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Effect of Inventory Change in a Liquid – Solid Circulating Fluidized Bed (LSCFB)

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Abstract:
Circulating fluidized beds (CFB) play a major role in the chemical industry especially as heterogeneous catalytic reactors. Research on hydrodynamic properties of Liquid – Solid CFBs (LSCFB) is significantly under-reported as compared to Gas – Solid CFBs (GSCFB). Steadily, prominent research is being established in fields like food industry (whey protein recovery), waste management (removal of heavy metals from radioactive wastes) and others, which use LSCFBs. In this context, it is important to have significant knowledge about the changes occurring in hydrodynamic properties like solid hold-up, rate of solid circulation etc., on changing certain critical physical properties such as inventory height. An LSCFB of height 2.95 m and riser outer diameter 0.1 m was chosen and the effect of inventory height on the properties was studied by taking the initial inventory heights as 15 cm, 25 cm and 35 cm. The hydrodynamic studies concentrated on axial solid holdup, average solid holdup, solid circulation rate and slip velocity. On increasing the inventory, uniformity of axial solid holdup was confirmed along with studying holdup patterns. Solid flux was seen to follow an inverse relationship to holdup, as expected. The change in slip velocity with varying inventory was also checked, and was found to decrease with inventory. The distribution parameter, C_o of the drift flux model was used to determine the extent of non-uniformity in solid distribution. C_o was calculated to be less than unity in the range of 0.983–0.994, suggesting non-uniformity in solid distribution, with higher solid concentration by the walls compared to the core.

Keywords: LSCFB, inventory, axial solid holdup, slip velocity, solid circulation rate

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1 Introduction

Since the commissioning of fluidization as a field of science, research in this area has been profound and extensive. The basic idea of fluidization conceptualized by Richardson and Zaki [1] now finds applications in many fields owing to some of its notable advantages during operation, like high heat and mass transfer rate, near ideal behaviour and easy handling [2]. Implementation of these concepts to fluidized bed reactors has given rise to the development of circulating fluidized beds which recirculate the solids within the system, essentially improving its efficiency.

Liquid-solid circulating fluidized beds (LSCFBs) use a liquid medium to fluidize solid particles, which upon entraining are separated from the liquid by passing through a separating device such as a cyclone separator to be directed through the down comer section back to the foot of the main fluidizing part of the system known as the riser. LSCFBs have found applications in many fields including food, hazardous waste management and municipal waste management industries. Research work published in these above mentioned fields particularly focus on Biological Nutrient Removal (BNR) from landfill leachate [3], removal of Cesium from highly radioactive waste [4], removal of biological nutrients from municipal waste water [5, 6] and continuous protein recovery [7, 8].

With an increase in applications of LSCFBs it is important to understand the hydrodynamics of the system in order to improve its efficiency. Hydrodynamic properties such as solid hold up, solid circulation rate, slip velocity and radial distribution coefficient C_o constitute some of the basic properties and since solid inventory is a major factor that affects the change in these hydrodynamic properties, an effort has been made to learn its effects on the system.

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2 Methods and materials

A 2.95 m long LSCFB was designed with Perspex tubing of inner diameter 8 cm as the riser column and 2 m as the riser height, taking into consideration the volumetric flow requirements of the experiment, as shown in Figure 1. A solid-liquid separator was placed above the riser column. To prevent the formation of solid dead spots, this separator was angled at 60°. Thus ensuring a smooth flow of solid particles to the downcomer, which in turn is designed to be parallel to the riser column. The combination of a butterfly valve and a graduated scale on the downcomer, allows the obstruction of solid flow and the reading of solid accumulation, respectively. At the lower end of the column, the primary distributor housed 9 stainless steel standpipes, occupying 23.76 % of the total bed area. Below the primary distributor, a perforated steel plate with 72 circular perforations, each 3 mm in diameter, acted as the auxiliary distributor. This occupied 10.12 % of the total bed area. A centrifugal pump was used to pump the water from a loft tank placed close to the rotameter system.

