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Prediction of solids residence time distribution in cross-flow bubbling fluidized bed

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ABSTRACT

Cross-flow bubbling fluidized beds (BFBs) have been widely used in dual fluidized bed systems such as chemical and heat looping. Understanding the residence characteristics of solids in such system is important for better design and optimization of reactors. Previously we experimentally measured the residence time distributions (RTDs) of sands in a cross-flow rectangular BFB by using coal particles as tracer. A computational investigation of solids RTD using multi-fluid Eulerian method combined with the species transport equation showed that the RTD of sands could be correctly represented by that of coal particles, and the simulation results well agreed with experimental data. Parametric studies demonstrated that, under the considered operation conditions, the influence of tracer injection time period on the predicted solid residence times was nearly ignorable. Simulation results revealed that in the investigated cross-flow BFB the solids RTD is closely related to solids inventory and solids flux. Through proper data processing, it was found that the descending part of solids RTD profile can be uniquely fitted by an empirical exponential function. A semi-empirical approach was thus developed and further validated, for the first time in the literature, to predict the entire profile of solids RTD, in which the ascending part of solids RTD profile is obtained through CFD simulation whereas the descending part is given by the fitted empirical exponential function.

1. Introduction

Gas–solid fluidized bed has been widely adopted to handle various chemical processes due to its excellent mass and heat transfer characteristics, high gas and solids throughputs, and continuous powder handling capability. The conversation and selectivity of chemical reactions occurring in gas–solid fluidized beds are highly dependent on the solids mixing behavior in the reactors [1]. Solids residence time distribution (RTD), reflecting solids mixing behavior and flow hydrodynamics, is one of the key parameters for evaluating the reaction performance in fluidized beds. Therefore, for proper design, optimization, and scale-up of fluidized bed reactors, it is crucial to gain understanding and further accurate prediction of solids RTD in a gas–solid fluidized bed system.

Experimentally, stimulus impulse technique has been widely applied to investigate the solids RTD in fluidized beds. In this technique, a small amount of tracer particles, whose properties should be as close as those of bulk bed material, are injected into the system within a short time period after the system achieves a steady state. The concentration of tracer particles is then measured at some downstream position to obtain a RTD curve. Limited by detection or separation techniques, the demanded tracer properties and short tracer injection time are generally difficult to be guaranteed in experiments [2,3]. In the literature, various kinds of tracer particles have been chosen by different researchers, such as radioactive particles [2], colored particles [4], magnetic particles [5] and particles with different sizes [6]. In the past decades, many researchers have concentrated on how to improve the accuracy of experimental measurement on the choice of tracer particles and detection or separation methods of tracer particles [7,8]. For the solids, RTD in fluidized beds itself, researchers usually focused only on the influences of operation conditions such as superficial gas velocity or solids flux [8–10]. Harris et al. [8] used a fast tracer response technique to investigate the influences of superficial gas velocity and solids flux on solids RTD in a circulating fluidized bed (CFB) combustor. Chan et al. [10] investigated the solids RTD in dilute and core-annular fluidization regimes and proposed empirical correlations for them to predict the variance of RTD spread with superficial gas velocity. Van de Velden et al. [1] analyzed solids RTD and back-mixing behavior within extensive ranges of superficial gas velocity and solids flux, and examined the transition line between mixed and plug flow in a CFB riser.

With fast development of high-performance computer technology, Computational Fluid Dynamics (CFD) has been increasingly employed

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as an efficient and powerful method to investigate solids RTD in fluidized beds. Compared with physical experiments, CFD simulations have the advantages that the injection conditions and properties of tracer particles can be precisely controlled. Wu et al. [11] simulated the solids RTD in fluid catalytic cracking (FCC) processes accommodated in a riser or downer reactor using the Eulerian–Lagrangian method. Their simulation results showed that the formation of particle cluster had notable influence on the spatial distribution of particle residence time. Shi et al. [12] investigated solids RTD in the riser of a CFB using a Computational Particle Fluid Dynamics (CPFD) approach and found that solids back-mixing mainly took place in the lower part of the riser. Based on the Eulerian–Eulerian models including with the species transport equation, Hua et al. [13] discussed the influences of inter-phase drag model, solids diffusion coefficient and tracer injection time on the predicted solids RTD. Liu et al. [14] investigated the influences of internals on the predicted solids RTD in FCC strippers. Li et al. [15] discussed the influences of jetting conditions on back-mixing behavior of solids in jet circulating fluidized beds.

