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ORIGINAL ARTICLE

Solid holdup in liquid solid circulating fluidized bed with viscous liquid medium

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Abstract Average solid holdup in the axial direction was investigated in a liquid solid circulating fluidized bed riser (LSCFB), with liquids of different viscosities. The effect of operating parameters including; primary, secondary and total velocity, particle diameter and density was studied. Experiments were conducted using water and glycerol at different concentration having viscosities in the range 1–1.36 cp. The results indicated that the solid holdup in the riser was axially uniform for viscous liquids and increases with increase in auxiliary velocity. The average solid holdup decreases with increase in total velocity and increases with increase in viscosity for sand–glycerol, glass bead–glycerol system. The experimental measurements were compared with the existing holdup model prediction that varied linearly with viscosity. Further, a correlation was developed to estimate average solid holdup in the riser, and the performance of the expression was compared with the present experimental data.

1. Introduction

In recent years there has been a considerable interest in the study of liquid solid circulating fluidized bed (LSCFB) operating at high velocity where particle entrainment is significant. To maintain the bed, it would be essential to separate the entrained particles and recirculate them through the bed where particle entrainment is significant. LSCFB have a number of attractive features which makes them suitable for processes where liquid and solid contacting is important. Effective solid liquid contacting, uniform temperature, accommodating different particulate materials with high liquid throughputs, less back mixing and improved heat transfer performance have shown to be of advantage in some chemical and bio process industries [1–3]. LSCFB find applications in wide variety of industrial processes such as production of linear alkyl benzene, continuous protein recovery from waste whey solutions, biological nutrient removal in municipal waste water and in the removal and recovery of cesium from liquid radioactive nuclear streams [4–6]. These processes generally involve a liquid phase reactant and a solid phase catalyst or adsorbent. Principal reactions or adsorption processes are conducted in a vertical riser column while regeneration of the deactivated

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Nomenclature

d_p	particle diameter (m)
g	acceleration due to gravity (m/s^2)
H	axial distance from bottom of the riser (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)
G_s	dimensionless solids circulations rate where $\overline{G}_s = \frac{G_s}{(\mu_l g \Delta\rho\rho_l)^{1/3}}$
$\overline{U}_1$	dimensionless superficial liquid velocity $\overline{U}_l = U_l(\rho^2/\mu_l g \Delta\rho)^{1/3}$
$\bar{d}_p$	dimensionless particle diameter $\bar{d}_p = d_p(\rho g \Delta\rho\rho_l/\mu_l^2)^{1/3}$
G_a	Galileo number ($dp^3\ g\rho l^2/\mu_l^2$)
J_a	superficial auxiliary liquid velocity (m/s)
J_f	superficial primary liquid velocity (m/s)
J_l	superficial total liquid velocity (m/s)
U_{l1}	primary or main liquid velocity (m/s)
U_{12}	secondary or auxiliary liquid velocity (m/s)
Lo	dimensionless superficial liquid velocity
$\Delta p/\Delta z$	static pressure gradient(Pa/m)

Greek symbols

ε_s	average solid holdup
ε_1	bed voidage
ℓs	density of solids (kg/m^3)
ℓl	density of liquids (kg/m^3)
ℓ_m	density of medium (kg/m^3)
μ_1	viscosity of water (cP)
$\Delta\rho$	density difference ($\rho_s - \rho_1$) (kg/m^3)

catalyst or desorption of adsorbents is performed in the down comer. The design and scale up of continuous liquid solid system requires the knowledge of the flow pattern, phase holdup and solid circulation rate.

In the liquid–solid circulating systems, particles tend to distribute uniformly in the axial direction of a riser except for heavier particle where non uniformity appears in the radial direction .It has been proved that lighter particle show a relatively flatter radial profile than the heavier particles. Refs. [7–10] characterized the microflow structure of LSCFB and compared with the fast fluidization in the gas solid circulating fluidized bed (CFB). The circulating fluidized bed regime was divided into initial and fully developed zone. However light particles always shows axial uniformity in flow structure, but heavy particles present non-uniformity in the initial zone of circulating fluidized bed. Liang et al. [11,12] conducted experiments to study the hydrodynamic variables in a liquid solid riser. Based on the experimental results with different particles, a flow regime map was proposed defining the dimensionless superficial liquid velocity and solid circulation rate and it was observed that circulating fluidized bed regime is characterized by non uniform radial distribution. Dynamic leak was noticed by Vidhyasagar et al. [13,14] at high liquid velocities when the primary liquid distributor is near to the solids feed pipe from the storage vessel and they also observed that the critical transitional velocity that demonstrates the expanded bed from CFB regime was to be different for different methods. The effect of operating parameter, particle density, particle diameter and the solid feed pipe diameter on the axial solid holdup distribution was analyzed [15,16].

