

# SOLID HOLDUP AND CIRCULATION RATE IN A LIQUID-SOLID CIRCULATING FLUIDIZED BED WITH VISCOUS LIQUID MEDIUM

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**Abstract** - Experiments were conducted in a liquid-solid circulating fluidized bed with different viscous liquids and particles to study the hydrodynamics, average solid hold up and solid circulation rate. The effects of operating parameters, i.e., primary liquid flow rate in the riser, auxiliary liquid flow rate, total liquid flow rate and viscosity of the liquid were studied for solids of different density and particle size. Results show that the circulating fluidization regime starts earlier for more viscous solutions because of the decrease in critical transitional velocity. The onset of solid holdup increases with an increase in liquid viscosity for sand and for glass beads. The solid circulation rate increases with an increase in total velocity and auxiliary velocity, and also increases with increasing viscosity.

**Keywords:** - LSCFB; Viscous effect; Axial solid holdup solid circulation rate.

## INTRODUCTION

Conventional liquid-solid fluidization has been studied intensively and almost all liquid-solid systems show particulate fluidization, resulting in uniform axial and radial solid holdup at liquid velocities below the particle terminal velocity (Richardson, 1954; Kunii and Levenspiel, 1991; Di Felice, 1995). The advantages include: enhanced mass and heat transfer rates, improved interphase contact, better control of solid holdup, less back mixing and higher throughput. For processes involving large amounts of small or light particles in liquid media and liquid-solid reactions and in which the particles must be circulated for frequent regeneration, liquid-solid circulating fluidized beds have considerable promise as ideal liquid - solid contactors. Due to these ad-

vantages, liquid-solid fluidized beds are used in the field of biochemical (Zhu *et al.*, 2000), environmental, metallurgical and petrochemical Engineering. A better understanding of this process can be achieved by focusing on the hydrodynamics and transport phenomena. A typical Liquid-Solid Circulating Fluidized Bed (LSCFB) consists of a riser with primary and secondary flow, a solids separator and a downcomer, which feeds the solids to the riser.

For the development of an appropriate model and design of a LSCFB as a reactor or a contacting device, estimation of various transport properties and kinetic and mixing parameters are required. The hydrodynamic information of interest includes the flow regime, flow pattern at each phase, solid circulation rate and solid holdup. Previous work has been done on the hydrodynamics in the riser of LSCFBs

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and its overall operation. Liang (1996; 1997) and Zheng and Zhu (1999) reported a uniform distribution of solid holdup in the axial direction and a non-uniform radial distribution in the riser. Natarajan *et al.* (2008) measured the solid velocity and solid hold up by varying the solid density and solid inventory and concluded that the solid inventory in the down comer and solid feeding system strongly influenced the solid velocity, phase holdup and operating range of LSCFB. Vidyasagar *et al.* (2008; 2009) studied the flow properties at various liquid velocities and the solid inventory in the down comer at two different locations of the primary liquid distributor, and also reported the hydrodynamics by three experimental methods keeping the solid feeding structure similar.

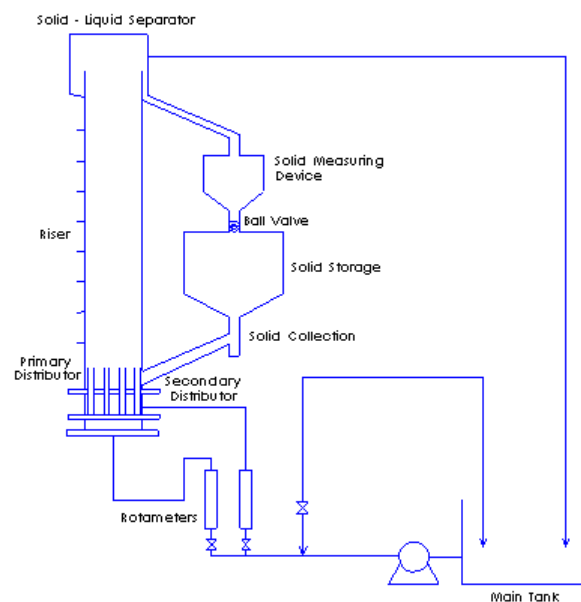
Zheng (2004), Cho *et al.* (2005) and Shin *et al.* (2005) studied the effects of liquid viscosity on hydrodynamics, transport properties, heat transfer coefficient and radial dispersion with the riser operated in the variable inventory mode. The effect of liquid viscosity on the fixed inventory mode was studied by Vidyasagar *et al.* (2011) for different solid inventories and macroscopic flow properties such as pressure gradient, critical transitional liquid velocity to circulating fluidized bed regime, average solid holdup, axial solid hold up distribution and solid circulation rate.

