Chemical Engineering Science 119 (2014) 261–273

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Local characterization of a gas–solid fluidized bed in the presence of thermally induced interparticle forces

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HIGHLIGHTS

- The effect of interparticle forces on local hydrodynamics of gas–solid fluidized bed is studied.
- The dynamic two-phase flow structure of the bed can be greatly influenced by interparticle forces.
- Enhancing interparticle forces will increase the tendency of the gas passing through the bed in the emulsion phase.
- Increasing interparticle forces will increase the meso-scale bubbling to turbulent regime transition velocity.

ARTICLE INFO

Article history:
Received 23 April 2014
Received in revised form
14 July 2014
Accepted 15 August 2014
Available online 23 August 2014

Keywords:
Gas–solid fluidized bed
Interparticle forces
Hydrodynamics
Local measurements

ABSTRACT

This article reports the results obtained from an extensive experimental campaign aimed at investigating the effect of interparticle forces (IPFs) on the local flow structure of a gas–solid fluidized bed. A polymer coating approach was used to enhance and control the degree of cohesive IPFs in a gas–solid fluidized bed. In this work, the local transient solids concentration (bed voidage) was carefully measured with the help of an accurate optical fiber probe at different temperatures and gas velocities covering both bubbling and turbulent fluidization regimes. Also, the Radioactive Particle Tracking (RPT) technique was employed to track the trajectory of a tracer mimicking the behavior of solid particles in two systems, one with the least amount of IPFs in the bubbling regime and the other with the highest amount. Experimental results showed that by increasing the level of IPFs in the bed the fixed bed and emulsion phase voidage in the bubbling regime increased and demonstrated higher capacities in holding gas inside their structures. In addition, the emulsion phase fraction increased, the tendency of the fluidizing gas passing through the bed in the emulsion phase enhanced in the bubbling regime, the frequency of the bubble/emulsion phase cycle decreased, and the meso-scale transition from bubbling to turbulent fluidization regime delayed until reaching higher superficial gas velocities.

1. Introduction

Gas–solid fluidized beds are used extensively in industries for mixing, drying, adsorption, agglomeration/granulation of particles, and catalytic and non-catalytic reactions because of their excellent mixing ability and high heat and mass transfer rates between particles and fluidizing medium in situations of relatively low pressure drops (Vazquez et al., 2007; Si and Guo, 2008; van Ommen and Mudde, 2012). It has been verified by observation and experiments that a two-phase flow structure with a dynamic distribution of phases with voidage from ε_{mf} (bed voidage at minimum fluidization) to 1 exists for bubbling and turbulent fluidized beds (Davidson et al., 1985; Cui et al., 2000, 2001b). In the bubbling regime, the dilute/bubble phase (the dispersed phase), which mainly contains gas, and the dense/emulsion phase (the continuous phase), which mainly contains particles, form the two phases. However, in the turbulent regime, elongated and irregular bubbles and violently moving solid clusters are recognized as the two extreme phases of the flow structure while there is no obvious distinction between these two phases (Lin et al., 2001; van Ommen and Mudde, 2012).

In general, bubbling and turbulent gas–solid fluidized beds, which operate at high solids concentration, are known as intrinsically complex systems due to the sophisticated dynamic behavior of both gas and solids flow structure formation and evolution (Li et al., 1998, 2000; Zhu et al., 2008). This is caused by the non-linear interaction between gas and solids, which can strongly influence the gas–solid distribution between bubble and emulsion phases while its variation can have considerable effect on the various

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http://dx.doi.org/10.1016/j.ces.2014.08.037
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processes taking place in the bed (van Ommen and Mudde, 2012). For instance, on the one hand, the presence of bubbles results in particles mixing in the bed and, hence, enhancing the heat and mass transfer rates (van der Schaaf et al., 2002). On the other hand, since the gaseous reactants in the bubble phase are hardly in contact with the catalyst particles (van der Schaaf et al., 2002), and the emulsion phase is a lot more efficient in bringing about the chemical reaction between gas and solids (Rowe et al., 1978), the presence of bubbles can yield a decrease in the conversion of gaseous reactants in the gas–solid fluidized bed reactor. In this regard, any operating variable that can alter the dynamic gas–solid distribution in the bed can subsequently have an influential impact on the apparent reaction and heat/mass transfer rates in the fluidized bed and, furthermore, on the overall reaction rate in fluidized bed reactors.

Interparticle forces (IPFs) are among the most important parameters that can affect the fluidization characteristics of the particulate materials. In regard to the importance of IPFs, there is no question that the fluidization behavior of very fine Geldart group C powders (Geldart, 1973) is dominated by IPFs (Shabanian et al., 2012). Many empirical observations reported in the literature have clearly shown that different types of fluidization behavior may be exhibited by the same powder depending on the operating conditions (gas viscosity, gravity, gas adsorption, temperature, pressure, presence of eutectics) (Rietema and Piepers, 1990; Rietema, 1991; Poletto et al., 1993; Rapagna et al., 1994; Tardos and Pfeffer, 1995; Xie and Geldart, 1995; Formisani et al., 1998, 2002; Lettieri et al., 2000; Li and Kuipers, 2002; Lin et al., 2002; Cui and Chaouki, 2004; Zhong et al., 2012). This is, in fact, in close relation with the variation in the balance between IPFs and hydrodynamic forces (HDFs) in the particulate system. Variation in the level of IPFs due to any operational reason is inevitable, especially in the near future due to the necessity of extreme conditions operation of low quality feedstocks while the local flow structure of the gas–solid fluidized beds in the presence of this influential operating parameter is poorly understood. Thus, it is essential to understand the flow structure of the bed in the presence of IPFs in order to efficiently ameliorate the design and operation of industrial gas–solid fluidized beds.

