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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.

Keywords: Solid–liquid fluidized bed, Solid–liquid circulating fluidized bed, Hydrodynamics Modeling

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 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.

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.

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 ⁻¹)	47-53
Exchange capacity, (meq.mL ⁻¹)	1.2

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. Experimental set-up: (1) loading section; (2) regenerating section; (3) solid return pipe; (4) riser column; (5) solid feed tank; (6) SS stage with SS mesh; (7) down-comer; (8) overflow; V. valve; D. diffuser/solid distributor (all dimensions are in millimeters).

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 counter-currently. 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 down-spouts to encompass weir heights of 25 and 15 mm, respectively. A schematic of the SS stage configuration is given in Fig. 2(A). An arrangement was also made to measure the pressure drop across a stage using a U-tube manometer with measurement precision of $\pm 5\%$. Chlorobenzene with iodine (having specific gravity of 1.10) was used as the manometric fluid.

The loading and regeneration sections were connected to each other by an SS pipe having an inner diameter of 10 mm and length of 200 mm. The flow of solid particles from the loading section to regeneration section was controlled by a butterfly valve V2 appended to the interconnecting SS pipe. There were two distributors at the bottom of each section: (i) a specially designed conical distributor, providing an open area of 17.30% for the primary liquid flow, and (ii) a secondary liquid distributor made of an SS stage with an open area of 10.40% for the auxiliary liquid flow. Fig. 2(B) presents the geometrical details of the specially designed conical distributor for the primary liquid inlet. The total liquid flow to the section is a summation of primary and auxiliary flow rates. The auxiliary liquid flow rate mobilizes the solid particles underneath the primary distributor to ease solid particle flow from one section to another.

The solid particles moved via a solid return pipe (having an inner diameter of 25 mm and length of 500 mm) to the riser column wherein solid particles were carried to the solid-liquid separator. The separator (having an inner diameter of 300 mm and length of 500 mm) was used to charge solid particles from the top to the loading section through a solid transport line wherein solid transport was controlled by valve V1. Solid particles were kept in an expanded state by liquid phase charged from the bottom of the separator via a calming section of 150 mm. The separator was provided with a top outlet for the discharge of liquid via a mesh to avoid the loss of fine solid particles. The solid particles moved from the separator to multistage column in an orderly manner via a solid return pipe. The solid return pipe had a special valve for measurement of the mass flow rate of solid particles. Fig. 2(C) shows the dimensional details of the specially designed valve. With the valve open, the solid-liquid mixture was collected for a known length of time. During the measurement, no solid-liquid flow was permitted to the multistage column.

Methodology of operation

The solid transport lines, connecting loading and regenerating sections, and regenerating and riser sections, were closed initially using valves V₂ and V₃, respectively. The primary and auxiliary liquid streams started to flow in loading and regenerating sections and fresh solid particles were subsequently charged using valve V₁ at the top of the loading section via a diffuser D₁ that distributed solid particles uniformly. Initially, in the loading section, as the flow rate of the liquid stream gradually increased, the solid bed on one stage expanded up to the weir height and subsequently flowed to the next lower stage. This happened because solid particles continued to pour from the adjacent upper stage through the downspout, creating a difference between bed depths from the center to the periphery of the stage, depending on the type of downspout (center or circumferential) in that stage. The state of fluidization in each stage was thus cross-current, although the overall flow of solid and liquid phases was in the counter-current direction.

A similar flow pattern was obtained in the regeneration section when valve V_2 was gradually opened and solid particles were allowed to enter the section for a given liquid flow rate in the section. When solid particles reached the bottom of the regenerating section, valve V_3 was gradually opened to circulate solid particles to the solid–liquid separator.

For a given set of operating conditions, the system was allowed to reach a steady state over a period of 2 h and all the experiments were performed after achieving the steady state. The experiment was repeated for different liquid flow rates and solid circulation rates and a given solid particle size. All experiments were carried out three times and average values were noted.

In the proposed system, the loading and regenerating sections were interconnected by a solid transport line through which solid particles flowed from one section to another. Because two distinct operations are expected to be carried out in loading and regenerating sections using two liquid steams having fairly different properties, the dynamic seal between these two sections is of critical importance for successful operation. The dynamic seal was realized by maintaining a particle plug in the solid transport lines, allowing solid particles to flow in fixed-bed mode.