Many industrial processes require a viscous liquid as a processing fluid and it is very important to know the influence of viscosity on hydrodynamics, especially on the solid holdup and the solid circulation rate in the riser of an LSCFB. A critical analysis of the literature indicated the absence of studies of the effect of liquid viscosity on macroscopic properties with various particles of different density. Hence the present investigation focused on the study of the effect of liquid viscosity, liquid flow rate and particle density on macroscopic flow properties, namely the pressure gradient, average solid holdup distribution, axial flow and solid circulation rate for LSCFB risers.

## EXPERIMENTAL

The liquid-solid circulating fluidized system consisted of a riser, liquid solid separator, solid recycle down comer and a distributor (Figure 1). The riser was made of acrylic with an inside diameter of 0.1 m. The total height of the column was 2.4 m and the test section height from the auxiliary distributor plate was 2.0 m. The base of the riser had two distributors, one for primary liquid flow and the other for auxiliary

liquid flow into the riser. The primary distributor had stainless steel tubes that occupied 18% of the total bed area. The secondary liquid distributor had a brass plate with 2 mm openings, along with a fine mesh that gave 7.3% of the total cross sectional area. Initially, the liquid from the reservoir was pumped and admitted as two streams. The main stream entered the riser through the primary liquid distributor and the secondary through the auxiliary distributor fitted via respective rotameters. The auxiliary liquid stream controlled the quantity of particles recirculating from the storage vessel into the riser and its function was to fluidize the particles at the base of the riser. When the secondary liquid flow rate was set to zero, no particles can enter the riser from the solid storage tank due to the high resistance caused by the particle layer at the bottom of the riser. The riser was provided with pressure taps at 150 mm intervals. The pressure taps were connected to a multilimb manometer to record the pressure drop across the column during the experiment. Liquid and solids co-currently moved upward through the riser and separated in the liquid-solid separator. The separated solids returned to the down comer through the solids returning point and the solid circulation rate measuring devices. The liquid left the liquid-solid separator at the liquid outlet placed at the separator and moved to the reservoir.



**Figure 1:** Schematic of the Experimental LSCFB Setup.

In a typical experiment, the riser column was packed with particles to a known height. Primary liquid was admitted into the column through flow

meters at short intervals until the bed expanded to its entire length. When the solids were about to entrain from the top of the riser, the secondary liquid was introduced and circulation between the riser and the down comer started. The riser had pressure taps at regular intervals of 0.150 m connected to a multilimb manometer to measure the pressure drop in each section of the riser. The solid circulation rate was determined by closing the ball valve and measuring the time required to accumulate a definite height of solids above the valve. The solids height in the tube and its weight were precalibrated for each fluid-solid system to estimate the weight of solids circulated per unit time. The solid circulation rate measurement was repeated thrice to check the consistency of system performance. The experiments were continued by increasing the primary liquid velocity until the transport regime was reached. This procedure was repeated for various fixed secondary velocities. Experiments were conducted with particles of different sizes and densities. The sizes and quantity of the particles were obtained by sieving and conformed to the standards. The physical properties of liquid and solid used in the present study are covered in Tables 1 and 2.