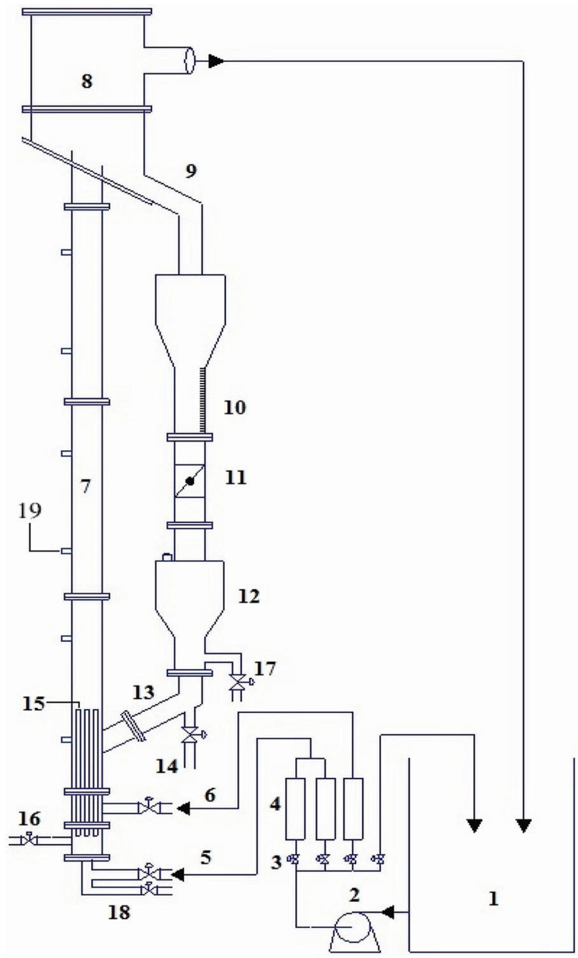

Figure 1: Schematic diagram of the experimental setup. (1) Liquid reservoir; (2) Pump; (3) Valve; (4) Flow meter; (5) Primary Liquid Inlet; (6) Auxiliary Liquid Inlet; (7) Riser; (8) Liquid – solid Separator; (9) Solid Return Pipe; (10) Graduated Scale (mm); (11) Butterfly Valve; (12) Downcomer; (13)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

Depending on the stage of experimentation, solid inventory of a calculated height is filled at the base of the riser column. The solids are then fluidised by 20 % (v/v) of aqueous glycerol from the loft tank, at velocities higher than the critical transition velocity. The primary velocity is varied at a constant auxiliary velocity using the calibrated rotameter. The pressure drop and solid circulation readings are calculated for every primary velocity. The above procedure is then repeated for altered auxiliary velocities.

Pressure tapping's are present along the riser column at six equidistant points. The pressures along these points are noted using a multi-limb manometer system which is connected to these tappings. Solid holdup is then calculated using eqs (1)–(3). The combination of the butterfly valve and graduated scale is used to calculate the solid circulation rate for a particular combination of primary and auxiliary velocities, by calculating the time taken for solids to accumulate a predefined length of the graduated scale when the butterfly valve is shut. For concurrent readings, the procedure is repeated 2–3 times. Using eq. (4), the solid flux is calculated. Slip velocity being another important parameter, is calculated using eq. (5).

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

$$\varepsilon_s + \varepsilon_l = 1 \tag{2}$$

$$\varepsilon_s = \frac{h}{\Delta z}\frac{(\rho_m - \rho_l)}{(\rho_s - \rho_l)} \tag{3}$$

$$G_s = \frac{w_s}{A} \tag{4}$$

$$V_{slip} = \frac{U_l}{\varepsilon_l} - \frac{U_s}{\varepsilon_s} \tag{5}$$

Experiments have been conducted by pumping aq. Glycerol solution in combinations of different primary and auxiliary velocities on varying heights of solid inventory. Glass beads of 1.2 mm diameter and 2500 kg/m^3 density were used as the solid particles in the LSCFB. The physical properties of the materials and medium in the system are tabulated in Table 1 along with the range of variables used, in Table 2.

