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Novel multistage solid–liquid circulating fluidized bed: Hydrodynamic characteristics

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ABSTRACT

The present work proposes a novel radially cross-flow multistage solid–liquid circulating fluidized bed (SLCFB). The SLCFB primarily consists of a single multistage column (having an inner diameter of 100 mm and length of 1.40 m), which is divided into two sections wherein both the steps of utilization or loading (e.g., adsorption and catalytic reaction) and regeneration of the solid phase can be carried out simultaneously in continuous mode. The hydrodynamic characteristics were studied using ion exchange resin as the solid phase and water as the fluidizing medium. The loading and flooding states were determined for three particle sizes; i.e., 0.30, 0.42, and 0.61 mm. The effects of the superficial liquid velocity and solid feed rate on the solid hold-up were investigated under loading and flooding conditions. The solid hold-up increases with an increase in the solid feed rate and decreases with an increase in the superficial liquid velocity. An artificial-intelligence formalism, namely the multilayer perceptron neural network (MLPNN), was employed for the prediction of the solid hold-up. The input space of MLPNN-based model consists of four parameters, representing operating and system parameters of the proposed SLCFB. The developed MLPNN-based model has excellent prediction accuracy and generalization capability.

Introduction

The solid–liquid circulating fluidized bed (SLCFB) is a new candidate in the realm of fluidization. SLCFBs offer distinctly attractive features over batch fixed and expanded beds: (i) an ability to accommodate both the steps of utilization or loading (e.g., catalytic reaction and adsorption) and regeneration in a continuous mode for higher throughputs (where most importantly, the amount of solid phase can be theoretically equivalent to a break-through quantity), (ii) lower pressure drop, (iii) efficient mass transfer and heat transfer, and (iv) reduced back-mixing. These unique characteristics substantially lower the overall operation time and capital investment, making the SLCFB an attractive candidate in diverse industrial processes, such as the production of linear alkyl benzene (Liang et al., 1995; Liang & Zhu, 1997; Xu, Han, Chen, Wang, & Jin, 2004), continuous recovery of fermentation products (Lan et al., 2000; Lan, Bassi, Zhu, & Margitis, 2002a, 2002b; Mazumder, Zhu, & Ray, 2010; Prince, Bassi, Haas, Zhu, & Dawe, 2012), removal and recovery of cesium from liquid radioactive nuclear waste streams (Feng, Jing, Wu, Chen, & Song, 2003), wastewater treatment (Chowdhury, Nakhla, & Zhu, 2008; Cui, Nakla, Zhu, & Patel, 2004; Islam, George, Zhu, & Chowdhury, 2009; Li, Nakla, & Zhu, 2012; Nirmala & Muruganandam, 2013), and continuous enzymatic polymerization of phenol in bio-refining (Trivedi, Bassi, & Zhu, 2006).

SLCFBs studied so far primarily consist of a riser column that is operated in a circulating fluidization regime and a main column that is operated in a conventional fluidization regime. The loading operation is usually carried out in a main column and the regeneration operation in a riser column. An integration of circulating and conventional fluidization regimes in existing SLCFBs eventually gives rise to certain limitations, such as (i) the proper pressure balance requirement for stable operation with no mixing of the liquid phases between the riser and main sections, (ii) the expectation of greater liquid-phase mixing and solid-phase mixing in the riser section because the SLCFB operates at superficial liquid velocities higher than the terminal settling velocities of solid particles, and (iii) possible failure when the loading/regeneration of the solid phase is time intensive, demanding an enormously tall riser

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section. It has also been well reported in the literature that the flow structure of the riser column is nonuniform with respect to the bed voidage and liquid velocity in the radial direction (Chavan, Kalaga, & Joshi, 2009; Kalaga, Reddy, Joshi, Dalvi, & Nandkumar, 2012; Liang et al., 1996; Roy & Dudukovic, 2001; Sang & Zhu, 2012; Zheng, Zhu, Marwaha, & Bassi, 2002). The nonuniform flow structure adversely affects the driving force for transport processes and subsequently reduces the overall performance of the SLCFB. Furthermore, owing to the radial nonuniformity, the empirical relationships developed for the conventional fluidization regime to determine the velocity–voidage relationship and drag coefficient cannot be applied to describe the circulating fluidization regime (Liang et al., 1997; Natarajan, Velraj, & Seeniraj, 2008; Natarajan, Ramalingam, Ramadoss, & Seeniraj, 2011). The practical design and scale-up of the SLCFBs thus remains a big challenge owing to the complex flow structure prevailing in the riser column.