**Table 1: Physical properties of the solid and operating velocities of liquid used in present study.**

Variables	Range
Primary liquid velocity, m/s	0.02477 - 0.099 m/s (sand) 0.1344 - 0.2618 m/s (glass bead)
Auxiliary liquid velocity, m/s	0.028 - 0.04954 m/s (sand) 0.1061 - 0.1592 m/s (glass bead)
Total Liquid velocity, m/s	0.056-0.1415 m/s (sand) 0.2477-0.42109 m/s (glass bead)
Viscosity of liquid, cP	1.00 -1.36
Particle density, kg/m <sup>3</sup>	2400 (sand) 2490 (glass bead)

**Table 2: Physical properties of the liquids and solids used in the present study.**

Fluidizing liquid	Density (kg/m <sup>3</sup> )	Viscosity (cp)	Terminal velocity of particles (m/s) Sand	Terminal velocity of particles (m/s) Glass beads
Tap water	1000	1	0.0700	0.2919
5 vol % aqueous glycerol	1011	1.085	0.0675	0.2626
15 vol % aqueous glycerol	1036	1.36	0.0614	0.2562

All experiments were carried out at ambient temperature. The solid holdup was measured by noting the pressure gradient at different locations along the

riser. Average solid holdup was determined for each measured section using Equation (1).

$$-\frac{\Delta P}{\Delta Z} = (\rho_s \varepsilon_s + \rho_l \varepsilon_l) g \quad \text{with } \varepsilon_s + \varepsilon_l = 1 \quad (1)$$

## RESULTS AND DISCUSSION

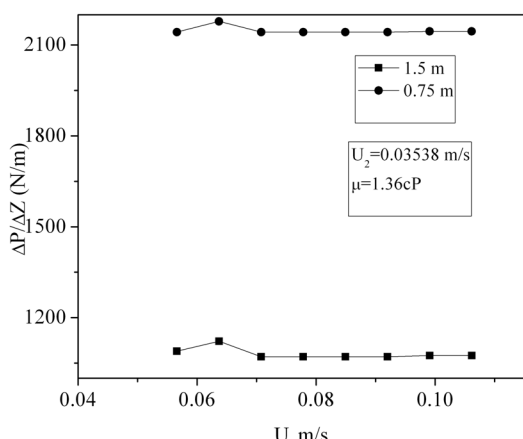
The fluidization in the liquid-solid system is controlled by the liquid flow rate. With increasing flow rate, the liquid-solid system passes through fixed bed, fluidized bed, particulate fluidization regime and then the circulating fluidization regime. Visual observation of the liquid-solid circulating fluidization phenomenon was possible because the test section was made of acrylic.

The fluid in the liquid-solid circulating fluidized bed was controlled by varying the primary liquid flow rate and the auxiliary liquid flow rate. The function of the auxiliary flow was to push the solids to the top of the riser and allow the solids from the solid feeding pipe to enter into the riser. The experimental data of the present study cover a wide range of average solid holdup  $\varepsilon_s$ , solid circulation rate  $G_s$  and solid velocity  $U_s$  in the circulating fluidization regime. All these parameters are controlled by adjusting the ratio of primary and secondary flow rate and hence the auxiliary distributor and solid feeding pipe act as a non-mechanical valve.