Sang and Zhu [17] reported the effect of particle properties on solid holdup in the riser of LSCFB experimentally based on three parameters namely superficial liquid velocity, normalized superficial liquid velocity and the excess superficial liquid velocity and it was reported that excess superficial liquid velocity is more appropriate parameter to evaluate the effect of particle properties on the solid holdup. Roy et al. [24] simulated hydrodynamic features of a LSCFB using computational fluid dynamics using an Eulerian–Eulerian approach to deal with the two phase flow aspects to deal with the solid–fluid interaction. They proved that only a 3-dimensional calculation will be able to resolve the flow phenomena required to establish circulation such as the entrainment and carryover of the solids and the liquid solid separation at the top are non axis symmetric.

However mostly all investigations were carried out in LSCFB with tap 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 Vidhyasagar et al. [18]. The effect of liquid viscosity on the riser operated in variable inventory mode was studied by a few investigators with respect to solid behavior and flow structure [19,20,23]. There were few reports [19–21] available on the effect of viscosity on mixing, heat transfer, regime transition and radial solids distribution in the case of variable inventory mode of LSCFB. Viscous liquids are involved in industrial processes as processing fluids for many applications. LSCFB with viscous fluids has significant effect on determining the solid holdup of the system. The present objective is to examine the variables which control the solid holdup in the axial direction under wide range of operating conditions for liquids of varying viscosity. In addition the effects of liquid viscosity, flow rate, particle density on the solid holdup and there axial distribution were also studied. Suitable empirical correlation to represent the average solid holdup in the riser for different particles was developed.

2. Materials and methods

The LSCFB consisted of a riser column (diameter – 0.1 m; height – 2.4 m), liquid solid separator and down comer as shown in Fig. 1. The riser had pressure tapings at a regular interval of 0.150 m connected to multi limb manometer to measure the pressure drop in each section of the riser. The base of the riser has two distributors one for primary liquid flow and the other for auxiliary liquid flow into the riser. In the primary liquid distributor 11 stainless steel tubes of 14 mm extending into the riser were fixed uniformly to ensure uniform liquid distribution along the cross section of the riser occupies 18% of the total bed area. The auxiliary distribution has a porous plate which occupies 7.3% of the total cross sectional area and has a provision to insert the primary distributor tubes.

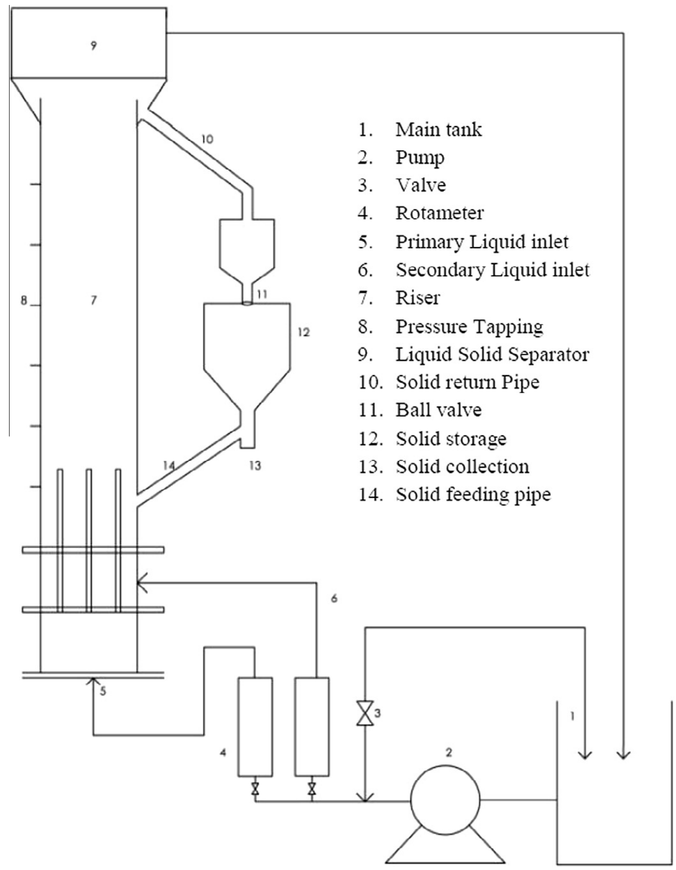

Figure 1 Schematic of the experimental setup LSCFB.

