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Viscosity Effects on Solid Circulation Rate in a Liquid Solid Circulating Fluidized Bed

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Abstract: Liquid-solid circulating reactors form the heart of emerging alkylation processes for the production of motor fuel additives and also for the manufacture of linear alkyl benzene. To design a liquid-solid circulating fluidized bed system hydrodynamics be studied first but there is still limited understanding on how particles were circulated in Liquid Solid Circulating Fluidized Bed (LSCFB) with viscous fluids. The hydrodynamics characteristics of the LSCFB of varying viscosity were analysed in terms of solid circulation rate, particle velocity and pressure drop for different fluids. Experiments were conducted using water and glycerol at different concentrations with varying viscosities. Solids of different densities and diameter were used for the study. Results show that circulating fluidization regime starts earlier for higher viscous solution because of decrease in critical transitional velocity. Sand compared to glass bead showed a higher solid circulation rate under similar operating conditions. The solid circulation rate increases with increase in total velocity, auxiliary velocity and also increases with increasing viscosity.

Key words: LSCFB, varying viscosity, hydrodynamics, solids circulation rate

INTRODUCTION

Solid particles are often of great interest in the chemical process industry, mineral processing, pharmaceutical production, energy related processes etc. A number of possible configurations are available for carrying out such reactions and contacting operations (fixed bed, packed beds, fluidized beds, dilute phase transport systems) The CFB (circulating fluidized bed) has come to prominence in the past two decades in terms of major applications.

LSCFB is a new type of contacting device having potential applications in the field of food processing, biochemical processing, environmental engineering, petrochemical and metallurgical processing. Zhu *et al.* (2000) provided a critical review based on the result collected from the literature on the liquid-solid circulating fluidized beds to raise the attention of researchers and industrial practitioners for the promising multiphase contactors. Lan *et al.* (2002) and Zheng and Zhu (2000) characterized the micro flow structure of LSCFB and compared with the fast fluidization in the gas solid circulating Fluidized Bed (CFB).

The design and scale up of continuous liquid-solid system requires the knowledge of the flow patterns, phase holdup and solid circulation rate. Thus, it is important that the hydrodynamics be studied first. Since, the riser of a LSCFB is accompanied by the down comer with continuous circulation of solids between them, solid circulation rate becomes the one of the primary variables that determines the performance of the riser as a reactor. Few studies have been carried out on the hydrodynamics. Natarajan *et al.* (2008, 2009) experimentally studied the effects of particle size, density and variation of liquid velocity on the flow characteristics, regime transition and stable operating range of LSCFB were studied. Shilapuram *et al.* (2009) described three methods of operation of LSCFB and reported experimental average solids holdup at different primary and auxiliary liquid velocities for three methods of operation. These authors also verified that the macroscopic flow properties (flow regimes, onset of average solids holdup and average solids holdup and solids circulation rate in the riser) are different by different methods of operation. Sang and Zhu (2012) experimentally studied the effect of particle properties on solid holdup in the riser of LSCFB, varying three parameters namely superficial liquid velocity,

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normalized superficial liquid velocity and the excess superficial liquid velocity. It was observed that excess superficial liquid velocity is a more appropriate parameter to evaluate the effect of particle properties on the solid holdup. However mostly all investigations were carried out in LSCFB with water as a liquid phase. The effect of liquid viscosity on the solid inventory with riser operated in a fixed inventory mode was done by Vidyasagar *et al.* (2011). There were papers (Cho *et al.*, 2005; Shin *et al.*, 2005) that detailed the effect of viscosity on mixing, heat transfer, regime transition and radial solids distribution for the variable inventory mode of LSCFB. In many applications, viscous liquids are used in industrial processes as processing fluids. The LSCFB with viscous fluids has a significant effect on determining the solid circulation rate of the system. Systematic study is still needed for the comprehensive understanding of solid circulation rate with variation in particle properties. The critical analysis of the literature indicates the effect of liquid viscosity on solid circulation rate was not studied extensively so our study aims at estimating the solids circulation rate and pressure drop in a liquid-solid circulating fluidized bed for water and glycerol-water solution. In addition the effects of flow rate and particle density on the solid circulation rate were also studied.

