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Effect of Liquid Viscosity and Solid Inventory on Hydrodynamics in a Liquid - solid Circulating Fluidized Bed

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ABSTRACT

A comprehensive hydrodynamic study of a Liquid - Solid Circulating Fluidized Bed (LSCFB) is conducted with changes in viscosity of the fluidizing medium and the inventory height of solids initially fed into the system. An LSCFB of height 2.95m and riser outer diameter 0.1m was chosen for experimentation. The three liquid media systems with varying viscosities that were chosen were water, glycerol 10% (v/v) and glycerol 20% (v/v). Effect of inventory on the hydrodynamics was also studied, by taking initial heights of inventory to be 15cm, 25cm and 35cm. The hydrodynamic studies concentrated on pressure gradients along the axial pressure tapings, axial solid holdup, average solid holdup, solid circulation rate and slip velocity. Uniformity in axial solid holdup and average solid holdup was validated for changes in viscosity and inventory. Solid flux was seen to follow an inverse relationship to holdup. The changes in slip velocity with varying viscosity and inventory were studied, and found to decrease with both variables. The distribution parameter, C_o of the drift flux model was found to be in the range of 0.983-0.994, suggesting non-uniformity in radial solid distribution, with higher solid concentration by the walls compared to the core of the column.

Keywords: Fluidization; Liquid - solid circulating fluidized bed; Solid holdup; Solid circulation rate; Slip velocity; Viscosity and inventory.

NOMENCLATURE

A	cross sectional area of the measuring cylinder
Ar	Archimedes number
C_0	distribution parameter of drift-flux model
C_d	drag Coefficient
d_p	particle diameter
g	acceleration due to gravity
G_s	solid circulation flux
h	height of pressure tapping
j	superficial velocity of two phase mixtures (U_s+U_l)
L_0	inventory height
L_{riser}	riser height
Re_p	Particle Reynolds number
t	time taken for the solids to accumulate over a height H cm
U_1	primary liquid velocity
U_2	auxiliary (secondary) liquid velocity
U_l	total liquid velocity (U_1+U_2)
U_{mf}	minimum fluidizing velocity
U_s	superficial solid velocity
U_t, u_t	terminal Velocity
V_{slip}	slip velocity
w_s	solid circulation rate
ΔP	pressure drop in axial position
Δz	position of the pressure tapping from the riser base
ε	average void fraction
ε_l	void fraction
ε_s	solid holdup
μ, μ_l	liquid viscosity
μ_w	viscosity of water
ρ_l, ρ_g	liquid density
ρ,ρ_s	particle density
ρ_m	manometric fluid density

1. INTRODUCTION

Richardson and Zaki (1954) pioneered into the study of fluidization, opening up a field of science that has since gone on to play a vital role in several industries, particularly the chemical industry. Kunii and Levenspiel (1991) defined fluidization as a technique in which fine solid particles are transformed into a fluid like state, through suspension in a fluid, thereby imparting fluid properties to an otherwise immobile solid bed. When fine particles are fluidized at a sufficiently high fluid flow rate, the terminal velocity of the solids is exceeded beyond the terminal velocity, the solid particles tend to move into a mobile phase and finally entrain beyond the critical transitional velocity for the particular system. For steady state operation, entrained particles have to be collected and returned to the bed. In fluidized beds, smooth and steady recirculation of solids through the dip-leg or cyclone, becomes necessary. It has also been shown that there exists a critical transition velocity, which demarcates the conventional fluidization regime and the circulation regime.

In a liquid - solid system, at high liquid velocity, circulation of particles becomes high and hence the hydrodynamic characteristics in the Liquid - Solid Circulating Fluidized Bed (LSCFB) becomes complex due to turbulence caused between the two phases. The hydrodynamic study (particularly solid holdup and circulation rate) and the testing of axial uniformity of these circulating fluidized beds, when influenced by differing operating parameters, thus becomes important (Natarajan *et al*., 2014; 2015).