Fig. 2. Geometrical details of auxiliary devices: (A) SS stage; (B) primary distributor; (C) specially designed valve for measurement of the solid circulation rate with (a) denoting open position, (b) representing closed position (all dimensions are in millimeters).

Measurement techniques
Bed voidage

Two methods (i.e., visual observation and the pressure gradient method) were used to calculate the average voidage of the bed at a given superficial liquid velocity. In the first method, the average voidage was calculated by taking the solid-phase balance at the initial and final fluidized states for a given superficial liquid velocity:

$$\frac{\pi}{4} D^2 H_0 (1 - \varepsilon_{L0}) = \frac{\pi}{4} D^2 H (1 - \varepsilon_L) \quad (1)$$

where the subscript “0” denotes the initial fixed-bed conditions, H is the bed height, D is the diameter of the column, and ε_L is voidage. In the second method, the pressure gradient between the two pressure taps was measured by assuming that wall friction and acceleration effects are negligible. The pressure gradient is given as

$$-\left(\frac{dP}{dz}\right) = (1 - \varepsilon_L)(\rho_s - \rho_L)g \quad (2)$$

where dP/dz is the pressure gradient, g is gravitational acceleration, ρ_L is the density of the liquid phase, and ρ_s is the density of the solid particle.

Solid circulation rate

The solid circulation rate was measured using the specially designed valve. The solid–liquid mixture was collected for a predetermined time. During collection of the solid–liquid mixture, solid flow to the multistage column was completely precluded. For a given set of experimental conditions, the solid circulation rate was measured three times and the average value noted.

Results and discussion

Swelling of the resin

The polymeric structure of resin swells considerably when brought in contact with water. Hence, the physical properties of resin, such as the particle size and density, change. This ultimately affects the terminal settling velocity of the solid particle (Chavan & Joshi, 2008; Murli, Chavan, & Joshi, 2007). The swelling ratio S_R is defined as

$$S_R = \frac{V_{SR}}{V_{DR}} \quad (3)$$

where V_{SR} and V_{DR} are volumes of the swollen resin and dry resin, respectively. The solvation of fixed ionic groups and counter ions of resin mainly contributes to the swelling of resin because of the ability of the fixed ionic groups and counterions to form ion-dipole bonds. The negative pole of water is attracted towards the quaternary ammonium group (N^+) of the resin whereas the positive pole is attracted towards the counter ion (Cl^-). A cluster of water molecules therefore forms around each fixed charge and respective counter ion. This, in turn, swells the resin.

In the present work, the swelling ratio was found to be 1.25. The diameter of the solid particle therefore increases to 1.10 times the diameter of the particle on a dry basis. The change in diameter of the solid particle affects the terminal settling velocity of the solid particle, which in turn affects the expansion characteristics of the bed. The next section clarifies the effect of swelling on the hydrodynamic characteristics of the solid–liquid fluidized bed.

Expansion characteristics

Resin particles of different sizes (0.30, 0.42, and 0.61 mm) were fluidized separately at different superficial liquid velocities in the range of 1–15 mm/s to determine their expansion behavior. The solid mass balance and pressure gradient methods were used to calculate the average voidage of a bed at a given superficial liquid velocity. Fig. 3 compares the results obtained with

the two methods. There is good agreement between these two methods with average standard deviation of 1.15%. The Richardson–Zaki equation was fitted to experimental data and the terminal settling velocity of solid particles was determined. The solid lines in Fig. 3 show the fitting of the Richardson–Zaki equation to experimental data. The Richardson–Zaki parameters for a given particle size are reported in Table 2. The terminal settling velocity of solid particles changes upon swelling. For example, the terminal settling velocity of the 0.61-mm particle is 14.42 mm/s when calculated on a dry basis. However, no entrainment was observed when experiments were carried out at a superficial liquid velocity of 15 mm/s. This is owing to the swelling of the resin. The swelling of the resin increased the diameter of the particle to 1.10 times the diameter of the particle on a dry basis. The terminal settling velocities of solid particles measured were 7.28, 10.10, and 16.18 mm/s for solid particle sizes of 0.30, 0.42, and 0.61, respectively. The corresponding values obtained using the solid-particle drop method were 6.89, 10.05, and 16.16 mm/s, respectively. The theoretical values of terminal settling velocities were 6.03, 9.75, and 16.15 mm/s for solid particle sizes of 0.30, 0.42, and 0.61, respectively. The theoretical values of terminal settling velocities were calculated using the empirical correlation proposed by Khan and Richardson (1987), which is applicable over a wide range of particle Reynolds numbers ($0.01-3 \times 10^5$). The effect of the column wall was neglected in the afore mentioned calculation owing to the high ratio of the column diameter to particle diameter ($D/d_p > 100$) (Joshi, 1983).