The end of the primary distributor tube is soldered with the mesh to avoid entry of solid particles inside the tube during operation and shutdown. The porous plate auxiliary distributor is wounded with a mesh to prevent solid flow into the distributor. The liquid and the solid flow rates were controlled independently by adjusting the main and auxiliary liquid flow rates. The auxiliary liquid stream controls the quantity of particles recirculating from the storage vessel in the riser. Additional liquid from the auxiliary distributor added to riser bottom causes more particles to enter into the riser and each flow rate was measured by a separate rotameter.

Particles from the riser bottom were carried to the top of the riser by the total liquid flow, (sum of primary and auxiliary liquid flow). The upper end of the riser projects 120 mm centrally into the liquid solid separator. Entrained particles were separated by a liquid solid separator at the riser top and returned to the storage vessel after being passed through solid flow rate measuring device. The Liquid leaves the liquid solid separator at the liquid outlet placed at the separator to the reservoir. In the solid circulation measuring section, the column was graduated along the length above the ball valve. During the operation when the ball valve was closed, it enabled the solid collected in the calibrated tube for a known height and the corresponding time was noted. The solid feeding pipe was joined to the riser well above the auxiliary liquid distributor and the other end was joined to the bottom of the conical section of the storage vessel.

In a typical experiment, riser column was packed with particles to a known height, primary liquid was admitted in to the column through flow meters at low intervals till the bed expands the entire length. When the solids were about to entrain from the top of the riser secondary liquid was introduced and circulation between riser and down comer starts. After attaining steady state, pressure drop along the length of riser and solid circulation rate was noted. Solid circulation rate was determined by closing the ball valve and the time involved to accumulate a definite height of solids above the valve was noted. The accumulated solid height in the tube and its weight which was precalibrated for each fluid–solid system, gives the weight of solid circulating per unit time. The experiments were continued at increasing primary liquid velocity until transport regime was reached keeping the secondary velocity constant. The same procedure is repeated for different constant secondary velocity by varying primary velocity. Experiments were conducted with two different particles of different sizes and density. The size and quantity of the particles were obtained by sieving and confirming to the standards. All experiments were carried out at ambient temperature. The solid holdup was calculated by noting the pressure gradient at different locations along the riser. Average solid holdup was determined for each measured section using Eq. (1). The effect of wall friction was neglected

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

where $\varepsilon_s + \varepsilon_l = 1$, sand with an average diameter of 0.5 mm and density of 2400 kg/m^3 and glass bead of average size 2 mm and density 2460 kg/m^3 were used as dispersed phase.

The materials are sieved in a standard screen and the average size fractions are chosen for experimental study. Tap water and aqueous glycerol were used as continuous phase. 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 Tables 1 and 2. The minimum fluidizing velocity U_{mf} and terminal velocity U_t of the particle are estimated using Eqs. (2)–(4) as given by Kunni and Levenspiel [25].

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

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

where C_D is given by

$$C_D = \frac{24}{\mathrm{Re}_p} + 3.3643\mathrm{Re}_p^{0.3471} + \frac{0.4607\mathrm{Re}_p}{\mathrm{Re}_p + 2682.5} \quad (4)$$

3. Results and discussion

The test section is made of acrylic and hence visual observation of liquid solid circulating fluidization was possible. At low liquid velocity particulate type fluidization was observed and at higher velocity the solid particles are entrained by the liquid into the fully developed regime. The experimental data of the present study covers a wide range of the average solid holdup ε_s, axial solid holdup $\varepsilon_{s,\mathrm{loc}}$ and solid velocity $U_{s.}$ All these parameters were controlled by adjusting the ratio of primary and secondary flow rate and hence auxiliary distributor and solid feeding pipe act as a non mechanical valve· The total liquid superficial velocity above the main distributor was the sum of primary and auxiliary velocity.