Table 1: Physical properties of the fluidizing liquid.

Fluidizing liquid	Density (kg/m^3)	Viscosity (cP)	Terminal velocity (m/s)
20 vol% aq. Glycerol	1060.4	1.73	0.14946

Table 2: Range of variables under study.

Variable name (Units)	Operating range
Primary liquid velocity (m/s)	0.3177–0.1243
Auxiliary liquid velocity (m/s)	0.1326
Total liquid velocity (m/s)	0.4365–0.2127
Inventory heights (cm)	15 25 35

Table 3: C_o values for different inventories with 20% Glycerol (v/v).

Liquid	Inventory	C_o
20% Glycerol (v/v)	15 cm 25 cm 35 cm	0.992 0.993 0.994

3 Results and discussions

Fluidization was controlled by changing primary and auxiliary liquid flow rate in the experimental LSCFB column. Vidyasagar et al. [9], elaborated three modes of operation of a LSCFB. It was found that, the third mode was more stable than the other two modes. Hence a similar strategy was followed in the study. In this, 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, hence giving 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 the primary and the 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.

3.1 Axial solid holdup

In the riser, pressure drop is caused primarily due to solid acceleration, column wall friction and friction caused by solid – liquid interaction. Owing to the not so high fluidization velocity and smooth solid acceleration, 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 calculated from eqs (1–3), by noting the pressure gradient at different locations along the riser.

The solid holdups along the riser were calculated for different inventories and have been plotted in Figure 2. It can be seen from Figure 2 that the axial solid holdup is uniform throughout the riser, for different inventories and there exists a similar flow structure in the axial distribution of solid holdup at every section of the riser, for the given primary velocity. Zheng et al. [10], Liang et al. [11], Vidyasagar et al. [9], Gnanasundaram et al. [12] etc., 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.

