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Hydrodynamic similarity in liquid–solid circulating fluidized bed risers

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ABSTRACT

Hydrodynamic similarity in the liquid–solid circulating fluidized bed systems under different operating conditions was investigated. The experimental data obtained from this work and in the literature show that when the scaling parameter, $G_s/(\rho_p j_l)$, is modified as (j_a/j_l), ratio of auxiliary liquid velocity to total liquid velocity, a detailed hydrodynamic similitude of the liquid–solid circulating fluidized risers under different operating conditions can be achieved. Furthermore, the experimental results from different liquid–solid flow systems show that as long as $(j_a/j_l)^{0.3}$ remains constant, the solid concentrations in the zone of CFB risers increase linearly. Archimedes number, Ar, Galileo number and Froude number, Fr_D were used to use the modified scaling parameter, (j_a/j_l), without power. Experimental results show that as long as $Ar^{-0.07}(j_a/j_l)$, $Ga^{-0.07}(j_a/j_l)$ and $Fr_D^{-0.07}(j_a/j_l)$ is maintained, the similarity of the liquid–solid circulating fluidized bed riser is obtained using the new similarity parameter without using power. The empirical similarity parameter, (j_a/j_l), appears to have incorporated the effects of operating parameters (G_s and j_l).

1. Introduction

Liquid–solid circulating fluidized beds (LSCFBs) are gaining in popularity for their wide range of potential applications because of their many advantages including significantly high mass and heat transfer rates, improved liquid–solid contact efficiency due to high slip velocity between phases, more operational flexibility, significantly reduced back mixing, and easy control of large quantity of particles [1]. Intensive studies have been carried out to investigate the axial solid holdup distributions [2–6], radial solid holdup distributions [7,8], local liquid velocity profiles [2,3,5,9–11], solid circulation profiles [2,3,5,9–11], slip velocity behaviors [12] and application of core-annulus and drift flux models to study the behaviors of bed [12–15].

Liquid–solid contact efficiency, heat and mass transfer rate, and chemical reaction performance of CFB risers depend, to a large extent, on the complex flow behaviors of such reactors and thus understanding of the hydrodynamics in CFB risers is the key to successful modeling, design and scale up of CFB reactors [16]. The design, scale up and operation of such liquid–solid continuous systems require information of phase holdup and flow patterns referred to as the hydrodynamic characteristics. Numerous papers have reported that the solid holdup is dependent on operating conditions, e.g. the superficial liquid velocity, the auxiliary liquid velocity, density and diameter of the particles and solid circulation rate [2–11].

Liquid–solid CFB risers have been investigated extensively in recent time because of their practical application, as well as their intrinsic academic interests. It is impractical to design, scale up and operate CFB reactors according to theoretical models at this stage of the model development and consequently the design, scale up and operation of this reactor remain a challenging task [16]. A properly scaled down experimental equivalent of a large CFB employs dimensionless input parameters that are the same as for the large CFB and consequently the output parameters, in dimensionless form, will be the same in both units. However, there are two different methods used in the literature to determine values of the small-scale input parameters. The first method is simply to maintain as many parameters of the small unit equal to the parameters of the large unit as possible. The second method, maintains equal values of a number of dimensionless groups for the CFB and the small (model) unit. The first method may seem to be more practicable one in scaling up from an existing CFB to a larger one, but, the second method is more scientific and it may therefore be preferred as a starting point for designing a small (model) experimental CFB. As a scientific way, many sets of dimensionless scaling parameters designed to endure hydrodynamic similitude in different scale circulating fluidized bed reactors have been proposed by different researchers based mainly on the dimensional analysis of governing equations [17,18] based on the dimensional analysis of governing equations derived by Anderson and Jackson [19] for gas–solid circulating fluidized bed. But such dimensionless scaling parameters are not developed and applied to the liquid–solid circulating fluidized beds so far.

All typical sets of dimensionless scaling groups in the literature as listed in Table 1 are only composed of eight parameters [18] (superficial

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Table 1
Typical sets of dimensionless scaling groups.

Authors	Dimensionless scaling parameters	
Van der Meer et al. (1999) [17]	Five dimensionless groups	$G_s(/\rho_p U_g)$, U_g/U_t, $Fr_D = U_g^2/gD$, ρ_p/ρ_g, $\rho_g\ d_p U_g/\mu_g$
	Four dimensionless groups	$G_s(/\rho_p U_g)$, U_g/u_t, $Fr_D = U_g^2\ gD$, ρ_p/ρ_g
	Three dimensionless groups	$G_s(/\rho_p U_g)$, U_g/U_t, $Fr_D = U_g^2/gD$
	Two dimensionless groups	$G_s(/\rho_p U_g)$, U_g/U_t
Glicksman (1984) [25]	Full set	$G_s/\rho_p U_g$, $Fr_D = U^2/gD$, ρ_g/ρ_p, $Ar = \rho_p\ \rho_g\ gd^3{}_p/\ \mu^2{}_g$, d_p/D
Glicksman et al. (1993) [24]	Simplified set	$G_s/\ \rho_p U_g$, $\rho_p U_g\ d^2{}_{p,}/\mu_g D$, $Fr_D = U^2{}_g/gD$, ρ_g/ρ_p

gas velocity, solid circulation rate, mean particle diameter, particle density, riser hydraulic diameter, gas density, gas viscosity, gravity). According to Van der Meer et al. (1999) all these eight parameters are in general sufficient to control the detailed hydrodynamics of gas–solid flow in circulating fluidized bed risers apart from bed geometry, particle sphericity, particle/particle and particle/wall coefficients of restitution and friction, electrostatic forces, cohesion and particle size distribution. Furthermore, for a given gas–solid or liquid–solid flow system, six of the above eight parameters are constants and thus the hydrodynamics of the given gas solid flow system depends only on the other two parameters (superficial gas/liquid velocity and solid circulation rate). In practical operation of liquid–solid circulating fluidized bed riser, superficial liquid velocity and solid circulation rate would change inevitably with working conditions from time to time. Hence steady reaction performance of the riser is of extreme importance to ensure the consistency of hydrodynamics of riser under different operating conditions; thus, it is necessary to study the hydrodynamic similarity in a riser under different operating conditions.