MATERIALS AND METHODS

The schematic of the fabricated experimental setup used in the present study is shown in Fig. 1. It consists of riser, liquid-solid separator, solid recycle down comer and a distributor. The riser was made up of Acrylic with an outside diameter of 0.1 m. The total height of column is 2.4 m. The base of the riser has two distributors, one for primary liquid flow and the other for auxiliary liquid flow into the riser. The liquid-solid separator is a cone based cylindrical vessel. The riser is provided with pressure tapings at 150 mm intervals connected to a multilimb manometer with carbon tetra chloride as a manometric fluid to record the pressure drops across the column. The liquid pumped from the reservoir is admitted as two streams with main stream entering the riser through the primary liquid distributor and the secondary through the auxiliary distributor. When the combined velocities of the primary and auxiliary are higher than the critical liquid velocity it enables the particles to move concurrently to the top of the riser and then the particles are separated in the liquid solid separator. At steady state pressure drop is measured at different locations along the riser. The separated solids return to the downcomer through solids returning point and solid circulation rate measuring

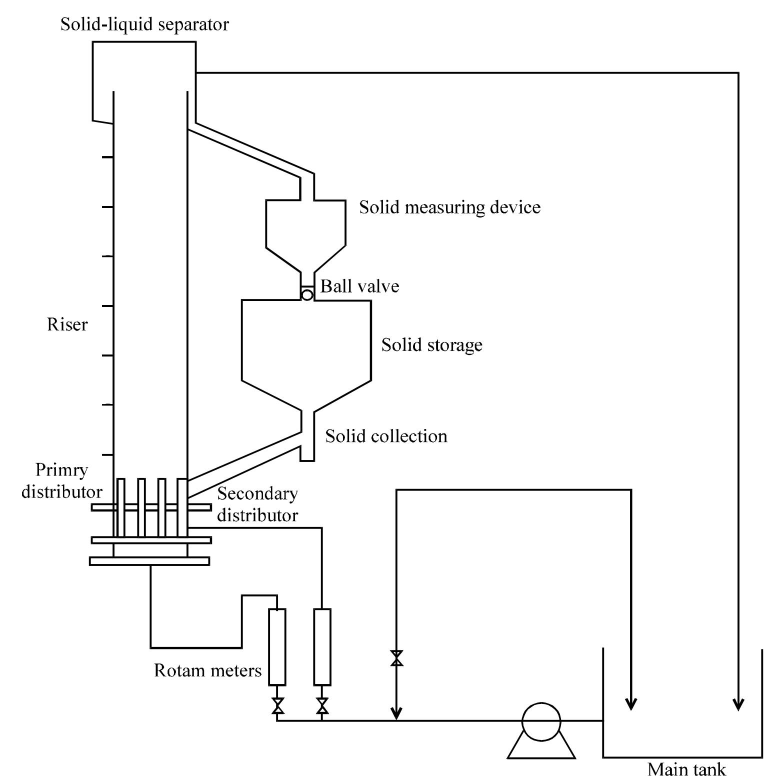

Fig. 1: Schematic of experimental setup LSCFB

Table 1: Physical properties of the liquids and solids used in the present study

Fluidizing liquid	Density (Kg m^{-3})	Viscosity (cp)	Terminal velocity of sand particles (m sec^{-1})	Terminal velocity of (m sec^{-1}) glass beads
Tap water	1000	1	0.0700	0.2919
5% vol of aqueous glycerol	1011	1.085	0.0675	0.2626
15% vol of aqueous glycerol	1036	1.36	0.0614	0.2562