The increasing interest in the liquid - solid system, employed in fluidization is due to its advantages over the gas - solid system. These include minimized dead zones, uniform axial heat and mass transfer, and reduced back mixing, all due to the particulate flow that is encountered in such a system. The possibilities of employing an LSCFB system commercially, is wide ranging and studies conducted on the applications, point to the same. In applications where quick reactivation of catalysts is important, such as in the production of linear alkyl benzene, the LSCFB becomes an obvious candidate (Liang *et al*., 1995). Also, the LSCFB has proved a reliable technology for Biological Nutrient Removal (BNR) from landfill leachate (Eldyasti *et al*., 2010), for removal of Cesium from highly radioactive waste (Feng *et al*., 2003), in simultaneous enzyme catalyzed reaction and regeneration using Soybean Peroxidase (SBP) enzyme (Trivedi *et al*., 2005, 2006), for continuous protein recovery from whey (Lan *et al*., 2002), in the elimination of organic carbon and nitrogen using a Circulatory Fluidized Biological Bed Reactor (CFBBR) (Cui *et al*., 2004; Patel *et al*., 2006), in treatment of aniline polluted water (Zheng *et al*., 2016) etc. Natarajan *et al*., (2007) developed a general expression which is useful for predicting radial distribution or for analyzing and interpreting experimental data, derived for an LSCFB. The analysis was conducted by taking into account the variation in radial liquid velocity and difference in radial solid holdup of the particles. More evidently, analysis of the drift flux model (Natarajan *et al*., 2008(b)) conducted in the same study, yielded the conclusion that radial distribution favored the wall region over the core region of the column. This is proven mathematically using the distribution coefficient, Co. When the value of this parameter drops below 1, non-uniformity, with solids favoring the wall is seen. Vidyasagar *et al*., (2011) on the analysis of the results of his experimentation, obtained a regression model for solid holdup. It was noted that the model obtained was not dimensionless as is required to satisfy the dimensionless nature of the solid holdup. Thus, the system has been modeled overcoming this apparent shortcoming.

Nirmala *et al*., (2014; 2015) studied the average solid holdup in the axial direction in an LSCFB with liquids of different viscosity. They investigated the effect of operating parameters, particle diameter and density. The liquid mixture used by them was water and glycerol system of different concentrations. They found that the solid holdup in the riser was axially uniform for viscous liquids and the average solid holdup decreases with increase in total velocity and increases with increase in viscosity. They also reported that the variation from initial zone to circulating zone occurs approximately at total liquid velocity of 1.33 times the terminal velocity of the particle.

In industries that employ the use of fluidized beds and LSCFBs in particular, it should be noted that in most cases, the liquid media like crude or food slurries are more viscous than water. Scarce research has been conducted on viscous media employed in an LSCFB. Hence, studies on the distribution coefficient of a viscous media system, becomes interesting and important. The hydrodynamics of operation on varying inventory is also of significance in terms of scaling up production, variable loads etc. Therefore, an effort has been made to investigate the influence of different inventories on axial hydrodynamics, to study the effect of different viscosities on axial hydrodynamics and to analyze the distribution parameter C_o and slip velocity.

2. MATERIALS AND METHODS

A carefully analyzed, efficient design of an LSCFB was chosen, as shown in Fig. 1. Perspex tubing (acrylic) of 2m length and 8cm inner diameter acts as the riser column. The primary distributor is a set of 9 stainless steel standpipes, which occupy 23.76% of the bed area. The auxiliary distributor is a perforated steel plate of 72 perforations, each of 3mm diameter, which occupies 10.12% of the bed area. Liquid is pumped into the primary and the auxiliary distributor from a loft tank, using a centrifugal pump. The riser is attached with a solid-liquid separator on top, whose base is angled at 60^o, to facilitate easy flow of solids into the downcomer. This prevents accumulation of solids and the formation of dead spots. The downcomer collectively consists of a graduated scale, a butterfly valve, a solid storage vessel and a return leg that connects the downcomer to the bottom section of the riser.

