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Original Research Paper

Study of slip velocity and application of drift-flux model to slip velocity in a liquid–solid circulating fluidized bed

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ABSTRACT

The increasing applications of liquid–solid circulating fluidized bed in chemical/biochemical industries require a better understanding of hydrodynamics of such system. This work aims to experimentally investigate the slip between the phases in a LSCFB. The variation of slip velocity with superficial liquid velocity, solids velocity, bed voidage and particle size and density is discussed. The apparent slip velocity of the phases is higher than the particle terminal velocity of a single particle. The R–Z equation developed based on the homogenous flow characteristics underpredicts the slip velocity in a LSCFB. The drift-flux model which considers the radial non-uniformity and slip between the phases was applied to the data of the present study. The predicted value by the model agreed with the apparent slip velocity well. The study also proposed an empirical correlation to predict the slip velocity. The empirical correlations aggress well with the experimental data.

1. Introduction

It is generally accepted that the liquid–solid fluidized beds expand in a homogeneous manner with a spatially and uniformly distributed concentration of solids particles in both axial and radial directions. This homogenous behaviour for the liquid–solid systems forms the basis for the number of mathematical flow models, proposed to predict the flow characteristics. Richardson and Zaki [1] proposed a correlation, known as the Richardson–Zaki equation, to predict the relationship between the bed voidage and the liquid velocity in the conventional fluidized bed. This correlation has been found to be useful over a wide range of operating conditions by many researchers and serves as a building block for a number of models developed for liquid–solid fluidization [2]. Although they treated the bed expansion as a fluidized bed, the discussions fundamentally referred to the slip velocity caused by the gravity and fluid drag forces interaction with other particles. Due to the limited operating range and the severe solids dispersion for the conventional liquid fluidization, the need for a new type of liquid–solid fluidization arose to catch up with the progress in industrial process. Progresses in Food technology, Biochemical processing, petrochemical process, production of linear alkylbenzene, and Protein recovery from waste streams have also required new types of liquid–solid contacting equipment. These led to the inception of the liquid–solid circulating fluidized bed [3]. This type of reactor is usually operated at a liquid velocity higher than the particle terminal velocity so that it would be necessary to feed new particles or recirculate particles back to the bed at the bottom. A new regime, viz. the liquid–solid circulating fluidization regime at which the LSCFB is operated, is also identified by Liang et al. [4] between the conventional fluidization regime and transport regime. Comparing with conventional liquid–solid fluidization, the LSCFB provides the key advantages such as high fluid–solids contact efficiency, significant reduction in liquid and solids dispersion, high mass transfer rates, easy addition and withdrawal of solids into/from the fluidized beds, etc. [4].

Slip velocity, the velocity of the carrying fluid relative to the moving solids; reflects the interaction between liquid and solids, influence of liquid and solids mixing, solids residence time distribution, and liquid to solids heat and mass transfer characteristics. The slip velocity, thus, also referred as Relative velocity is an important contributing parameter to the phase holdup in two-phase flow. Therefore, detailed studies of slip velocity have become essential. The literature however doesn't provide quantitative description and estimation of slip velocity from the experimental conditions. Kuramoto et al. [5] studied the macroscopic

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Nomenclature

List of symbols

C_o	distribution parameter (–)
j	superficial velocity of the two-phase mixture ($=j_l+j_s$) (m/s)
j_a	superficial auxiliary liquid velocity (m/s)
j_f	superficial primary liquid velocity (m/s)
j_l	superficial total liquid velocity, ($=j_f+j_a$) (m/s)
j^s	solids circulation rate expressed as superficial solids velocity,($w_s/A\rho_s$) (m/s)
n	Richardson–Zaki index
u_l	true liquid velocity (m/s)
u_r	local slip velocity obtained by Eq. (2) (m/s)
$\bar{u}_r$	cross-sectional average slip velocity defined by Eq. (10) (m/s)
u_s	true solids velocity (m/s)
u_{sj}	weighted average drift velocity (m/s)
u_t	particle terminal velocity (m/s)