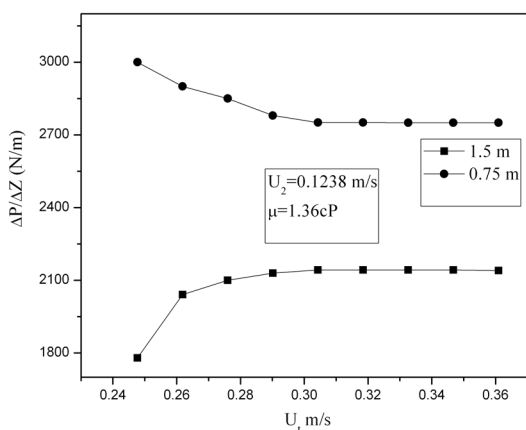
### Pressure Drop Profile

Figure 2 shows the variation of the pressure gradient plotted as a function of total superficial velocity at two axial locations, i.e., 1.5 m and 0.75 m along the length of the riser for a  $\mu = 1.36$  cp viscous solution for sand and Figure 3 for a glass bead system with  $\mu = 1.36$  cp solution in a circulating fluidized bed regime. The pressure gradient obtained was used to compute the average bed voidage in the fluidized bed, which in general determines the overall flow pattern. Figures 2 and 3 show that the pressure gradient at the upper level (1.5 m above the liquid distributor) is similar in trend to that of the lower level (0.75 m above the liquid distributor). At the axial position at 0.75 m (lower position), the pressure gradient in the bottom section is higher than in the top section (1.5 m). This is due to the decrease in solid concentration in the top section, which results in the decrease of the pressure gradient. Similar results were obtained for both the solids, sand and glass bead, for all viscous solutions and auxiliary velocities. It can be noted in Table 2 that the terminal

velocity for sand is 0.0614 m/s, whereas for glass beads it is 0.2562 m/s for  $\mu = 1.36$  cP, which in turn changes the critical transitional velocity from conventional to CFB for both the solids. It was further observed that the circulating fluidized bed regime started before the superficial total liquid velocity reached the terminal velocity of the particles for glass beads due to the early equivalence of the interstitial liquid velocity to the terminal velocity of the particles. Vidyasagar *et al.* (2011) studied dense phase expansion, fluidized bed and CFB pressure drop profiles corresponding to a state of transition from conventional to CFB regime for various viscous solutions in glass bead systems.



**Figure 2:** Variation of pressure gradient along the riser with total liquid velocity- Sand-glycerol (1.36 cP).

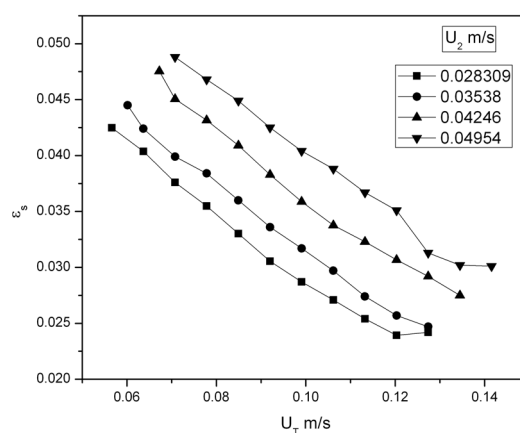


**Figure 3:** Variation of pressure gradient along the riser with total liquid velocity for Glass beads-glycerol (1.36 cP).

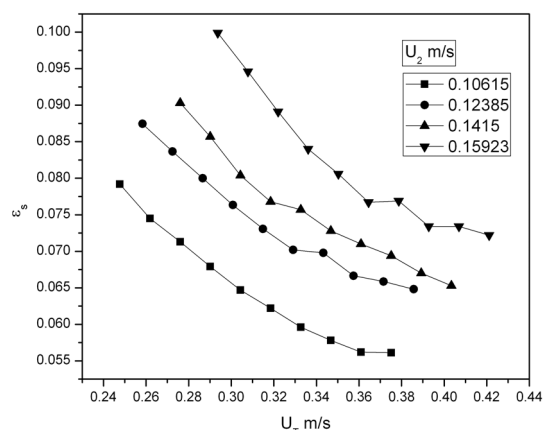
### Average Solid Holdup

The variation of solid holdup in the riser was plotted in Figure 4 for the glass beads-water system and in Figure 5 for the sand-water system for varying

total velocity  $U_T$  and constant auxiliary velocity ( $U_2$ ). Natarajan *et al.* (2008) and Vidyasagar *et al.* (2008) showed that solid holdup depends upon the auxiliary liquid velocity and initial solid inventory for a water-particle system. The present study also demonstrated that, for the given auxiliary velocity, the solid holdup decreased with respect to the corresponding increase in primary and total velocity. It can also be seen that, with an increase in auxiliary velocity, the solid holdup in the riser increases. This is due to the fact that, at low auxiliary velocities, there is a slow movement of solids in the return pipe with low solid loading in the riser, and the flow of solids into the return pipe increases with an increase in secondary velocity.