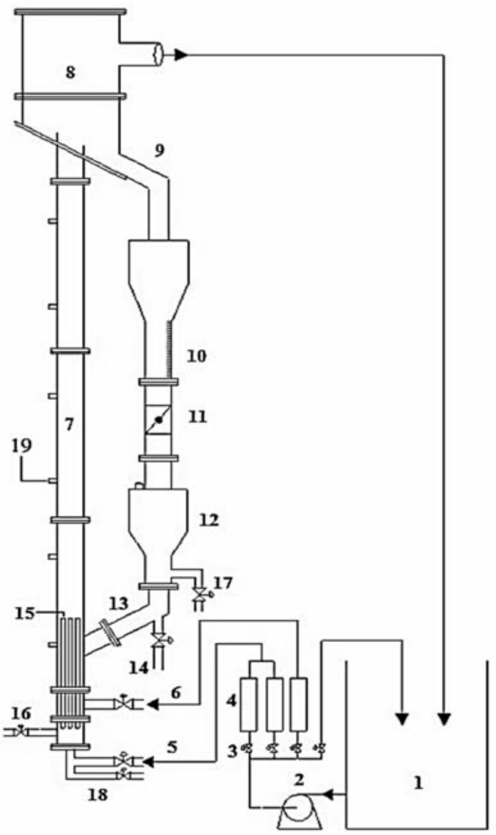

Fig. 1. Schematic diagram of the experimental setup. (1) Liquid reservoir; (2) Pump; (3) Valve; (4) Flow meter; (5) Primary Liquid Inlet; (6) Auxiliary Liquid Inlet; (7) Riser; (8) Liquid - solid Separator; (9) Solid Return Pipe; (10) Graduated Scale (mm); (11) Butterfly Valve; (12) Downcomer; (13) Return leg; (14)Solid Discharge; (15) Stand Pipe Distributors; (16) Air Inlet Provision; (17) Tertiary Liquid Inlet Provision; (18) Drain; (19) Pressure Tappings.

The experimental procedure is reported earlier in Nirmala *et al*., (2015). In each experiment, the pressures drops and the solid circulation rate are calculated. Initially, the riser column is filled with solid particles up to a calculated inventory height and the fluidizing liquid is pumped into the column. The required readings of pressure and circulation rate are recorded for various primary velocities above the critical transitional velocity of the particle, at a constant auxiliary velocity. This procedure is repeated for different auxiliary velocities.

Solid circulation rate is calculated by shutting the butterfly valve that is fixed below the graduated scale in the downcomer region and finding the time taken for the solid beads to accumulate over a predefined length. This procedure is repeated 2-4 times, for concurrent readings.

The pressure gradient is calculated by finding the pressures at six equidistant locations along the riser's length. Solid holdup is then calculated from the pressure gradient using equations (1.1-1.3). The solid flux calculated is the superficial solid velocity obtained, using equation (2). Slip velocity is another important hydrodynamic property, calculated using equation (3).

$$-\frac{\Delta P}{\Delta Z} = (1-\varepsilon)(\rho_s - \rho_l)g \tag{1.1}$$

$$\varepsilon_s + \varepsilon_l = 1 \tag{1.2}$$

$$\varepsilon_s = \frac{h}{\Delta z}\frac{(\rho_m - \rho_l)}{(\rho_s - \rho_l)} \tag{1.3}$$

$$G_s = \frac{w_s}{A} \tag{2}$$

$$V_{slip} = \frac{U_l}{\varepsilon_l} - \frac{U_s}{\varepsilon_s} \tag{3}$$

Experiments have been carried out by varying the inventory height of the solid particles, the viscosity of fluidizing medium and the auxiliary liquid velocity. Solid particles used were glass beads of 1.2mm diameter and 2500kg/m^3 density. The viscosity of the fluid used was measured using Haake viscometer 550. The physical properties of the liquid and its operating ranges used in present study are shown in Table 1 and 2. The minimum fluidizing velocity U_{mf} and terminal velocity U_t of the particle are estimated using equations 4 to 6 as given by Kunni and Levenspiel (1991).

$$U_{mf} = \frac{\mu_l}{d_p \rho_l}\left[\left(33.7^2 + 0.0408 Ar\right)^{1/2} - 33.7\right] \tag{4}$$

$$u_t = \left[\frac{4 d_p (\rho_s - \rho_g) g}{3 \rho_g C_D}\right]^{1/2} \tag{5}$$

where C_D is given by,

$$C_D = \frac{24}{\mathrm{Re}_p} + 3.3643\,\mathrm{Re}_p^{0.3471} + \frac{0.4607\,\mathrm{Re}_p}{\mathrm{Re}_p + 2682.5} \tag{6}$$

The physical properties of the fluidizing liquid and the range of variables under study have been tabulated in tables 1 and 2 respectively.