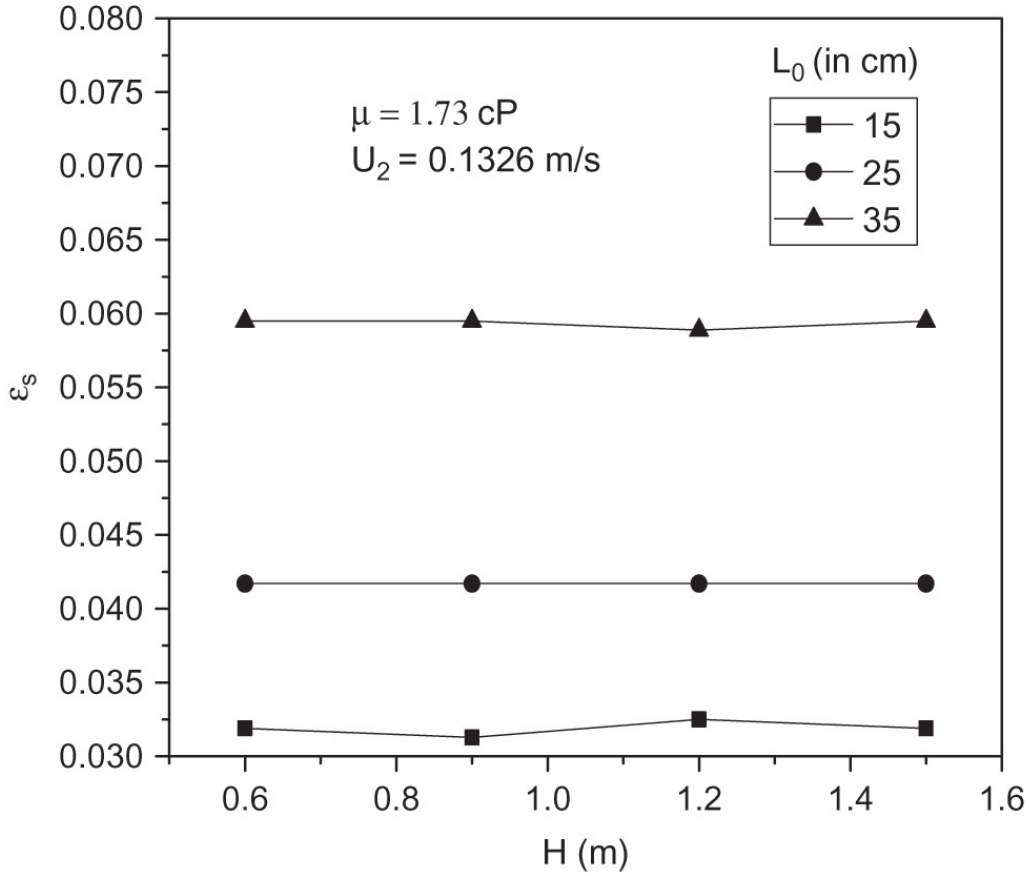

Figure 2: Effect of inventory on axial solid holdup (viscosity: 1.22 cP; auxiliary velocity: 0.1105 m/s).

3.2 Average solid holdup

Figure 3 depicts the variation in average solid holdup (average of all the axial solid holdups, which