devices. The solid circulation rate device is calibrated to give the weight of solids circulated in a known time. The solid circulation rate was determined by closing the ball valve and noting the time required to accumulate a defined height of solids above the valve. The experiments were continued with an increasing primary liquid velocity until the transport regime was reached, while keeping the secondary velocity constant. The procedure was repeated for different, constant secondary velocities by varying the primary velocity. Experiments were conducted with two different particles of varied sizes and density. The size and quantity of the particles were obtained by sieving and conforming to the standards. All experiments were carried out at ambient temperature. Sand (average diameter: 0.5 mm and density: 2400 kg m^{-3} and glass beads (average size: 2 mm and density: 2460 kg m^{-3}) were used as a dispersed phase. Tap water and aqueous glycerol were used as continuous phase. The physical properties of the liquid used in the present study are shown in Table 1.

RESULTS AND DISCUSSION

The experimental data of the present study covers a wide range of the solid circulation rate G_s and solid velocity U_s. All these parameters are controlled by adjusting the ratio of primary and secondary flow ratess. Solids circulation rate is an important variable that determines the performance of the riser as a reactor as it gives solid superficial velocity, decides time of contact with flowing fluid phase and the extent of conversion.

Solid circulation rate

Effect of primary and auxiliary liquid flow rates: Quantity of the solids fed and the total liquid velocity were the variables affecting solid circulation rate in a circulating fluidized bed. Solid velocity is estimated from solid flux based on the riser cross section and the density of the solids. Both the parameters could be employed to describe the amount of solids circulating from the down comer to the riser at unit time per unit area and it is reasonable to use superficial solid velocity as different type of particles and different solid densities are involved (Sang and Zhu, 2012). Figure 2a and b shows the variation of solid velocity with variation in total velocity (sum of primary and auxiliary liquid velocities) and secondary velocity for sand and glass bead. For a given total

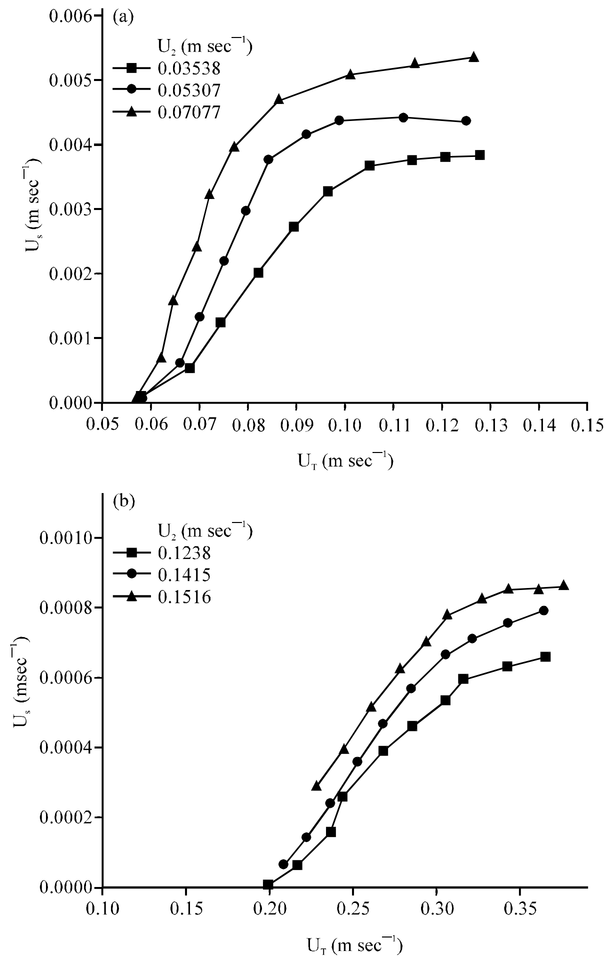

Fig. 2(a-b): (a) Effect of total liquid velocity on solid velocity for sand-water system and (b) Effect of total velocity on solid velocity for glass bead-water system

velocity solid circulation rate increases with increase in auxiliary velocity, with increase in auxiliary velocity more solids were introduced into the riser from the down comer as the function of it is to regulate solid flux. At a fixed auxiliary liquid velocity the solid circulation rate rises steeply and then plateaus as shown in the Fig. 2a for sand and b for glass bead. It is also noted that at different auxiliary velocities superficial solid velocity initially increases with superficial total liquid velocity. Increase in solid velocity with superficial total liquid velocity shows two regions. In the region 1, solid circulation rate