3.1. Axial solid holdup

3.1.1. Effect of auxiliary liquid velocity on axial solid holdup

The effect of axial solid holdup for different viscous solutions at four different locations along the length of the riser for glass bead–glycerol at 1.36 cP is shown in Figs. 2 and 3. It is observed that there exist a similar flow structure in the axial distribution of solid holdup at the lower section (H = 0.6 m), the middle section (0.9 m and 1.2 m), and the upper section (H = 1.5 m) of the riser for the given primary velocity. Previous researchers [9,11,14], have reported such axial distribution along the riser. It can also be observed that at every axial position solid holdup is found to increase with increase in auxiliary velocity as the movement of solids in the return pipe increases with increase in auxiliary velocity. For the given fluid with viscosity 1.36 cP and primary velocity (0.0494 m/s) the axial solid holdup is uniform for both solids: sand and glass bead. Further it is observed that there is a

Table 2 Range of variables covered in the present study.

Variable name	Range
Primary liquid velocity, m/s	0.02477–0.099 (Sand)
	0.1415–0.2689 (Glass bead)
Auxiliary liquid velocity, m/s	0.028–0.04954 (Sand)
	0.1061–0.1592(Glass bead)
Total liquid velocity, m/s	0.056–0.1415 (Sand)
	0.2476–0.4210 (Glass bead)
Viscosity of liquid, cP	0.892–1.36
Particle density	2400 (Sand)
	2490 (Glass bead)

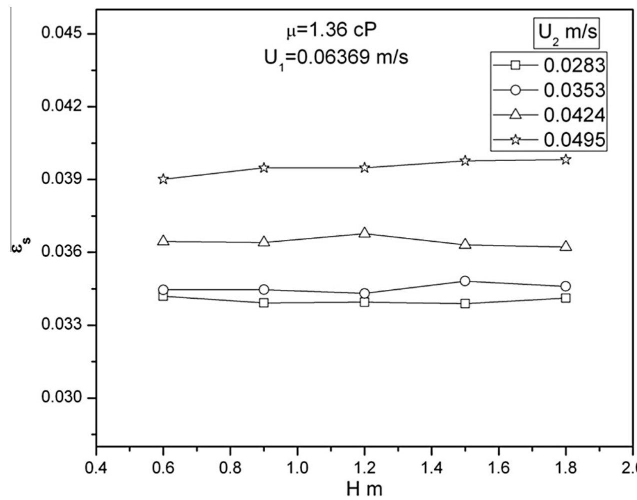

Figure 2 Effect of auxiliary velocity on axial solid holdup for sand–glycerol.

considerable height of dense phase at the bottom of test section for all operating conditions maintained in the test section. For heavy solid particles, the gravitational force is more predominant and particles have to accelerate initially so as to reach the fully developed regime since the contribution of drag is balanced by the gravitational component on the particles. As the density ratio $(\rho_s - \rho_l)/\rho_l > 1$, there exists accelerating or dense regime at the bottom of the test section. Figs. 2 and 3 also indicate the decrease in size or density of solids as in case of sand of density 2400 kg/m^3 and diameter 0.5 mm under given auxiliary velocity and total velocity increases the solid holdup in the riser. To obtain the required solid circulation rate and high solid holdup use of low size and density is required.

3.1.2. Effect of viscosity of liquid on axial holdup

Development of circulating bed regime is different for viscous fluids because of variation in critical transitional velocity;

Table 1 Physical property of the liquids and solids used in the present study.

S. no.	Fluidizing liquid	Density (kg/m^3)	Viscosity (cp)	Terminal velocity of particles (m/s)	
				Sand	Glass beads
1	Tap water	1000	1.000	0.0700	0.2919
2	5 vol% aqueous glycerol	1011	1.085	0.0675	0.2626
3	15 vol% aqueous glycerol	1036	1.360	0.0614	0.2562

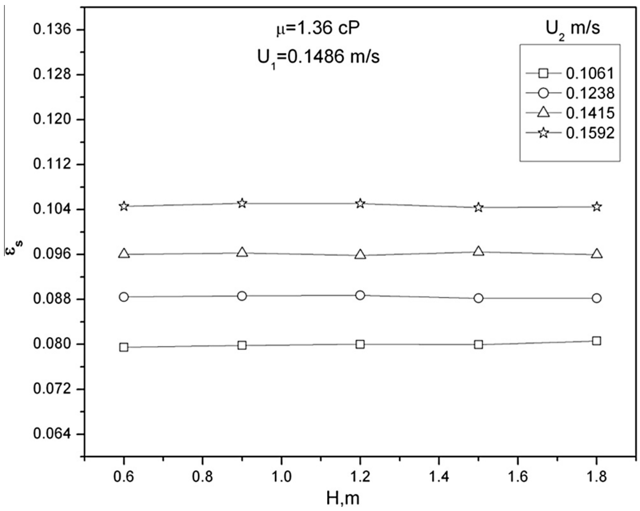

Figure 3 Effect of auxiliary velocity on axial solid holdup for glass bead–glycerol.