It is obvious that the dimensionless group $G_s/(\rho_p U_g)$ listed in Table 1 contains two variable parameters (G_s and U_g) in an identical CFB system. Based on the energy analysis of two phase flow by Li et al. [20], for co-current upward dilute gas–solid particulate flow under study flow condition, Xiaobo et al. [21] described that the dimensionless group $G_s/(\rho_p U_g)$ cannot exemplify the similarity of the solid concentration distribution in co-current upward gas–solid flow system under different operating conditions due to different degrees of particle aggregation and concluded that the dimensionless group $G_s/(\rho_p U_g)$ characterizes the solid concentration in the co-current upward gas solid dilute and particulate flow when the voidage of gas solid flow is greater than 0.997, cluster in gas–solid flow tends to disappear and the slip velocity gradually approached the particle terminal velocity, i.e. only when the solid concentration is extremely dilute. So far there is no study on using this dimensionless scaling parameter to study the similarity of liquid–solid circulating fluidized bed. Therefore, can the dimensionless group characterize the similarity of solid concentration in liquid–solid circulating fluidized bed? Can this dimensionless scaling parameter be applied to liquid–solid circulating fluidized bed? Can this dimensionless scaling parameter be applied to the entire operating range of the riser under different operating conditions?

Based on the above discussion, the focus of present study is to study the hydrodynamic similarity in an identical liquid–solid circulating fluidized bed and to develop a dimensionless similarity parameter. Numerous experimental data obtained from this work and in the literature are used for the proposed similarity parameter, for the first time for liquid–solid circulating fluidized bed.

2. Experimental

A schematic diagram of the experimental setup is shown in Fig. 1. It consists of a riser, liquid–solid separator, solid return pipe, solid storage vessel and inclined solid feed pipe. The riser is made up of Acrylic column with an internal diameter of 94 mm using multiple sections. The total height of the column is 2.4 m. The riser is provided with pressure tapings at 304 mm intervals. The pressure taps are connected to a common base multi-limb manometer to record the pressure drop in each section of the riser. The base of the riser has two distributors, one for the primary liquid flow and another for auxiliary liquid flow into the riser. The primary liquid flow distributor has 21 S.S. tubes occupying 39.5% of the total bed area extending 110 mm into the bed. The auxiliary liquid distributor has a porous plate with 2 mm openings to give 7.4% of free cross-sectional area. Liquid (tap water) from the reservoir is pumped into the riser in two streams, one stream into the primary liquid distributor and the other into the auxiliary liquid distributor. The combined primary and auxiliary liquid velocities (total liquid velocity), if higher than critical liquid velocity (velocity at which demarcation takes place from conventional liquid–solid fluidization regime to liquid–solid circulating fluidization regime, [3]), enables the particles to move concurrently to the top of the riser. The upper end of the riser projects centrally into the liquid–solid separator. The liquid–solid separator allows the particles to settle down from the liquid. The liquid leaves the liquid–solid separator at the liquid outlet placed at the top of the separator to liquid storage vessel. The separated solids from liquid–solid separator are returned through the solid return pipe and solid circulation rate measuring device into the storage vessel.

The solid circulation rate measuring device is calibrated to give the weight of solids that are collected in a known time. In the solid circulation rate measuring device, the column wall is marked with graph paper along the length. During the operation, a ball valve provided at the bottom of the device, when closed, enables the solids to collect in the calibrated tube for a fixed time. The solid height in the tube and their weight are pre-calibrated for each fluid–solid system to give the weight of solid circulating per unit time i.e. the solid circulation rate, w_s.

During the experiments, constant auxiliary liquid flow is maintained and the primary liquid velocity is increased by small increments (until the transport bed regime is reached) to study the effect of the liquid flow rate on the solid circulation rate and solid holdup. Sufficient time is maintained to enable the system to attain steady-state before the liquid velocity, the solid circulation rate, and the pressure differences across the sections are recorded. For each set of experimental conditions, at least three readings are taken and averaged to ensure the repetition and accuracy. All the experiments are carried out at an ambient temperature of $28^o \pm 1°$°C. The range of variables covered and physical properties of the solids used in the present study are given in Table 2. The solid fractions are obtained by sieving and conforming to the standards.

3. Results and discussions

3.1. Modification of $G_s/(\rho_p j_l)$

3.1.1. When j_l is held constant

Fig. 2 shows the variation of the solid holdup, ε_s, in the entire operating range of the liquid–solid circulating fluidized bed with the dimensionless scaling parameter, $G_s/(\rho_p j_l)$, under different superficial total liquid velocities, j_l,. Under various total liquid velocities, j_l, a good linear relationship between ε_s, and $G_s/(\rho_p j_l)$ can be observed, but the slopes of ε_s against $G_s/(\rho_p j_l)$ under different j_l are not the same. With increasing total liquid velocity, j_l, the corresponding slope decreases. It is also observed from Fig. 2 that for a given value of j_l the slope decreases with decrease in diameter of the particles also with a decrease in density of the particles. That is, the slope decreases as the terminal velocity decreases. Fig. 2 shows that the scaling parameter, $G_s/(\rho_p j_l)$, cannot guarantee the similarity of the solid concentration distribution in identical liquid–solid