Greek letters

ε_l	bed voidage (–)
ε_s	solids holdup (–)
ρ_l	liquid density (kg/m^3)
ρ_s	particle density (kg/m^3)
$\Delta\rho$	$=(\rho_s-\rho_l)$

flow structure of circulating liquid–solid fluidized bed. They reported that the axial distributions of the solids holdup were always uniform throughout the riser. The liquid–solid slip velocity was found to be appreciably higher than that in batch liquid–solid fluidized bed and therefore the Richardson and Zaki slip velocity equation becomes inapplicable for liquid–solid circulating fluidized beds. The authors noted that at high liquid velocities, the bed tended to form solid aggregates, and this led the slip velocity to be appreciably higher than the terminal velocity. Liang et al. [4] studied the flow characteristics of the LSCFB and noted that the slip velocity in the circulating fluidized bed was higher than particle terminal velocity. They noted the inapplicability of Richardson and Zaki equation for slip velocity and attributed the discrepancy to the non-uniform radial distribution of liquid and the particle velocities.

In gas–solids circulating fluidized beds (GSCFB), apparent slip velocity has been studied by some researchers who reported that the apparent slip velocity is much higher than the particle terminal velocity [6]. Yang et al. [7] reported a systematic study on local slip velocity and suggested that cluster formation and core-annulus segregation contribute to the over-estimation of the actual slip velocity. Yerushalmi and Cankurt [8] also reported that slip velocity is much higher than the terminal velocity of a single particle. This has been attributed to the existence of particle clusters and non-uniform radial distribution of solids holdup.

Experimental results show that under high liquid velocity and with particle circulation between the bed and the particle storage vessel, there is significant non-uniformity in the radial distributions of the bed voidage and liquid and particle velocity. Due to the radial non-uniformity of the flow structure and higher operating liquid velocity, significant errors will occur when the empirical relations for conventional liquid–solid system based on liquid flow rate and homogenous fluidization are used to describe the hydrodynamic characteristics and bed voidage and liquid velocity. The literature mentions non-applicability of Richardson and Zaki equation for slip velocity in LSCFB. Therefore, new correlations are needed to describe the relations between the bed voidage and the liquid velocity. The present study attempts to address the aforementioned deficiencies in the understanding of the slip velocity in LSCFB by collecting the experimental data over a wide range in operating conditions and by proposing correlations applicable for the data of the present study as well as the data reported in the literature. Modified drift-flux model [9] is also applied to determine the slip velocity using the Distribution parameter, Co, and drift velocity, u_{sj}. Slip velocity obtained using the experimental results are compared with the slip velocity obtained using modified drift-flux equation slip velocity.

2. Experimental

A schematic diagram of the experimental setup is shown in Fig. 1. It consists of a riser, liquid–solid separator, solids return pipe, solids storage vessel and inclined solids 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 function of the auxiliary liquid is to loosen up the particles at the bottom (above the auxiliary liquid distributor), push the solids up to tip of riser and allow the solids from the feeding pipe into the riser. Increasing the auxiliary liquid velocity, a slow moving bed is observed in the solids feed pipe to transport the solids into the riser. Hence, solids holdup and solids circulation rate in the riser can be controlled by adjusting the ratio of primary and auxiliary liquid velocities. Therefore, auxiliary liquid velocity acts as a control device for solids circulation rate and solids holdup hence auxiliary distributor and solids feeding pipe function as a non-mechanical valve. 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, Liang et al. [4]), enable 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 solids return pipe and solids circulation rate measuring device into the storage vessel.

The solids circulation rate measuring device is calibrated to give the weight of solids that are collected in a known time. In the solids circulation rate measuring device, the column wall is marked with graph paper along the length. The solids circulation rate is determined by closing the valve and noting the time needed to accumulate a predetermined height of (10 cm) solids above the valve. The time taken for each auxiliary liquid flow varies from 5 to 76 s. The