Table 1 Physical properties of the fluidizing liquid

Variable Name (Units)	Operating Range
Primary liquid velocity (m/s)	0.3177-0.1243
Auxiliary liquid velocity (m/s)	0.1326-0.0884
Total liquid velocity (m/s)	0.4365-0.2127
Inventory heights (cm)	15
	25
	35

3. RESULTS AND DISCUSSION

In the LSCFB, fluidization was controlled by varying primary and auxiliary liquid flow rate. When the third method of operation was implemented as suggested by Vidyasagar *et al*., (2009), initially as primary velocity was increased, particulate fluidization was observed. Further, at higher velocities, the solid particles were entrained in the liquid, indicating a fully developed circulating fluidization regime. At this point of entrainment, auxiliary liquid was introduced. This gave the added force for the solids to reach the mouth of the primary standpipe, from the secondary distributor and return leg inlet area. The total superficial liquid velocity inside the riser is the sum of both primary and secondary velocities. Also, the solid circulation rate being referred to in the text is superficial solid flux, i.e., the total mass flow rate of solids per unit cross sectional area of the riser.

Table 2 Range of variables under study

Fluidising Liquid	Density (kg/m^3)	Viscosity (cP)	Terminal Velocity (m/s)
Water	996.58	0.892	0.19559
10 vol% aq. Glycerol	1029.4	1.220	0.17204
20 vol% aq. Glycerol	1060.4	1.73	0.14946

3.1 Axial Solid Holdup

Pressure drop in the riser is caused primarily due to solid acceleration, column wall friction and friction caused by solid - liquid interaction. Since the fluidization velocity is not very high and the solid acceleration is smooth, the pressure drop due to solid acceleration and wall friction are not significant in the riser of the liquid circulating system. Hence, the wall effect is neglected and the solid holdup is measured by noting the pressure gradient at different locations along the riser. At steady state, the pressure drop is measured at six different locations 0.45; 0.75; 1.05; 1.35; 1.65 and 1.95m from the auxiliary distributor, along the riser using a multi limb manometer. Solid holdup, ε_s at h = 0.6m is obtained from pressure drop measured between 0.45m and 0.75m from the auxiliary distributor plate. This gives volume average of solid holdup at h = 0.6m. Similar estimation holds for other locations also. The first section which is located at 0.3m to the primary distributor is omitted due to large fluctuations in pressure drop. Average solid holdup is calculated between the lengths 0.6m and 1.8m along the riser.

It can be seen from fig. 2 and fig. 3, that the axial solid holdup is uniform for water and other viscous liquids throughout the riser, for different inventories. It is also noticeable that at a given constant secondary velocity, solid holdup decreases with increase in primary velocity. It is noted that there exists a similar flow structure in the axial distribution of solid holdup at every section of the riser, for the given primary velocity. Vidyasagar *et al*., (2009), Zheng *et al*., (1999), Liang *et al*., (1997) have also reported a similar axial distribution along the riser. An increase in axial solid holdup, with increase in auxiliary velocity can also be observed, suggesting high significance of the non-mechanical valve combination, with respect to the amount of solids held up axially in the riser.

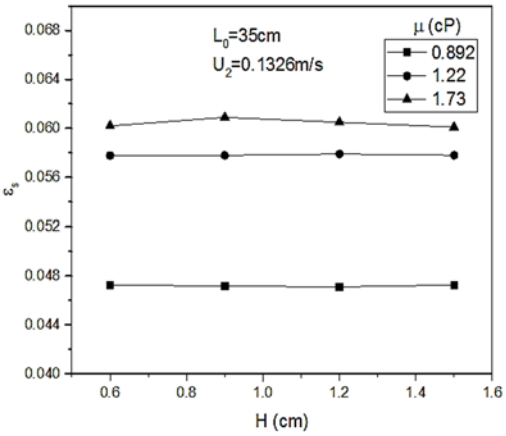

Fig. 2. Effect of viscosity on axial solid holdup (inventory: 35cm; auxiliary velocity: 0.1326m/s).