Table 2 Expansion parameters of the solid phase

Particle diameter, d_p (mm)		Terminal settling velocity, $V_{S\infty}$ (mm.s ⁻¹)		Richardson- Zaki parameter, n (-)	Reynolds number, Re (-)	Galileo number, Ga (-)
Dry basis	Wet basis	Theoretical	Experimental			
0.30	0.33	6.03	7.28	3.98	2.99	55.65
0.42	0.46	9.75	10.10	3.87	5.77	149.71
0.61	0.66	16.15	16.18	3.62	13.44	458.66

Fig. 3. Solid-phase expansion characteristics. Hollow symbols: solid-phase mass balance method; filled symbols: pressure drop method. (Δ) 0.30 mm; ($\diamond$) 0.42 mm; ($\square$) 0.61 mm. Solid lines show the fitting of the Richardson–Zaki equation to the experimental data.

Pressure drop in the multistage column under the fixed-bed regime
The pressure drop was measured in the multistage column across the stages in the fixed-bed regime. The solid particle bed was maintained approximately equal to the weir

heights of 15 and 25 mm on the stages, with there being 0.075 and 0.125 kg of resin per stage, respectively. These experiments were performed, in particular, to estimate the pressure drop due to the cross-current and counter-current flow of solid particles and liquid across the stage. The pressure drop in the fluidized bed becomes equal to the apparent weight of solid particles per unit area when the minimum fluidization state is reached and remains constant thereafter. Therefore, the pressure drop due to the cross-current and counter-current flow of the solid particles and liquid can be measured if the pressure drop due to the solid particle bed is subtracted from the total pressure drop arising when the column is operated under stable counter-current solid particle and liquid flows. Fig. 4 shows the effects of the solid particle size and weir height on the pressure drop across the stage. The pressure drop increases as the superficial liquid velocity gradually increases. However, the solid particles do not move and the bed height remains constant. At a certain superficial liquid velocity, the pressure drop across the bed counter balances the weight of the bed and any further increase in the superficial liquid velocity causes the particle to move. The superficial liquid velocity at which the pressure drop counter balances the weight of solid particles is called the minimum fluidization velocity. The minimum fluidization velocity of solid particles is determined by equating the pressure drop with the effective weight of the particles:

$$\Delta P_{mf} = L_{mf}(1 - \varepsilon_{mf})(\rho_s - \rho_L)g \quad (4)$$

Applying the Ergun equation (Ergun, 1952) to the point of incipient fluidization, a quadratic equation for the minimum fluidization velocity of spherical solid particles can be obtained:

$$\frac{150\mu_L V_{mf}(1 - \varepsilon_{mf})}{d_p^2 \varepsilon_{mf}^3} + \frac{1.75\rho_L V_{mf}^2}{d_p \varepsilon_{mf}^3} = (\rho_s - \rho_L)g \quad (5)$$

where the subscript ‘mf’ denotes the minimum fluidization condition. L is the weir height, d_p is the solid-particle diameter, V is the superficial liquid velocity, and μ_L is the viscosity of the liquid. The average bed voidage at the point of minimum fluidization was estimated by plotting the heights of the expanded bed under the fluidized bed conditions against the superficial liquid velocity. The trend line was extrapolated to the experimental value of the minimum fluidization velocity to estimate the bed voidage using the bed expansion ratio.

The experimental data were fitted to the Ergun equation. The solid lines in Fig. 4 show the fitting of the Ergun equation to the experimental data. The predicted values well match the experimental data. It is clear that the pressure drop increases with a decrease in the solid particle size for a given superficial liquid velocity. Under the fluidized bed conditions, the pressure drops for three particle sizes are the same and, as expected, equal the apparent weights of the resin particles. The minimum fluidization velocity, however, increases with an increase in particle size, which agrees with the theory.