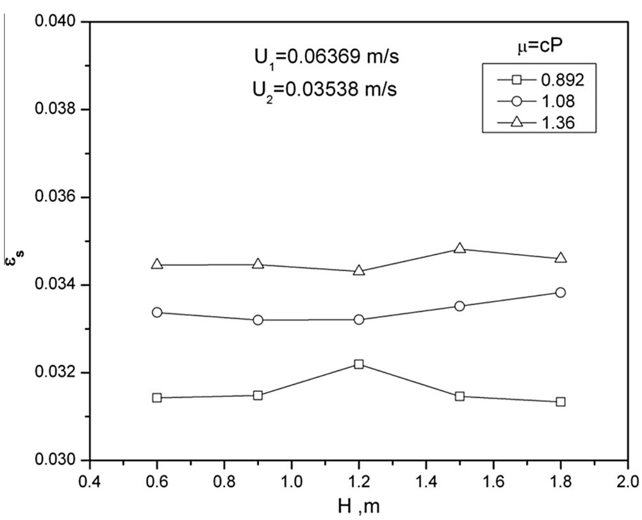

Figure 4 Effect of liquid viscosity on axial solid holdup for sand.

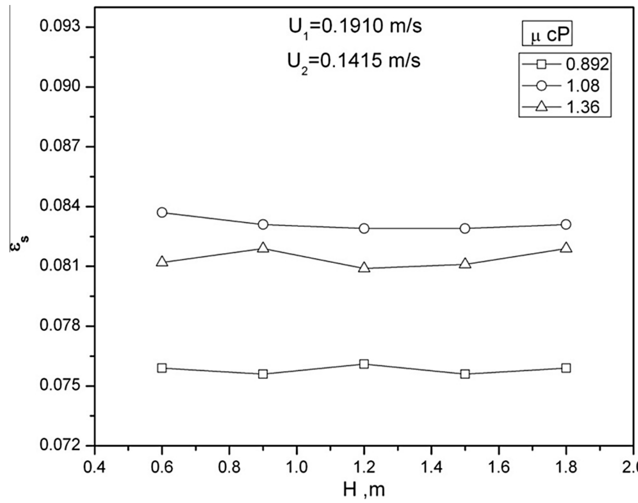

Figure 5 Effect of liquid viscosity on axial solid holdup for glass bead.

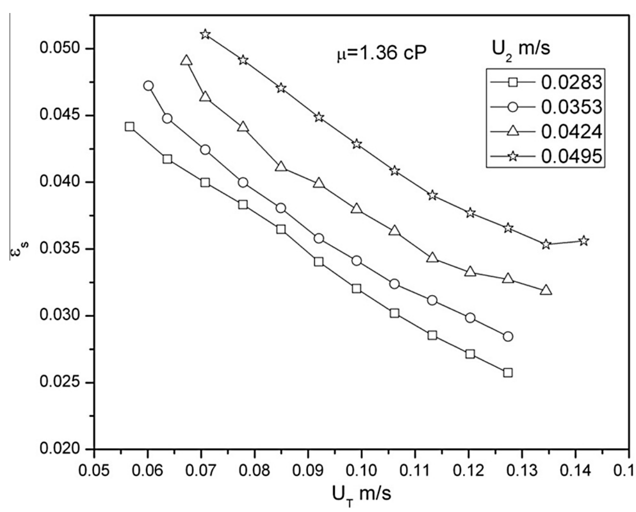

Figure 6 The effect of total velocity on average solid holdup for sand–glycerol system.

hence Figs. 4 and 5 show the effect of liquid viscosity on axial solid holdup for a constant primary and secondary velocity for sand and glass bead. At a given constant velocity, solid holdup at all axial position is found to increase progressively with increase in liquid viscosity. The reason behind this is, for the given total liquid velocity, mobility of solid increases with increase in liquid viscosity due to the fact that circulating fluidization regime starts much earlier for viscous system as its terminal velocity decreases with increase in viscosity.