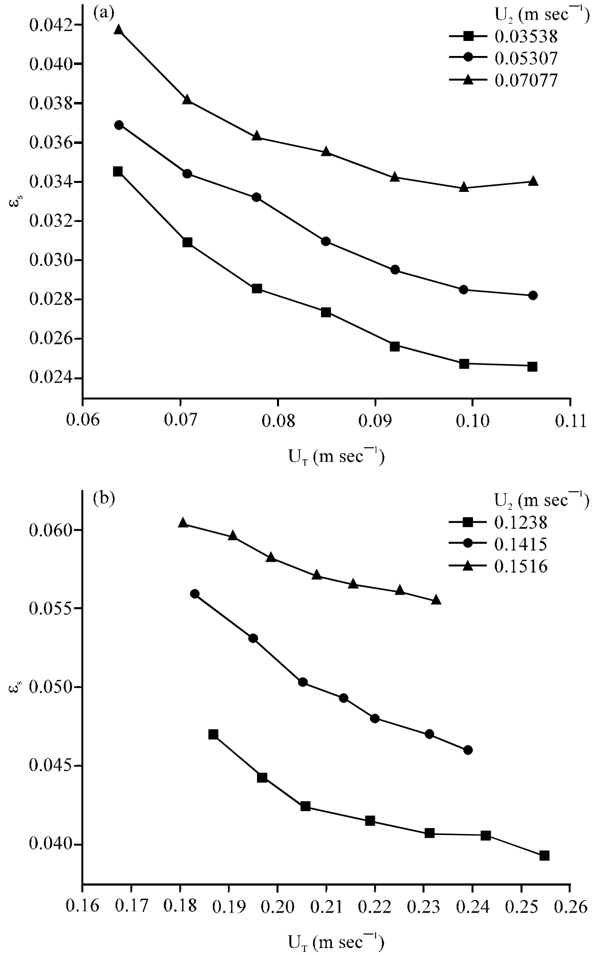

Fig. 3(a-b): (a) Effect of total velocity on average solid holdup for sand-water system and (b) Effect of total velocity on average solid holdup for glass bead-water system

increases rapidly with increasing velocity followed by region 2, in which solid circulation rate increases insignificantly as reported by Zheng *et al*. (1999) for both the system, zone 1 is found to increase linearly where as in zone 2 is not clearly shown due to difference in the configuration of non mechanical valve. In order to achieve a high solid circulation rate the liquid velocity should be higher than the critical velocity. Figure 3a and b show the variation of solid hold up with total liquid and auxiliary liquid velocities for sand and glass bead. It can be seen that solid holdup decreases with increase in total velocity and found to increase with auxiliary velocity it can also be seen that the solid hold up initially decreases quickly with increasing liquid flow rate for the given auxiliary velocity. When the fluidized bed is at low liquid velocity the decrease in solid holdup is drastic and then the decrease in solid hold up is very slow at high liquid velocity on the fully developed circulating zone. This is due to the reduced average residence time of particles at higher particle velocity which in turn reduces the cross sectional average solid holdup. It is worthwhile to note that the average solid holdup in the riser increases with increase in auxiliary velocity due to the fact that auxiliary liquid flow fluidizes the particles at the base of the riser and regulates the solid flow from the storage vessel in to the riser. Hence, more solids enter the riser at higher auxiliary liquid velocity and result in higher solid hold up in the riser. The rapid decrease in solid holdup corresponds to the initial increase in solid velocity and the slow decrease in solid hold up corresponds to the slow increase in solid velocity.