Fig. 4. (A) Pressure drop in the fixed bed and fluidized bed with particle size being (weir height = 25 mm): ($\square$) 0.30 mm; (Δ) 0.42 mm; ($\diamond$) 0.61 mm; (B) pressure drop in the fixed bed and fluidized bed for 0.61-mm particles with weir height being: ($\square$) 25 mm; (Δ) 15 mm. Solid lines show the fitting of the Ergun equation to the experimental data.

Operation of the proposed SLCFB

The operating window was established for the smooth and stable operation of the multistage column. The superficial liquid velocity was varied for a given solid circulation rate to determine two extreme conditions, namely loading and flooding. Although the multistage column operates in the conventional fluidization regime wherein the superficial liquid velocity ranges between the minimum fluidization velocity and terminal settling velocity, it is essential to determine flooding and loading states for stable operation of the system for given physical properties of the liquid and solid phases. There is a minimum solid flow rate for a given superficial liquid velocity below which the column is considered to be flooded. In the flooding state, the fluidizing medium, water in the present study, prevents the flow of solid particles from one stage to another through the downcomer. In the other extreme state, called the loading state, solid particles are excessively loaded on the stage for a given superficial liquid velocity at a certain solid flow rate. Under the loading condition, the solid particles choke the downcomer, preventing flow from one stage to another. Fig. 5 shows the operating window for particle sizes of 0.30, 0.42, and 0.61 mm. The filled symbols represent the maximum solid flow rate at a given superficial liquid velocity, which may be used for stable and smooth operation of the column without loading of the stages with excess solids. Similarly, the hollow symbols represent the solid flow rate at a given superficial liquid velocity, which may be used without flooding of the stage with water. The difference between the two values of the superficial liquid velocity therefore defines the operating range of fluidization without loading and flooding of the stages at a given superficial liquid velocity. For a particle size of 0.61 mm, as an example, at a superficial liquid velocity of 3.3 mm/s, the operating range of the solid circulation rate is between 1.30 and 2.10 g/s corresponding to flooding and loading in the multistage column. A solid circulation rate lower than 1.30 g/s gradually leads to the stage being flooded, whereas that higher than 2.10 g/s results in loading of the stages. In Fig. 5, the operating range is clearly marked with vertical double-headed arrows for a given size of solid particle.

Fig. 5. Operating window for a given particle size. Filled symbols: loading limit; hollow symbols: flooding limit; (□) 0.30 mm; (Δ) 0.42 mm; (◇) 0.61 mm.

It is concluded that the smooth and stable operation of the column does not solely depend on the superficial liquid velocity but equivalently depends on the solid circulation rate. It is therefore essential to adjust both the solid circulation rate and superficial liquid velocity to ensure stable operation within flooding and loading extremes. In other words, it is the ratio of the solid circulation rate to superficial liquid velocity (and not the individual velocities or flow rates) that is the criterion for smooth operation in a column and the ratio could be used as a design parameter for scaling up of the system. To consider the effects of the physical properties, solid circulation rate, and superficial liquid velocity on stable operation of the column, it is essential to obtain experimental data for a common platform. Accordingly, experimental results are presented in Fig. 6 wherein the ratio of the solid circulation rate to the massflow rate of the liquid phase (G_s/m_L) is plotted against the ratio of the superficial liquid velocity to the terminal settling velocity of the solid particle ($V_L/V_{S\infty}$). The terminal settling velocity of the solid particle is a characteristic fluidization property that considers the physical properties of the solid and liquid phases while G_s/m_L considers the operating parameters of the system. Fig. 6 shows the operating window when G_s/m_L values are plotted against $V_L/V_{S\infty}$. The filled and hollow symbols respectively represent loading and flooding states for a given size of the solid particles. As seen from the plot, G_s/m_L is fairly constant for a given $V_L/V_{S\infty}$ within loading and flooding limits. In other words, the solid circulation rate could be determined at any superficial liquid velocity within loading and flooding states of the column if the terminal velocity of the solid particle is determined. Furthermore, it is inferred that both loading and flooding curves decrease monotonically and converge asymptotically.