The present work proposes a novel multistage SLCFB that essentially consists of a single multistage column wherein the two steps of utilization, namely loading (e.g., catalytic reaction and adsorption) and regeneration, can be carried out simultaneously in the conventional fluidization regime. The operation of both loading and regeneration sections in the conventional fluidization regime inherently offers several advantages over the existing SLCFBs, such as efficient mass transfer and heat transfer, reduced back-mixing, and adjustment of the desired residence time for time-intensive loading/regeneration operations. Moreover, the correlations developed to predict design parameters, such as the dispersion coefficient, mass transfer coefficient, and heat transfer coefficient, for the conventional solid–liquid fluidized bed can be used in the practical design and scale-up of the proposed model with a sufficient degree of confidence (Kalaga et al., 2012; Kalaga, Dhar, Dalvi & Joshi, 2014). For the rational design of the proposed SLCFB, however, we ought to investigate (i) hydrodynamic characteristics so that the desired residence time can be adjusted depending upon the dynamics of adsorption (or catalytic reaction) and regeneration of the solid phase under consideration and (ii) mixing aspects such that the flow behavior of solid and liquid phases is as close to the plug flow as possible (where we need information regarding the extent of axial dispersion in solid and liquid phases with respect to the particle size, liquid velocity, number of stages, and other geometrical details of each stage), and (iii) mass transfer characteristics to estimate the solid–liquid mass transfer coefficient. The prime objectives of the present work were (i) to establish a stable operating window using a new stage configuration for smooth and uniform fluidization for a given solid phase and (ii) to set a criterion for the practical design and scale-up of the proposed SLCFB. Moreover, the effects of the superficial liquid velocity and solid circulation rate on the solid hold-up were studied within the operating window. Multilayer perceptron neural network (MLPNN)-based modeling was also explored to predict solid hold-up in the multistage column using experimental data from the present and previous studies.

Experimental section

Characterization of resin particles

A strong-base anion exchange resin (Tulsion 36, Thermax India Ltd.) was used as a solid phase. The characteristics of the resin are reported in Table 1. Resin particles were segregated into various sizes by sieving and particle sizes of 0.30, 0.42, and 0.61 mm were selected to investigate hydrodynamic characteristics.

Table 1
Resin properties given by the manufacturer.

Property	Strong base anion exchange resin (Tulsion 36)
Particle size (mm)	0.3–1.2
Particle density (kg/m^3)	1100
Matrix structure	Styrene-DVB
Functional group	N^+R_3
Ionic form	Cl^-
Moisture content (% kg water/kg wet resin)	47–53
Exchange capacity (meq/mL)	1.2

Swelling of the resin

Experiments were carried out using a conical glass flask to determine equilibrium swelling for particle sizes of 0.30, 0.42, and 0.61 mm. The solid particles of a given size were dried overnight at 60 °C in an oven before being used in the swelling experiments. A known amount of resin (1 g) was added to 25 mL water and kept overnight (12 h) in a shaker incubator to attain equilibrium swelling with continuous shaking. The changes in volume of resin (due to the sorption of water) were estimated by measuring the initial volume of dry resin and final volume of swollen resin (after the sorption experiment) using standard calibrated glass tubes and also by microscopic observations. All experiments were performed at least in triplicate and results presented are averages for the replicate experiments.

Expansion characteristics

The expansion characteristics of resin were investigated separately in an acrylic column with inner diameter of 100 mm and length of 1.2 m. The bed voidage for a given superficial liquid velocity was measured using the solid-phase mass balance method and pressure drop method (Chavan & Joshi, 2008). The well-known equation of Richardson and Zaki (1954) was fitted to experimental expansion data to determine the Richardson–Zaki parameter and terminal settling velocity of the particle. The terminal settling velocity of the particle was also determined employing the solid-particle drop method. A glass tube having an inner diameter of 50 mm and length of 1 m was used for experimentation. A solid particle of a given diameter was dropped from the top and the time taken for the solid particle to travel a predetermined distance (0.6 m) was noted. Experiments were conducted five times for a given solid particle size and average values were noted.

Proposed SLCFB

Experimental set-up

Fig. 1 is a schematic diagram of the proposed SLCFB. The SLCFB assembly mainly consists of a single column that was further divided into two sections (each having an inner diameter of 100 mm and length of 700 mm): (i) the loading section and (ii) regenerating section wherein solid and liquid phases come into contact countercurrently. Each section consists of five stages (each having an inner diameter of 100 mm and length of 100 mm) assembled together with flange joints. A stainless steel (SS) mesh with openings smaller than the solid particle size was fitted onto SS sieve plates that were sandwiched between each pair of adjoining flanges. Holes of 2 mm were provided on each SS sieve plate, providing a 5% open area for water flow. Solid particles moved across a stage to the next stage through a downspout, as the liquid flowed upward through mesh openings. Two types of SS stages were arranged alternatively in the multistage column using a pair of adjoining flanges. For one set of successive stages, the first stage consisted of a downspout that was fitted at the center of the stage while the second stage comprised two downspouts located around the periphery as circumferential downspouts. SS pipes having an inner diameter of 10 mm and lengths of 75 and 65 mm were used as the downspouts to encompass weir heights of 25 and 15 mm, respectively. A schematic of the SS stage configuration is given in Fig. 2(A). An