are obtained from pressure drop measurements) with total superficial velocities, at a specific viscosity and inventory.

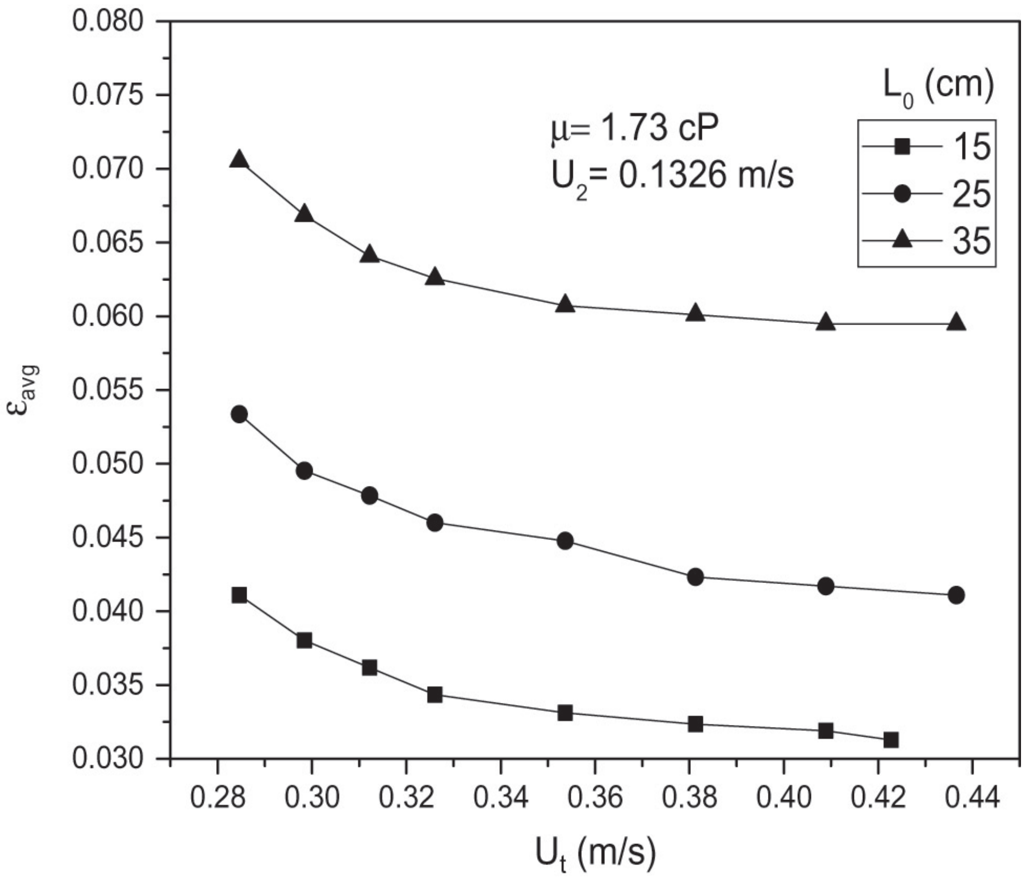

Figure 3: Effect of inventory on average solid holdup (viscosity: 1.73 cP; auxiliary velocity: 0.1326 m/s).