Fig. 6. Operating window of G_S/m_L in the multistage column. Hollow symbols: flooding state; filled symbols: loading state; ($\square$) 0.30 mm; (Δ) 0.42 mm; ($\diamond$) 0.61 mm.

Measurements of the pressure drop across the stage when the column operated under steady-state conditions with the resins and water flowing counter-currently show that the pressure drop is a function of G_S/m_L . Fig. 4 shows the pressure drop across the stage when the column is operated without solid flow across the stage; i.e., in the fixed-bed regime. The pressure-drop across the stage was measured to be 18.4 Pa under fixed-bed conditions. The pressure drop across the stage due to the cross flow and counter-current flow of solid particles in the downspout can be estimated by subtracting the pressure drop measured under the fixed-bed condition from the pressure drop measured under the steady-state operation of the column. In the present case, the maximum pressure drop was determined to be 40.23 Pa in the extreme case of loading corresponding to G_S/m_L equaling 0.475. Therefore, the pressure drop due to interaction between solid and liquid phases for cross and counter-current flow is determined to be 21.83 Pa. The pressure drop across the stage may be compared with the value of 981 Pa for hydrostatic pressure equivalent to a water column height of 100 mm on the stage. The comparative pressure drops in the column due to hydrostatic pressure, apparent weight of the solid resins, cross-flow on the stage and counter-current flow in the downspout tube were approximately calculated to be 96%, 1.80%, and 2.20%, respectively. The results show that the pressure drop due to interaction between the solid and liquid phases is negligible as compared with the hydrostatic pressure in the column.

Solid hold-up

The effects of the superficial liquid velocity and solid circulation rate on the solid hold-up were studied within the operating window for a given particle size. The total superficial liquid velocity is the sum of primary and auxiliary superficial liquid velocities. An increase in the primary liquid velocity or auxiliary liquid velocity increases the total superficial liquid velocity in the column. The auxiliary flow rate was maintained corresponding to the minimum fluidization velocity of the solid particles during the experimentation. Fig. 7 shows the effect of the superficial liquid velocity on the solid hold-up across the stage for a particle size of 0.61 mm at a given solid

circulation rate under the steady-state condition. The solid hold-up increases with an increase in the solid circulation rate and decreases with an increase in the superficial liquid velocity. A similar trend was observed for solid particle sizes of 0.30 and 0.42 mm.

Fig. 7. Solid hold-up versus the superficial liquid velocity for 0.61-mm particles. Solid circulation rate: (Δ) 1.5 g/s; ($\square$) 1.25 g/s; ($\diamond$) 1 g/s.

MLPNN modeling

The Richardson–Zaki equation is a simple and widely accepted equation used to study expansion characteristics of the solid phase for a given fluidizing medium wherein the effects of the physical properties of solid and liquid phases and the superficial liquid velocity on solid hold-up have been well emphasized. However, in the present case, the solid hold-up is also a function of the solid circulation rate in addition to the superficial liquid velocity and physical properties of solid and liquid phases. A similar observation was made in earlier studies of the hydrodynamic characteristics of a multistage SLCFB (Chavan et al., 2009; Singh, Verma, Kishore, & Verma, 2008). The present work employed the MLPNN-based approach to encompass the effect of the solid circulation rate on the solid hold-up in the multistage SLCFB. Previously, an artificial neural network approach was used to model and study the phase hold-up distributions in the riser section of an SLCFB (Razzak, Rahman, Hossain, & Zhu, 2012; Razzak, 2013). However, no study reported in the literature has predicted the solid hold-up in a multistage SLCFB using the artificial neural network approach, to the best of the authors' knowledge.

For the construction and assessment of the generalization capability of the MLPNN-based model to predict the solid hold-up, experimental data from previous studies (Chavan et al., 2009; Singh et al., 2008) and the present work were considered. An experimental data set, comprising 92 input–output patterns, was randomly partitioned at a ratio of 3:1 into training (69 patterns) and test (23 patterns) sets. While the former set was used in training the model, the latter was used in testing the generalization capability of the model. The proposed model was trained using the error

back propagation (EBP) algorithm from the IBM SPSS software package. The model architecture consists of four input nodes ($N = 4$) and a single output layer node. The four input layer nodes respectively represent (i) the solid circulation rate (g/s), (ii) the superficial liquid velocity (m/s), (iii) the diameter of the particles (mm), and (iv) the density of the solid particles (kg/m^3) while the single output node represents the corresponding solid hold-up value. The physical properties of the liquid phase, namely the density and viscosity, were not considered in developing the model because all previous investigators used the same fluidizing medium (i.e., water) to investigate the effect of the solid circulation rate on the solid hold-up.