**Figure 4:** The effect of total velocity on the average solid holdup for the sand-water system.



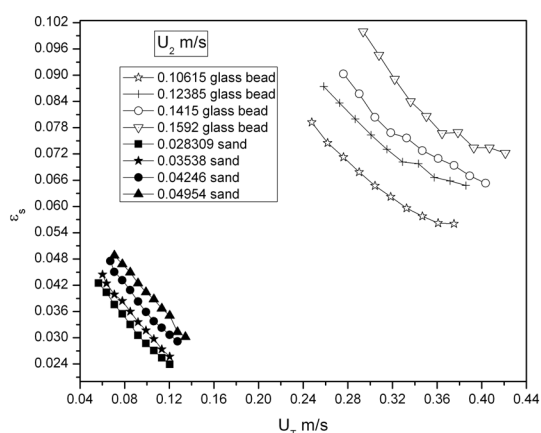
**Figure 5:** The effect of total velocity on the average solid holdup for the glass beads-water system.

Hence, for fixed total velocity, solid holdup increases with an increase in auxiliary velocity. It was observed that the variation of solid holdup shows a similar trend for both the sand and glass bead systems. There were two regions existing in the riser,

the developing flow region and the fully developed flow region. In the developing flow region located in the lower portion of the riser, solids are accelerated along with the decrease of solid holdup. At higher total velocity, the solid holdup shows a plateau, which indicates that the solid flow enters into the fully developed zone, which is consistent with the results of earlier studies.

### Effect of Liquid Viscosity on Solid Holdup

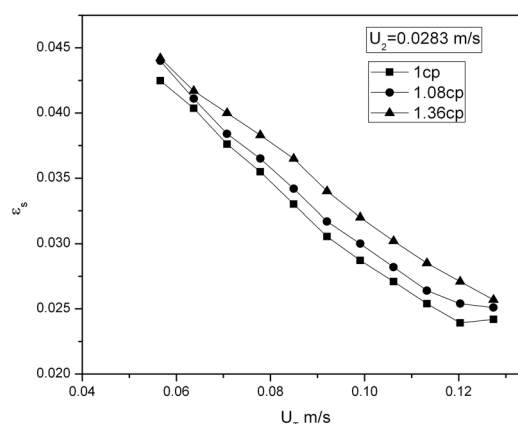
There is not much information available in the literature on the effect of liquid viscosity on solid holdup for solids of different density and size. The effect of liquid viscosity on solid holdup is shown in Figure 6 for sand-glycerol and for glass beads-glycerol of viscosity 1.36 cP. It can be seen that, with the decrease in solid density, solid holdup is shifted towards the left, indicating that solid circulation begins at lower velocity, corresponding to its terminal velocity; solid holdup was found to be higher for low liquid velocity. Maximum solid holdup was reported for the glass bead-glycerol system as larger particles lead to higher solid holdup. It is also noted that the glass bead-glycerol system needs higher superficial velocity to fluidize in the circulating regime because its terminal velocity is higher. For the given superficial velocity, solid holdup increases with an increase in solid density. Similar results have been reported by Natarajan *et al.* (2008) for a water system using silica gel and resin.