It can be observed that there is a steep drop in the solid holdup for lower values of the total velocity and a more gradual drop is noted for slightly higher values of the total velocity, in general. This can be owed 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 notable that the variation of solid holdup shows a similar trend for inventories.

Two regions, viz., the developing flow region and the fully developed flow region was noticeable in the riser. 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 shows that the solid flow enters into the fully developed zone, and was consistent to the results reported in earlier studies [9, 11–13].

3.2.1 Effect of inventory on average solid holdup

Also, from Figure 3, it is easily notable that with increase in inventory, solid holdup considerably 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 auxiliary velocity.

3.3 Solid circulation rate

The experimental study on solid circulation rate was carried out by varying liquid velocity and inventory of solids used for fluidization. All the results produced from the data analysis are in graphical form. It shows the variation of solid flux, G_s (kg/m^{2}s) with total velocity, U_t (m/s). Solid circulation rate is an important parameter of study, as it helps determine the performance of the riser, as a reactor. As a general expected trend, it can be noticed that with increase in total superficial velocity, solid circulation increases almost linearly.

3.3.1 Effect of inventory on solid circulation rate

Variation of solid flux with total velocity, at a constant viscosity and auxiliary velocity, varying only the inventory height of solids is represented in Figure 4. This figure gives 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.

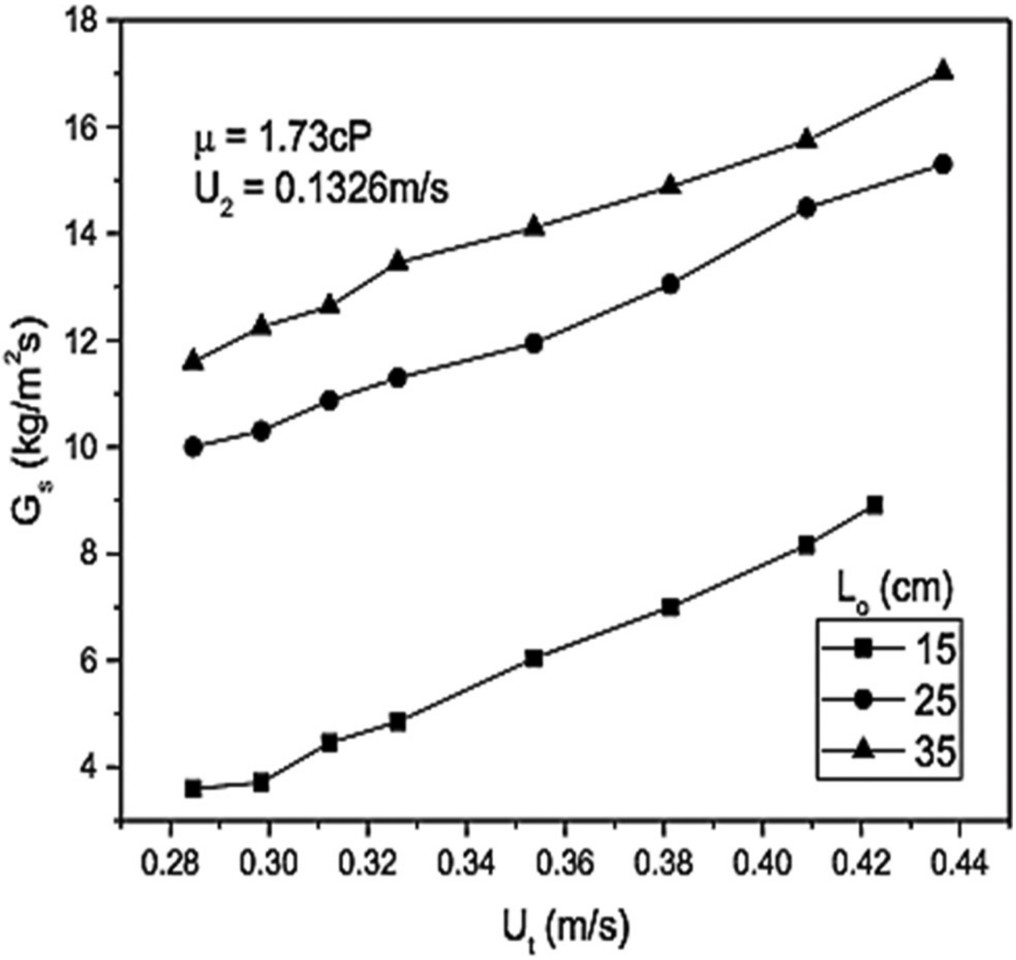

Figure 4: Effect of inventory on solid circulation rate (viscosity: 1.73cP; auxiliary velocity: 0.1326 m/s).

3.4 Slip velocity

Effects of inventory change on slip velocity are an important factor, which has been fairly under reported. The relative motion between the solid and liquid phase, known as the slip velocity is another essential hydrodynamic parameter, which is calculated using eq. (5).

3.4.1 Effect of inventory on slip velocity

An inverse relationship between inventory and slip velocity can be noticed from Figure 5, which has been graphed by keeping other possible variables like viscosity, auxiliary velocity, as constants. The observation can be explained by considering the fact that an increased volume of liquid moves into the no-slip and boundary area, thus eventually reducing the relative velocity between the mediums. Also, frictional effects play a major role in reducing the liquid velocity, in the solid- liquid interaction zone thus reducing the slip velocity, eventually.