To obtain an optimal MLPNN model, structural and training algorithm-specific parameters of the model, such as the number of hidden layers, number of hidden nodes in each layer, learning rate (η), and momentum coefficient (μ_{ebp}), were systematically varied. The criterion used to choose an optimal model was the minimum root mean squared error (RMSE) for the test set. The magnitudes of the MLPNN architectural and EBP specific parameters (η and μ_{ebp}) that led to an optimal MLPNN model are (i) one hidden layer, (ii) four nodes in the hidden layer, (iii) $\eta = 0.21$, and (iv) $\mu_{\text{ebp}} = 0.15$. Details of the model architecture for the proposed MLPNN-based model are listed in Table 3. The prediction accuracy and the generalization performance of the optimal MLPNN model were evaluated in terms of the coefficient of correlation (CC) and RMSE magnitudes with respect to the target and MLPNN model predicted solid hold-up values for the training and test set data; these are listed in Table 4.

Table 3 Details of the architecture of the optimal MLPNN-based model and the corresponding EBP algorithm parameter values.^a

Output variable	Input nodes	Number of hidden layers	Number of hidden nodes	Transfer function for hidden nodes	Transfer function for output node	Momentum coefficient (μ_{ebp})	Learning rate (η)
ε_s	4	1	4	Logistic sigmoid	Identity	0.15	0.21

^aOther details of the EBP-based models: (a) rescaling method used for the scale dependent variables: standardized; (b) learning mode: batch; (c) random number generator seed value with respect to the optimal MLPNN model: 150; (d) maximum number of training epochs: 120.

Table 4 Statistical analysis of the MLPNN-based model for predicting solid hold-up.

Model	Training set		Test set	
	CC_{trn}	$RMSE_{\text{trn}}$	CC_{tst}	$RMSE_{\text{tst}}$
MLPNN	0.964	3.53×10^{-2}	0.960	3.47×10^{-2}

The CC magnitude with respect to the output (solid hold-up) predicted by the MLPNN-based model and the corresponding desired (experimental) values for the training and test sets are 0.964 and 0.960, respectively, while the corresponding RMSE magnitudes are 3.53×10^{-2} and 3.47×10^{-2} . From the high (low) and comparable values of the CC (RMSE) for both the training and test set data, it is concluded that the MLPNN-based model performs well in predicting and generalizing the solid hold-up. The solid lines in Fig. 7 show the values of solid hold-up predicted by the MLPNN-based model. It is inferred that the predicted values well match the experimental values. Fig. 8 is a parity plot of the MLPNN-based model prediction values of the solid hold-up and their experimental counterparts. It is seen that all points fall on or very close to the 45° line, indicating a good match between the experimental and model-predicted solid hold-up values,

pertaining to the training and test set data, which supports the observation of the excellent prediction accuracy and generalization performance of the MLPNN-based model.

Fig. 8. Parity plot. (□) Training data; (▲) test data.

Conclusions

The following conclusions are drawn from the results of the present study.

1. The working of the novel multistage SLCFB was successfully demonstrated within the loading and flooding limits. The ratio of the solid circulation rate to the liquid flow rate (G_s/m_L), rather than individual solid and liquid flow rates, is a criterion of stable operation of the system.
2. The pressure drop in a multistage SLCFB without solid flow can be fairly predicted using the Ergun equation. The pressure drop due to the buoyancy of solid particles, for cross and counter-current flow of solid particles and liquid, was found to be negligible relative to the pressure drop in the column due to the hydrostatic head.
3. The solid hold-up increases with an increase in the solid circulation rate and decreases with an increase in the superficial liquid velocity.
4. The developed MLPNN-based model for the solid hold-up has excellent output prediction accuracy and generalization performance as indicated by the high training and test set correlation coefficients and low RMSE magnitudes. Owing to its higher prediction accuracy, this model has the potential to be the preferred in predicting the solid hold-up in multistage SLCFBs.

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