Although in the literature there are many reports about experimental and numerical studies on solids RTD in fluidized beds, most of the previous work focused on CFB riser systems. Dual fluidized bed (DFB) technology has been widely applied for efficient thermochemical conversation of fuels and chemical looping processes, which usually consists of a cross-flow bubbling fluidized bed (BFB) and a riser [16,17]. Different from conventional BFB, in the BFB of a DFB system the main flow direction of solids is perpendicular rather than parallel to that of gas. The gas enters the BFB from the bottom and flows out from the top of the bed, while raw fuel (and also the circulated heat carrier) is continuously fed into the BFB on one side and discharged from the opposite side directing to the riser. The residence time distribution of fuel particles determines the reaction efficiency in the BFB, then the stability and performance of a DFB system. To gain a basic understanding of solids RTD in cross-flow BFB systems, we previously conducted experiments to investigate solids RTD in a few of cross-flow BFBs under different operation conditions [18,19]. In our experiments, coal particles, whose density was different from that of bulk bed materials (sands), were chosen as tracer particles. Through CFD simulation, the basic objective of this research is to identify if the residence time of sands in the investigated system can be correctly represented by the measured residence time of coal particles. The residence time of solids in the investigated cross-flow BFB is rather long, making the CFD simulation extremely time-consuming. The second objective of this work is thus to develop an empirical method to correctly predict the long tail of solids RTD in the investigated cross-flow BFBs. The latter represents the first quantification attempt in the literature, whereas this prediction is highly needed for actual reactor design and optimization of heat and chemical looping processes.

This paper is organized as follows. The simulated system and adopted analysis method are described in Section 2. This is followed in Section 3 by a brief introduction of the simulation details. Experimental validation and parametric investigation are presented in Section 4. Based on the simulation results, in Section 5 a semi-empirical approach is developed to predict solids RTDs. A brief summary of conclusions is given in Section 6.

2. Simulation system

The simulation system was experimentally investigated by Gao et al. [18,19]. In the experiments, solids RTDs were studied in a rectangular Plexiglas bubbling fluidized bed under ambient temperature and atmospheric pressure. Fig. 1 gives a schematic diagram of the experimental apparatus. The bed was 450 mm in width, 200 mm in height and 40 mm in thickness. The bulk bed materials were silica sand with a mean diameter of 0.2 mm and density of 2600 kg/m^3. Coal particles with a mean diameter of 0.9 mm and density of 1405 kg/m^3 were chosen as tracer particles. In the experiments, silica sands were continuously fed into the bed through a charging bucket over the solids inlet and flowed out of the bed from the solids outlet at the opposite side. In front of the solids outlet a vertical plat baffle with distances to both bottom and right walls of 23 mm was installed to increase solids residence time and to avoid the possible short-cutting flow of solids. The solids inventory in the bed was controlled by adjusting the position of solids outlet. The bed material was fluidized by air introduced from the bottom of the fluidized bed.

After stable fluidization was achieved, tracer particles with an amount of 2% of bulk bed material weight were introduced into the system in a short time period. At the same time, the discharged bed material at the outlet was continuously collected with a time interval of 30 s to separate tracer particles from the collected samples via sieving. The mass fraction of tracer was $C(t)=\frac{m_{\mathrm{tr}}(t)}{m_{\mathrm{tr}}(t)+m_{\mathrm{sand}}(t)}$, and the RTD of the tracer was then determined by the time profile of its mass fraction, as.

$$E(t)=\frac{G_s}{M_{tr}}C(t), \tag{1}$$

where G_s is the mass flux of sand particles (kg/s), M_{tr} is the total mass of tracer particles (kg). The unit of $E(t)$ is then s^{-1}. Based on $E(t)$, the mean

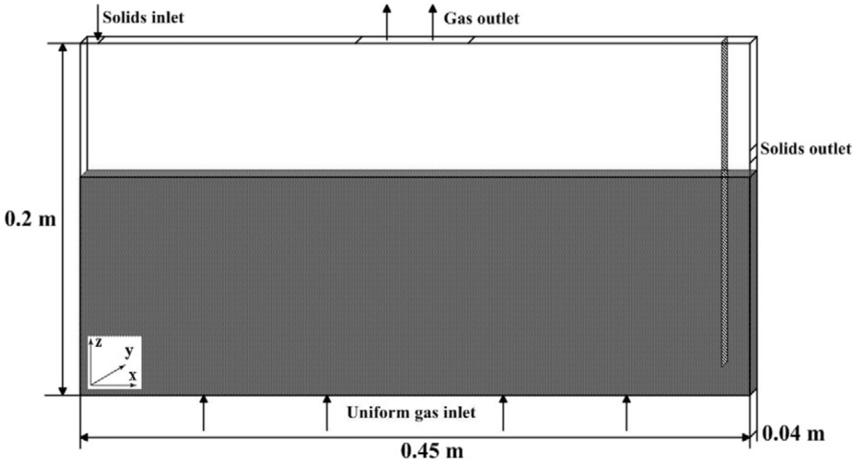

Fig. 1. Schematic diagram of simulation system.