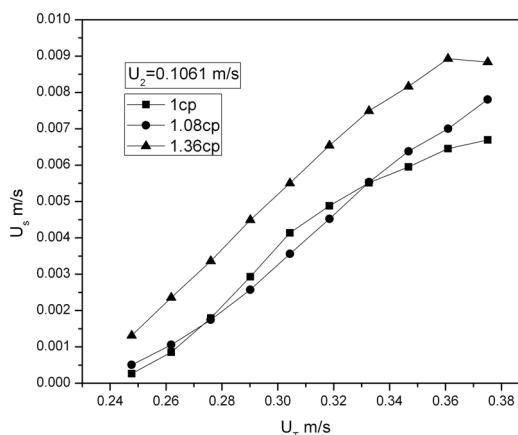
**Figure 6:** Effect of the density of particles on the variation of solid holdup with variation in total velocity.

For the same set of auxiliary liquid velocities for the water system, an increase in solid holdup was observed with increasing viscosity of the liquid. As shown in Figure 7 for sand-glycerol and in Figure 8

for the glass bead system. For the given total liquid velocity, the average solid holdup decreases with an increase in superficial total velocity as more particles are entrained, which in turn shows lower solid concentration. Glass beads of higher density and greater size required more superficial velocity to achieve the same holdup because their terminal velocity is higher. For the same total velocity, the solid holdup decreases with an increase in superficial velocity (Figure 2 and 3) for the water system, but with an increase in viscosity solid holdup is found to increase for both the sand and glass bead systems. This increase in solid holdup is due to the fact that the circulating fluidization regime starts much earlier for the viscous system because the terminal velocity decreases with an increase in viscosity. This observation is similar for both solids, shown in Figures 7 and 8. Hence, it can be concluded that both particle size and viscosity influence the solid holdup in a riser.



**Figure 7:** The effect of viscosity on the average solid holdup for the sand-glycerol system.

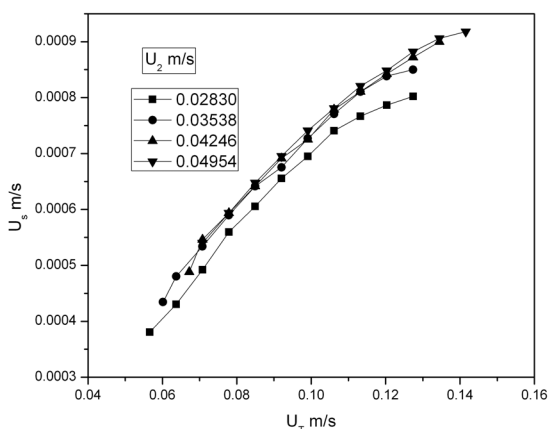


**Figure 8:** The effect of viscosity on the average solid holdup for the glass bead-glycerol system.

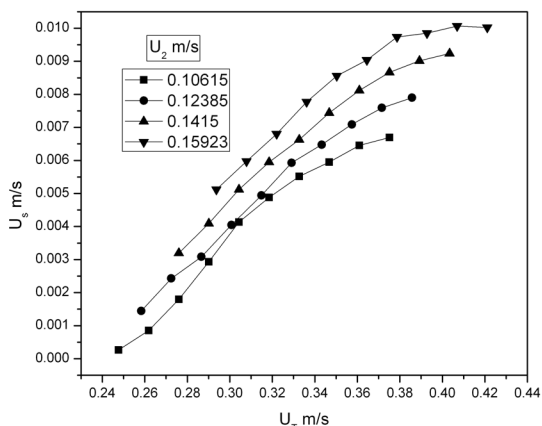
## Solid Circulation Rate

### Effect of Primary and Auxiliary Velocity on Solid Velocity

The quantity of the solids fed and the total liquid velocity were the variables affecting the solid circulation rate in a circulating fluidized bed. An increase in primary liquid velocity or auxiliary liquid velocity increases the total velocity in the riser. Figures 9 and 10 show the variation of solid velocity for the sand-water and glass bead-water systems respectively. For a given total velocity, the solid velocity increases with an increase in auxiliary liquid velocity, as more solids were introduced into the riser from the down comer, its function being to regulate the solid flux. On the other hand, when the auxiliary velocity is low, the solid input to the riser is low and the operating range in the solid velocity is small.



