based on the standard Eulerian–Eulerian TFM approach. The TFM approach has been proofed and obtained great progress in modeling gas fluidization of Geldart B and D particles and dilute gas–solid flow.