Effect of liquid viscosity: The variation of solid circulation rate with total liquid velocity for viscosity of 1.36 cP is shown in the Fig. 4a and b for sand glycerol and glass bead-glycerol system. The quantum of literature is less on the effect of liquid viscosity for solids of different density and size to show its effect on solid circulation rate. It may be noticed that the variation of solid circulation rate with liquid velocity for viscous system shows the similar trend for water system with a rapid increase in solid velocity with increase in total velocity and then plateaus in the fully developed zone. Effect of viscosity on solid velocity for the given auxiliary velocity is shown in the Fig. 5a for sand and in Fig. 5b for glass bead. The solid velocity is found to be higher for viscous solution than for water due to decrease in terminal settling velocity which in turn decreases the critical transitional velocity therefore circulating fluidization starts earlier for glass bead glycerol system Effect of liquid viscosity studied by Vidyasagar *et al*. (2011) for glass beads-glycerol system shows a similar prediction. For sand system of varying viscosity, solid circulation rate found to increase for viscous solution of 1.08 and 1.36 cP as circulating fluidized bed regime starts much earlier with lesser solid circulation rate. Maximum solid circulation velocity was observed for viscous solution of 1.08 cP.

Effect of density of particles: The quantum of literature is less on the effect of liquid viscosity for solids of different density and size to show its effect on solid circulation rate. Natarajan *et al*. (2008) studied the effect of particle density on solid circulation rate for water system. Figure 6 shows the variation of solid velocity with a variation in liquid velocity for solids of different density and size. It can be noted that flow behavior is similar in increasing trends for both the solids. Terminal velocity for lighter particles were low resulting in early circulation of

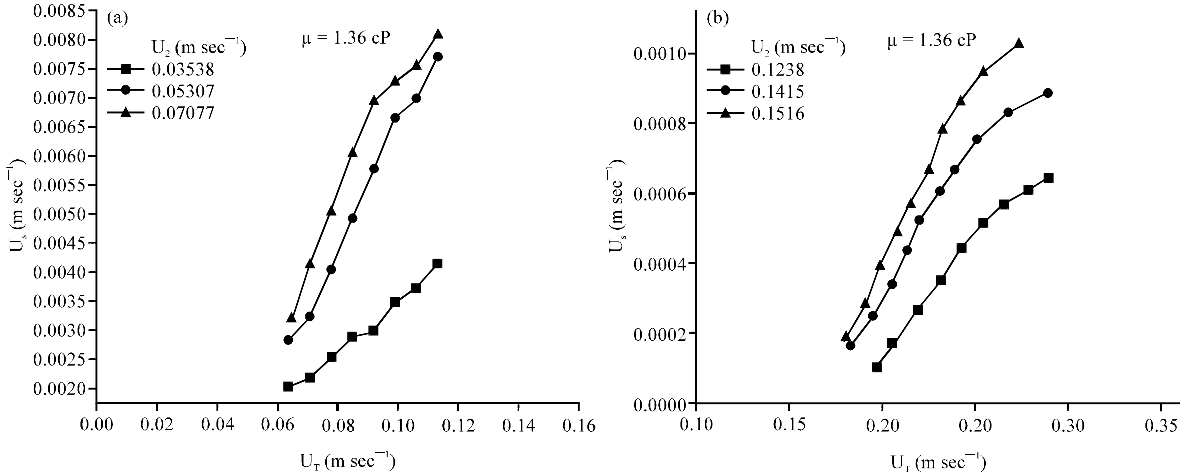

Fig. 4(a-b): (a) Effect of total liquid velocity on solid velocity for sand-glycerol system of 1.36 cP and (b) Effect of total liquid velocity on solid velocity for glass bead-glycerol system of 1.3 cP