**Figure 9:** The effect of total velocity on the solid circulation rate for the sand-water system.



**Figure 10:** The effect of total velocity on the solid circulation rate for the glass bead-water system.

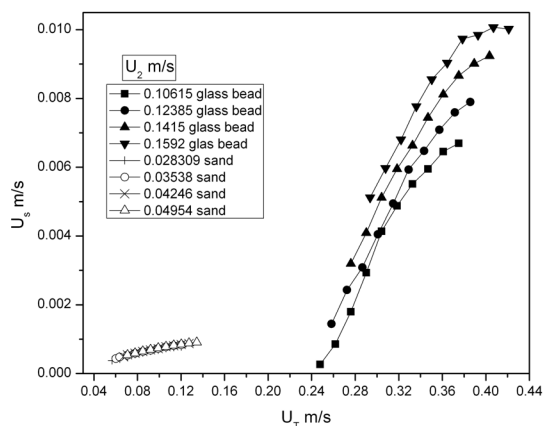
The data showed that the solid velocity curve rises steeply with an increase in auxiliary liquid velocity. It is also noted that an increase in solid velocity with liquid velocity shows two regions. In region 1, the solid velocity increases rapidly with increasing velocity, followed by region 2, in which the solid velocity increases insignificantly, as reported by Zheng (1999). In Figures 9 and 10 for both systems, zone 1 is found to increase linearly, whereas in zone 2 this is not clearly shown due to the difference in the configuration of the non-mechanical valve of the present study from that of other authors. In order to achieve a high solid velocity, the liquid velocity should be higher than the critical velocity.

### Effect of Liquid Viscosity on Solid Circulation Rate

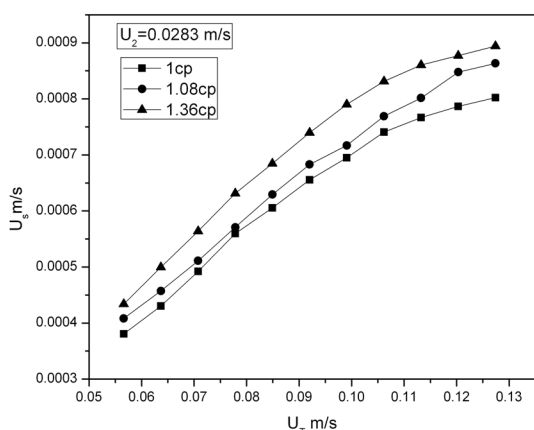
Less literature is available on the effect of liquid viscosity for solids of different density and size that show the effect on solid circulation rate. Moreover, there is no information available in the literature for the variation of solid velocity with a change in density for viscous solutions. Natarajan *et al.* (2008) studied the effect of particle density on solid circulation rate for the water system. Figure 11 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 with increasing trends for both the solids. Terminal velocities for lighter particles were low, resulting in early circulation of solids, which in turn increases the solid velocity rapidly; its transition from the initial zone to the fully developed zone is shown. Hence, the solid circulation velocity for sand (lower density material) is higher than that of glass beads (higher density). It is also worthwhile to note the effect of solid velocity on the total velocity curve, which shifts towards the left for lighter particles. The maximum liquid velocity corresponding to the maximum solid velocity is lower for low density material and for a given auxiliary velocity, the solid input to the riser increases and the liquid velocity at which circulation starts is lower for the lighter material.