Different approaches have been applied by researchers to study the effect of IPFs on the hydrodynamic behavior of gas–solid fluidized beds. Nonetheless, simple and precise control of the level of IPFs, which are uniformly distributed throughout the bed, with the least amount of implementational and operational limitations for the approach by which cohesive IPFs are introduced into the bed of powders are the most important criteria for the selection of an appropriate method for this purpose. Among the different approaches and in light of its valuable advantages, it has been demonstrated in earlier works by the present authors (Shabanian et al., 2011; Shabanian and Chaouki, 2013, 2014) that the polymer coating approach (Shabanian et al., 2011; Bouffard et al., 2012) is a superior method for investigating the influence of IPFs on the fluidization behavior of a gas–solid fluidized bed. With this method, the cohesive IPFs are introduced into the bulk of particulate materials by modifying the particle surface properties and adjusting the system temperature. More details about this approach can be found elsewhere (Bouffard et al., 2012).

To the author's knowledge there are only a limited number of studies (Willett, 1999; Seville et al., 2000) about the influence of IPFs on the local hydrodynamics of gas–solid fluidized beds at relatively low superficial gas velocities, close to the minimum fluidization velocity U_{mf} of a system without IPFs. Also, there is no clear information about the effect of IPFs on the detailed hydrodynamics of gas–solid fluidized beds at moderate and high superficial gas velocities (bubbling and turbulent fluidization regimes). In parallel, it is widely accepted that for a better understanding of the flow dynamics of multiphase systems it is of prime importance to know the inner details of such systems. In this respect, the objective of the present study is to provide clear insight into the influence of IPFs on the local dynamic flow structure of the bed. The solids concentration optical fiber probe and Radioactive Particle Tracking (RPT) technique were employed in this work while beds with different levels of IPFs were achieved with the assistance of the polymer coating approach.

2. Methodology

The experimental work initially required the production of base particles coated with a thin and uniform layer of polymer on the surface. This was achieved through an atomization process in a spheronizer machine. In the following step, the coated particles were used in a gas–solid fluidized bed and subjected to different operating temperatures by which the properties of the PMMA/PEA (poly methyl MethAcrylate/poly ethyl acrylate) coating and the observed IPFs were changed.

2.1. Particle coating process

The first experimental step was to prepare base particles uniformly coated with a thin polymer film. The polymer material that was coated on the surface of the base particles was copolymer PMMA/PEA, which was contained in a polymer suspension called Eudragit NE30D. A 450–700 μm cut of spherical sugar beads ($d_p = 580$ μm, $\rho_p = 1556$ kg/m^3), which is classified as Geldart group B particles at ambient conditions, was selected as the inert base particles. These particles can easily accept the PMMA/PEA polymer coating on their surfaces.

The polymer suspension, which consists of a solution of copolymer PMMA/PEA in a 2–1 mass ratio in water (%mass: water 70.0; PMMA/PEA 28.66; Noxynol100 1.33), was coated on the surface of the sugar beads through an atomization process to produce the coated particles. This process was achieved in a spheronizer machine, where the coated particles were simultaneously dried by the heated air to attain a uniform coating film on the surface of the base particles. Details of the coating procedure and its operating conditions can be found elsewhere (Shabanian et al., 2011; Shabanian and Chaouki, 2013, 2014).

It is worth mentioning that the thickness of the coating layer at the end of the coating process was approximately 5.0 μm. With such a thin coating layer variations in particle size and density for sugar beads were about only 1% for both parameters. This implies a close similarity of the fresh and coated sugar beads from Geldart classification's point of view.

2.2. Hydrodynamic study

All experiments for the hydrodynamic study were carried out under atmospheric pressure in a cold gas–solid fluidized bed. The column was made of a transparent Plexiglas pipe with a 15.2 cm internal diameter and was 3.0 m in height. A cyclone, placed at the air outlet of the column, returned back the entrained particles to the freeboard of the bed. Dried and filtered air, as fluidizing gas, was introduced into the bed through a perforated distributor plate. The distributor plate was 1 cm thick and made of aluminum. It consisted of 157 holes 1 mm in diameter arranged in a 1 cm triangular pitch. To minimize the electrostatic effect, the whole bed was electrically grounded.

In order to investigate the influence of IPFs on the hydrodynamic characteristics of a gas–solid fluidized bed fresh/uncoated and coated sugar beads were separately used in the fluidizing column at different operating temperatures. Experiments of fresh