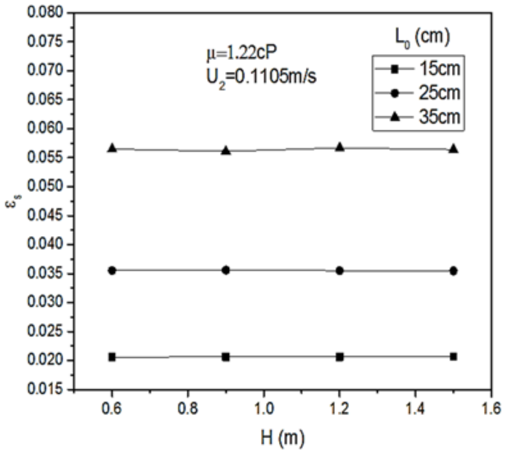

Fig. 3. Effect of inventory on axial solid holdup (viscosity: 1.22cP; auxiliary velocity: 0.1105m/s).

At constant auxiliary velocity, solid holdup at axial positions is found to increase with increase in liquid viscosity. This phenomenon can be explained by considering the fact that the terminal velocity of the solid particle decreases with increase in liquid viscosity, which implies that the solids tend to reach the transitional velocity earlier. The results obtained are in accordance with the previously reported data by Nirmala *et al*., (2014).

3.2 Average Solid Holdup

The average solid holdup in the riser is the average of all the local (axial) solid holdups, which are obtained from pressure drop measurements. Fig. 4 and Fig. 5 depict the variation in average solid holdup with total superficial velocities at a specific viscosity and inventory, respectively.

In general, it can be noted that there is a steep drop in the solid holdup curve for lower values of the total velocity and a more gradual drop is observed for slightly higher values of the total velocity. This may be due to the reduced average residence time of particles at higher particle velocity, which in turn reduces the average solid holdup at a particular axial point. Similar to axial solid holdup, an increase in average solid holdup has been observed with increase in auxiliary velocity. It was also observed that the variation of solid holdup shows a similar trend for all viscosities and inventories. In the riser, the two regions, viz., the developing flow region and the fully developed flow region was easily notable. In the developing flow region, located at the lower portion of the riser, solid acceleration along with a decrease in holdup was evident. At higher total velocity, solid holdup plateaus, which indicates that the solid flow enters into the fully developed zone, and was consistent to the results reported in earlier studies (Liang *et al*., 1997; Zheng *et al*., 1999; Natarajan *et al*., 2008; Vidyasagar *et al*., 2009).

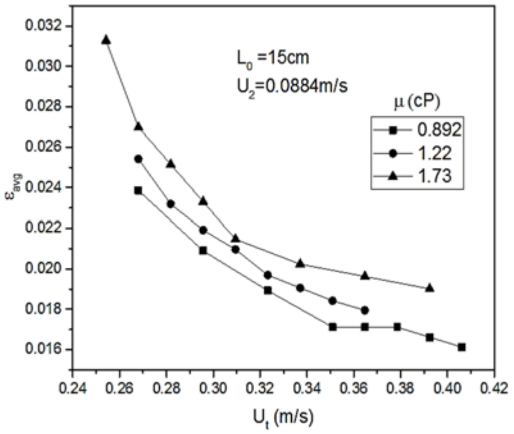

Fig. 4. Effect of viscosity on average solid holdup (inventory: 15cm; auxiliary velocity: 0.0884m/s).

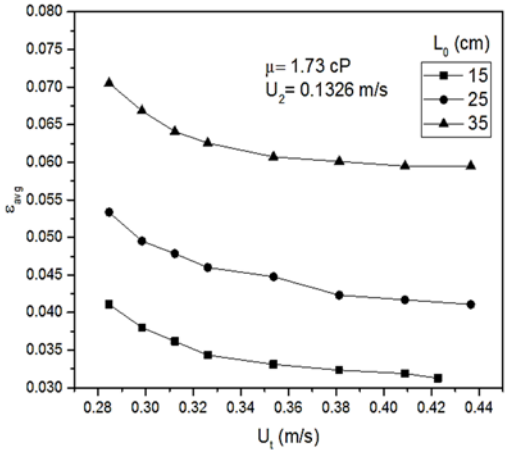

Fig. 5. Effect of inventory on average solid holdup (viscosity: 1.73cP; auxiliary velocity: 0.1326m/s).