The variation in solid velocity with total liquid velocity for sand-glycerol and glass beads-glycerol with respect to the viscosity effect is shown in Figures 12 and 13. It may be noticed that the variation of solid velocity with liquid velocity for the viscous system shows trends similar to the water system. The results showed that the circulating fluidization regime appeared at lower velocities with an increase in liquid viscosity. It is noteworthy that the variation in solid velocity with liquid velocity shows two regions in the circulating fluidization regime for a given

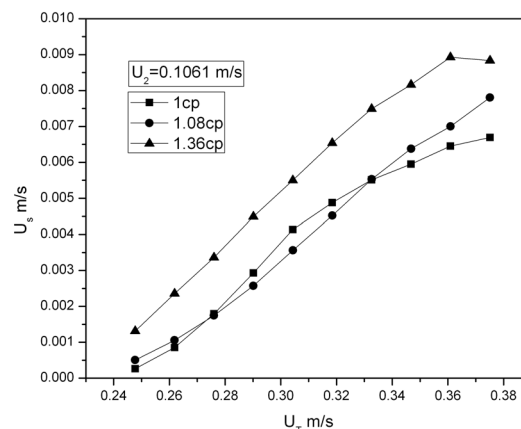
constant auxiliary velocity. A similar trend was also observed for the glass bead-glycerol and sand-glycerol systems with  $\mu = 1.36$  cP. The solid circulation velocity was found to be higher for the viscous solution than for water due to the decrease in terminal settling velocity, which in turn decreases the critical transitional velocity. Therefore, circulating fluidization starts earlier for the glass bead-glycerol system, as depicted in Figure 12. The effect of liquid viscosity studied by Vidyasagar *et al.* (2011) for a glass beads-glycerol system shows a similar result. For the sand system of varying viscosity, as shown in Figure 13, the solid circulation velocity increases for viscous solutions of 1.08 and 1.36 cP. For the more viscous solution, the circulating fluidized bed regime starts much earlier with more solid circulation velocity. However, the maximum solid circulation velocity was observed for the solution of viscosity 1.08 cP.



**Figure 11:** Effect of particle density on the variation of solid circulation rate with the variation in total velocity.



**Figure 12:** The effect of viscosity on the solid velocity for the sand-glycerol system.



**Figure 13:** The effect of viscosity on the solid velocity for the glass bead-glycerol system.

## CONCLUSIONS

The effect of liquid flow rate, primary and secondary velocity, viscosity of the liquid and particle density were studied in a liquid-solid circulating fluidized bed. The average solid holdup decreased with an increase in primary and total velocity and was found to increase with an increase in auxiliary velocity. For a given total liquid velocity, the solid holdup was found to increase with an increase in viscosity for both the sand and glass bead-glycerol systems. The increase of solid holdup with an increase in viscosity is due to the low critical transitional velocity and the increased energy spent to entrain solid particles. It is found that, with a decrease in solid density, solid holdup shifted towards the left, indicating that solid circulation begins at a lower velocity, corresponding to its terminal velocity. The solid circulation rate was found to increase with an increase in total velocity and auxiliary velocity. The circulating fluidized bed regime was reached at lower velocity with an increase in liquid viscosity from 1 cp to 1.36 cp due to the enhancement of shear stress acting on the particle, which results in an increase of drag force acting on the fluidized particles. It was also found that the maximum liquid velocity, corresponding to maximum solid velocity, was lower for the lower density material.

## NOMENCLATURE

$d_p$	particle diameter
$g$	acceleration due to gravity ( $m/s^2$ )
$G_s$	Solid circulation rate ( $kg/m^2 \cdot s$ )
$\Delta p/\Delta z$	Pressure gradient ( $Pa/m$ )

$U_T$	Total superficial liquid velocity (m/s)
$U_1$	Primary or main liquid velocity (m/s)
$U_2$	Secondary or auxiliary liquid velocity (m/s)
$U_t$	Particle terminal velocity (m/s)
$U_s$	Particle velocity (m/s)

### Greek Symbols

$\varepsilon_s$	Average solid holdup
$\rho_s$	Density of solids (kg/m <sup>3</sup> )
$\rho_l$	Density of liquids (kg/m <sup>3</sup> )
$\rho_m$	Density of medium (kg/m <sup>3</sup> )

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