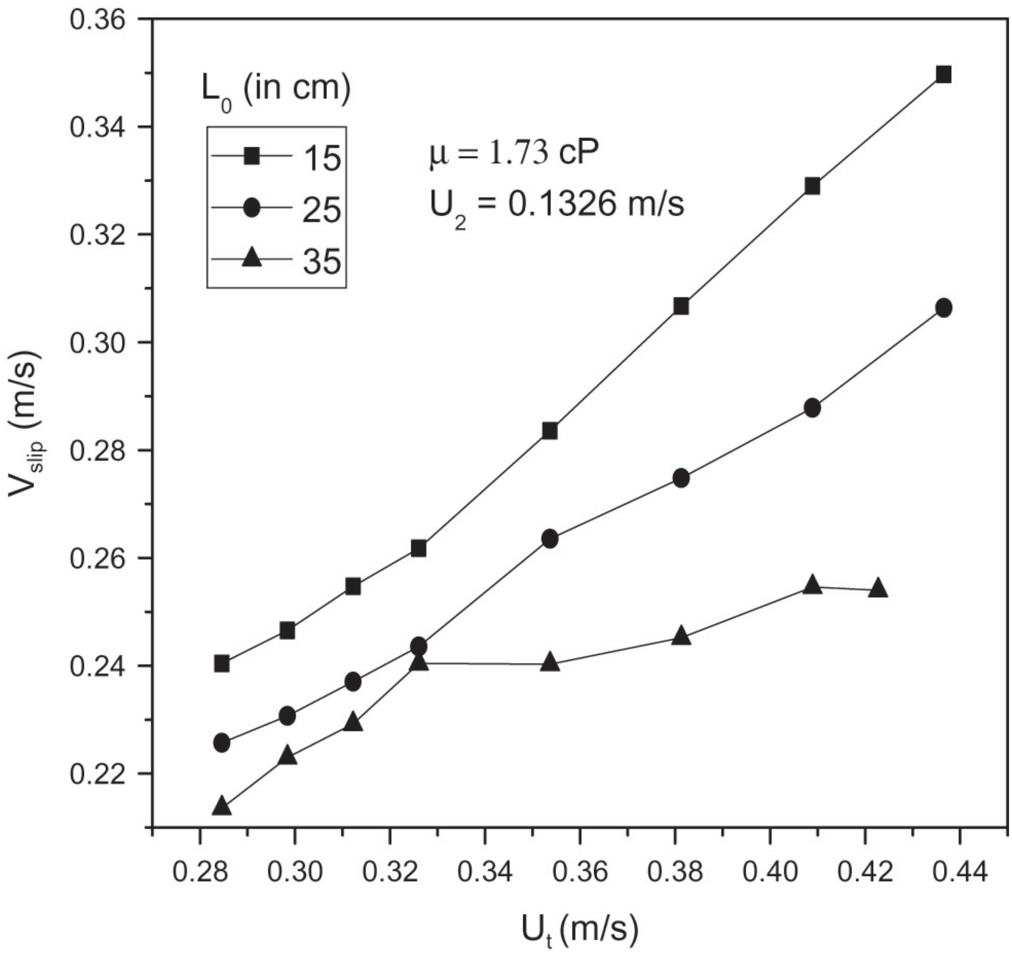

Figure 5: Effect of inventory on slip velocity (viscosity: 1.73cP; auxiliary velocity: 0.1326 m/s).

3.5 Distribution parameter (C_o)

The distribution parameter, C_o is a useful parameter for analyzing the non-uniform behaviour of the solid inventory in an LSCFB, first used by Natarajan et al. [14]. C_o is calculated using the eq. (6) and is presented in Table 3. It can be noted that in all cases, C_o Parameter is less than 1, confirming radial non uniformity. At the same time, it can be observed that the parameter value is gradually approaching towards 1, ie. a tendancy to approach uniformity, with increase in inentory.

$$C_0 = \frac{(\varepsilon_s.j)}{(\varepsilon_s).(j)} \tag{6}$$

4 Conclusions

The effects of inventory on the hydrodynamic properties of the LSCFB have been studied and suitable conclusions have been drawn. Uniformity in solid holdup at axial points has been validated and the values determined, increased with increase in inventory retaining the uniform behaviour. The average solid holdup was observed to drop rapidly as the liquid flow rate increased for lower liquid velocities, which was followed by a gradual decrease for higher liquid flow rates. A direct relation between solid inventory and average solid holdup can be noted. A direct relation between solid flux and inventory has been found and an expected inverse relationship between solid inventory and slip velocity is another interesting observation to be recorded. Distribution parameter, used to study radial behaviour of solid particles is found to increase with inventory, suggesting a tendency to radial uniformity as well.

Nomenclature

A: Cross sectional area of the measuring cylinder (m^2)

$C_{o:}$ Distribution parameter of drift-flux model (–)

G: Acceleration due to gravity (m/s^2)

$G_{s:}$ Solid circulation flux (kg/m^2s)

H: Height of pressure tapping (m)

j Superficial velocity of two phase mixtures ($U_s + U_l$) (m/s)

L_o Inventory height (cm)

T Time taken for the solids to accumulate over a height Hcm (s)

U_1 Primary liquid velocity (m/s)

U_2 Auxiliary (secondary) liquid velocity (m/s)

U_l Total liquid velocity ($U_1 + U_2$)

U_s Superficial solid velocity (m/s)

V_{slip} Slip velocity (m/s)

w_s Solid circulation rate (kg/s)

Greek symbols

ΔP: Pressure drop in axial position (Pa)

Δz: Position of the pressure tapping from the riser base (m)

E: Average void fraction (–)

$\varepsilon_{l:}$ Void fraction (–)

$\varepsilon_{s:}$ Solid holdup (–)

μ Liquid viscosity (cP)

μ_w Viscosity of water (cP)

ρ_l Liquid density (kg/m^3)

ρ_s Particle density (kg/m^3)

ρ_m Manometric fluid density (kg/m^3)

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