3.2.1 Effect of Viscosity on Average Solid Holdup

It is worth noting from Fig. 4 that, with increase in viscosity, solid holdup is found to increase. This may be attributed to the fact that primary velocity dominates the auxiliary velocity, which is responsible for the entrainment of more solids out of the riser and hence less solid holdup is observed for low viscous medium.

3.2.2 Effect of Inventory on Average Solid Holdup

From Fig. 5 it is easily observable that with increase in inventory, solid holdup drastically increases. The margin of difference in ranges of solid holdup is very high. This trend is due to the fact that an increased inventory increases the amount of solids distributed in the riser section. The trend remains unaltered even with change in viscosity or auxiliary velocity

3.3 Solid Circulation Rate

The experimental study on solid circulation rate was conducted by varying liquid velocity, inventory of solids and the fluid medium used for fluidization. All the results produced from the data analysis are in graphical form, signifying the variation of solid flux, G_s (kg/m^{2}s) with total velocity, U_t (m/s). While operated at a particular inventory, the solid circulation rate is not an independent variable and depends on the fluid flow, the total solid inventory, flow resistances and the carrying capacity of the system as reported by Beruti *et al*., (1995) and Roy *et al*., (2001). And, it is of prime importance to know the solid circulation rate because it determines the fluid - solid contact times and the performance of the riser, as a reactor.

The specific plots are so chosen from the collected data, so as to provide a complete understanding of variation of solid circulation rate with both viscosity and inventory.

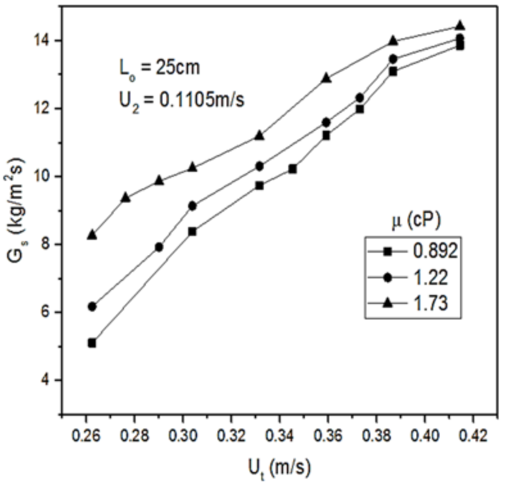

Fig. 6. Effect of viscosity on solid circulation rate (inventory: 25cm; auxiliary velocity: 0.1105m/s).

3.3.1 Effect of Viscosity on Solid Circulation Rate

The variation of solid flux with total velocity at a constant inventory and auxiliary velocity, varying only the viscosity of the fluid medium used for fluidization is shown in fig. 6. For this, water, a 10% glycerol solution and a 20% glycerol solution were used as the fluidizing medium. Solid flux is seen to increase with viscosity. This can be accounted to the fact that terminal settling velocity and hence critical transitional velocity, decreases with increase in viscosity. There is a rapid increase in solid flux initially, with total velocity, and this is followed by a plateaued region when fully developed flow is attained.

3.3.2 Effect of Inventory on Solid Circulation Rate

Fig. 7 represents the variation of solid flux with total velocity, at a constant viscosity and auxiliary velocity, varying only the inventory height of solids. These figures give us an accurate rendering of an easily understandable concept that, with increase in initial solid inventory, the solid flux increases. The amount of solids in a cross sectional area per unit time, is increased with increase in solid inventory.