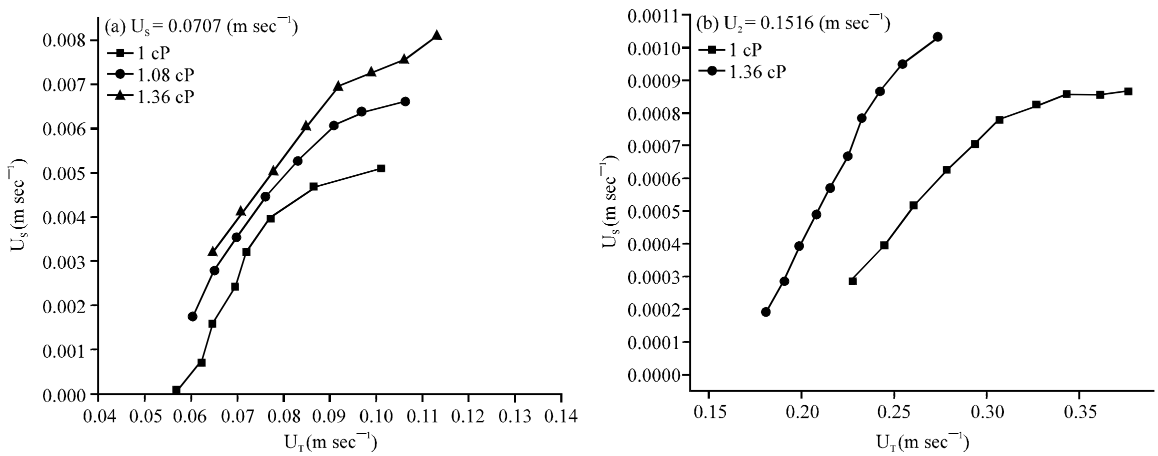

Fig. 5(a-b): (a) Effect of viscosity on solid velocity for sand-glycerol system and (b) Effect of viscosity on solid velocity for glass bead-glycerol system

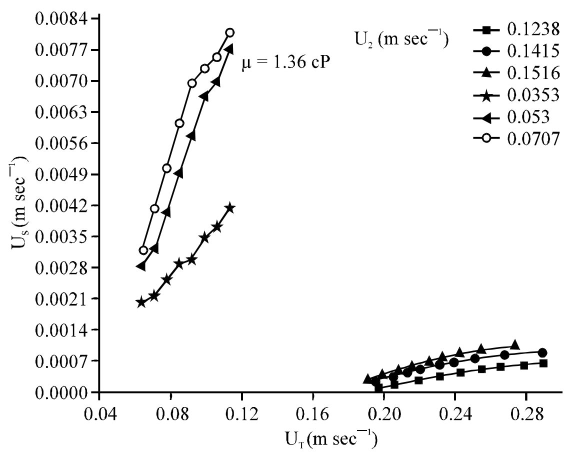

Fig. 6: Effect of density of particle on the variation of solid circulation rate with a variation in total velocity

solids which in turn increases the solid velocity rapidly and its transition from initial zone to fully developed zone is shown. Hence solid circulation velocity for sand (lower density material) is higher than that of glass bead of (high density). It is also worthwhile to note the effect of solid velocity on total velocity curve shift towards left for lighter particles. The maximum liquid velocity corresponding to maximum solid velocity is lower for low dense material and for the given auxiliary velocity solid input to the riser increases and the liquid velocity at which circulation starts is lower for lighter material.

CONCLUSION

The effect of liquid flow rate, primary and secondary velocity, viscosity of liquid and particle density were studied in a liquid solid circulating fluidized bed. The solid circulation rate is found to increase with increase in total velocity and auxiliary velocity circulating fluidized bed regime was reached at lower velocity with increase in liquid viscosity from 1cp to 1.36 cp due to the enhancement of shear stress acting on the particle which results in increase of drag force acting on the fluidized particles and it is also found that the maximum liquid velocity corresponding to maximum solid velocity is lower for low dense material. The study also identified that a decrease in the size or density of solid shifts the solid velocity versus total liquid velocity curve to left showing that higher solid velocity for solids of smaller size at lower total liquid velocity.

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