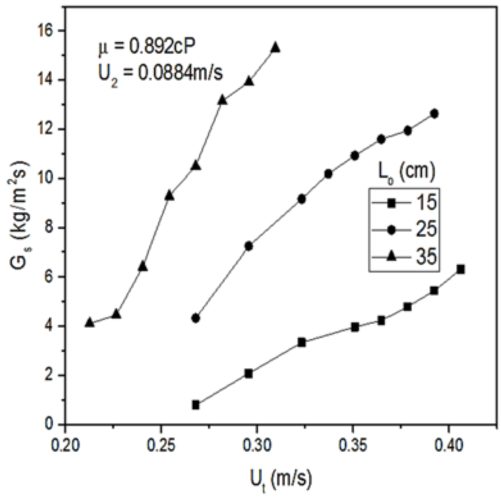

Fig. 7. Effect of inventory on solid circulation rate (viscosity: 0.892cP; auxiliary velocity: 0.0884m/s).

3.4 Slip Velocity

Slip velocity is another important hydrodynamic parameter in multiphase flow, which is the measure of the relative flow between the solid and liquid phase. The experimental slip velocity is calculated using equation (3).

3.4.1 Effect of Viscosity on Slip Velocity

A decrease in slip velocity has been observed with increase in viscosity from fig. 8, which is a plot between slip velocity and total liquid velocity. The graph has been mapped for a constant initial inventory of 15cm and auxiliary velocity of 0.1105m/s. The result obtained can be explained by taking into consideration the viscous effects of the fluidizing liquid and also the frictional forces which tend to retard the liquid flow.

3.4.2 Effect of Inventory on Slip Velocity

Effect of inventory on slip velocity can be comprehended by plotting a graph between slip velocity and total fluidizing liquid velocity, keeping viscosity, auxiliary velocity and other variables constant. From fig. 9, we can observe that an increase in inventory has an inverse effect on slip velocity. This phenomenon can be explained by considering the fact that, with an increase in inventory, the relative motion between the liquid and the solid particles decreases due to the increase in solid particles. A higher volume of liquid is observed in the no-slip and boundary area, thus giving rise to a reduced overall liquid velocity. This affects slip velocity, directly. Also, due to the increase in effects of physical factors such as friction on the flowing liquid in the solid-liquid interaction zone, the dip in slip velocity values with increase in solid inventory, can be explained.

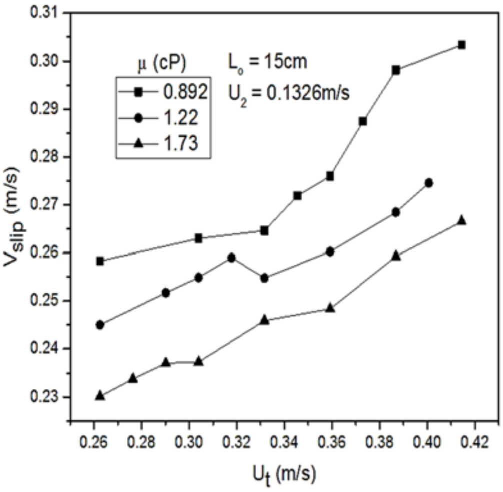

Fig. 8. Effect of viscosity on slip velocity (inventory: 15cm; auxiliary velocity: 0.1105m/s).

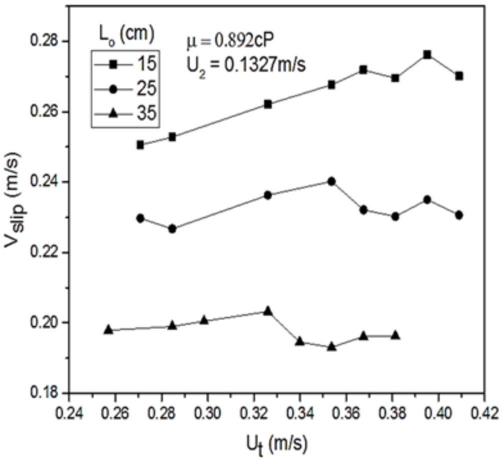

Fig. 9. Effect of inventory on slip velocity (viscosity: 0.892cP; auxiliary velocity: 0.1327m/s).

3.5 Distribution Parameter (C_o)

The distribution parameter, C_o was coined by Zuber and Findley (1965) to explain the non-uniformity observed in multi-phase flow. This parameter was first used to analyze the radial non-uniformity in an LSCFB by Natarajan *et al*., (2008b).

Mathematically, C_o is calculated using the equation (4).

$$C_o = \frac{(\varepsilon_{s.}.j)}{(\varepsilon_s).(j)} \tag{4}$$

C_o values less than unity have been observed for all the inventories, implying radial non uniformity. From fig. 10, we can observe an increase in C_o values with increase in both viscosity and inventory, suggesting a tendency to move towards uniformity.

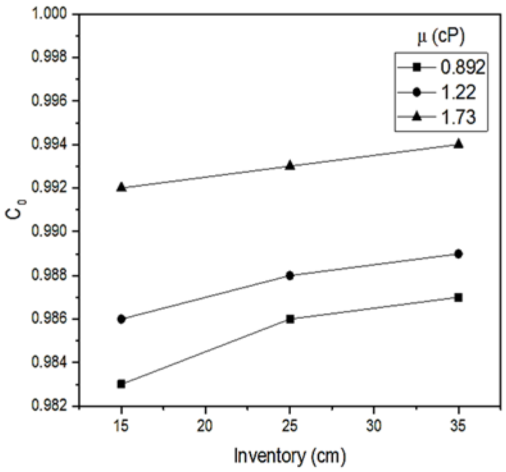

Fig. 10. Variation in C_o with inventory, at different viscosities.

3.6 Empirical Equation

Even though several research studies have been reported on LSCFBs (Natarajan *et al*., (2008), Basavarao *et al*., (2007) and Zheng *et al*., (2000)), the availability of relations to estimate the average solid holdup for viscous liquids are limited. Vidyasagar *et al*., (2011) and Chan *et al*., (2003) has reported solid holdup for viscous fluids apart from water. Vidyasagar *et al*., (2011) proposed a correlation that includes primary and auxiliary velocities, both in dimensional and dimensionless form, to calculate average solid holdup in terms of solid inventory and liquid viscosity. The solid holdup for viscous solutions in an LSCFB is controlled by the operating variables, i.e. primary liquid velocity, auxiliary liquid velocity, solid inventory, density and viscosity of a flowing liquid. Hence a new empirical correlation is proposed in the present study to estimate average solid holdup in terms of input operating variables. This is a dimensionless number which includes particle characteristics and flowing liquid viscosity.

Using the experimental data, average solid holdup is correlated to be equation (5).

$$\varepsilon_{avg} = Ar^{-0.1060}\left(\frac{U_1}{U_t}\right)^{-0.4963}\left(\frac{U_2}{U_t}\right)^{0.3481}\left(\frac{L_0}{L_{riser}}\right)^{0.9612}\left(\frac{\mu}{\mu_w}\right)^{0.1001}\left(\frac{\rho}{\rho_w}\right)^{1.3008} \tag{7}$$

A comparison between the mathematical and the experimental values has been graphically represented in Fig. 11. A regression fit of 95.6% has been achieved with this equation.

This empirical equation is valid for the variable ranges of:

$0.1243\ m/s \le U_1 \le 0.3177\ m/s$

$0.1326\ m/s \le U_2 \le 0.0884\ m/s$

$0.15\ m \le L_o \le 0.35\ m$

$0.00089\ Pa.s \le \mu \le 0.0017313\ Pa.s$

$996\ kg/m^3 \le \rho \le 1060.2\ kg/m^3$

Fig. 11. Comparison of experimental and predicted average solid holdup values

4. CONCLUSIONS

Effect of viscosity and inventory on the hydrodynamic properties of an LSCFB have been studied. From the observations noted above, we can conclude that.

- Axial holdup is uniform throughout the riser and it is found to increase with increase in viscosity and inventory.
- Average solid holdup decreases rapidly with increase in liquid flow rate, for low liquid velocities and then a sedated decrease is observed, for higher liquid flow rates. Higher values of average holdup have been observed for higher viscosity and inventory.
- Solid flux increases with increase in viscosity and inventory.
- Slip velocity is found to decrease with increase in viscosity and inventory.
- An increase in distribution parameter has been observed with increase in both inventory and viscosity, suggesting a tendency to move towards uniformity with increase in both the variable parameters.
- An empirical equation with regression fit of 95.6% has been formulated by taking into consideration the dimensionless property of average solid holdup.

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