3.2. Average solid holdup

3.2.1. Effect of solid holdup on total velocity

The effect of auxiliary velocity on solid holdup was studied by different authors for solid–water system [9–11,13,14]. The variation of solid holdup in the riser with change in total velocity keeping auxiliary velocity constant for liquids of viscosity $\mu = 1.36$ cP is shown in Fig. 6 for sand and in Fig. 7 for glass bead system. From the Figures it can be depicted that solid holdup decreases with increase in total velocity and found to increase with auxiliary velocity. It can be seen the solid holdup first decreases quickly with increasing liquid flow rate for the given auxiliary velocity when the fluidized bed is at low liquid velocity and then the decrease in solid holdup 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 rate function is to fluidize the particles at the base of the riser and to regulate 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 holdup in the riser. Maximum solid holdup was reported for glass bead–glycerol system as larger particles leads to higher solid holdup. It is also noted that glass bead glycerol system needs higher superficial velocity to fluidize in circulating regime as its terminal velocity

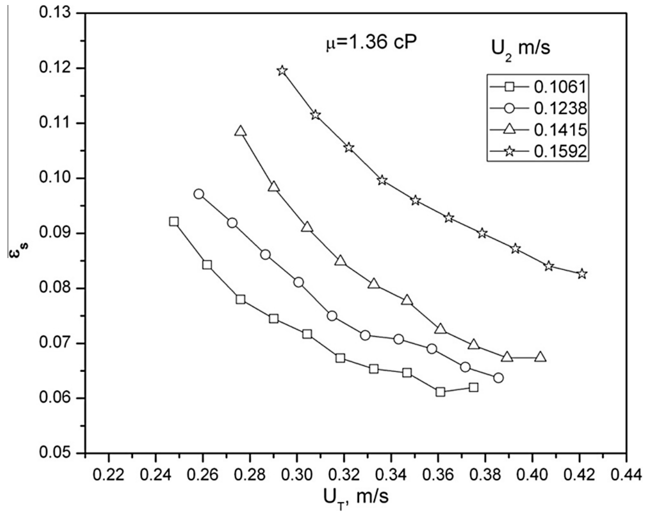

Figure 7 The effect of total velocity on average solid holdup for glass bead–glycerol system.

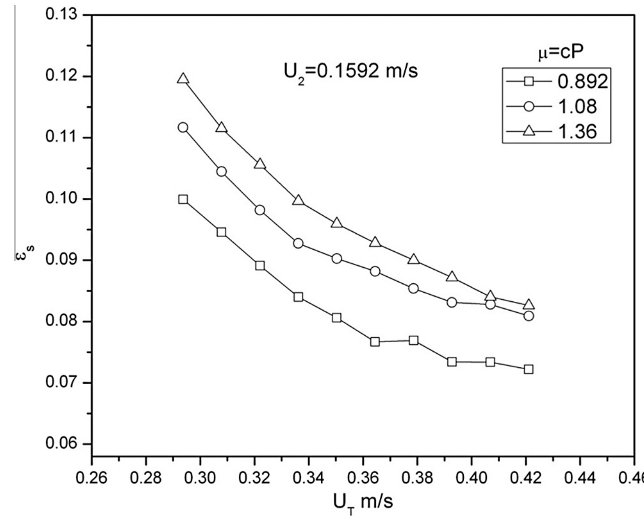

Figure 9 Effect of liquid viscosity on average solid holdup for glass bead-glycerol.

is higher. For the given superficial velocity solid holdup increases with increase in solid density. Similar results have been reported [15] for water system using silica gel and resin.

3.2.2. *Effect of liquid viscosity on average solid holdup*

The effect of liquid viscosity on solid holdup is shown in Figs. 8 and 9 for sand glycerol, rand glass bead glycerol of viscosity 0.892, 1.08 and 1.36 cP respectively for various primary velocities. For the same total velocity for viscous solution the solid holdup decreases with increase in superficial velocity for water system, but with increase in viscosity solid holdup is found to increase for all the solids sand, resin and glass bead system. This increase in solid holdup is due to the fact that circulating fluidization regime starts much earlier for viscous system as its critical transitional velocity decreases with increase in viscosity. It can be seen that with the decrease in solid density, solid holdup is shifted toward left indicating that solid circulation begins at lower velocity corresponding to its terminal velocity and solid holdup was found to be higher for low liquid velocity. Maximum solid holdup was reported for glass bead–glycerol system as larger particles leads to higher solid holdup.

Hence it can be concluded that both particle size and viscosity influence solid holdup in a riser.

3.2.3. *Effect of auxiliary liquid velocity on average solid holdup*

The variation of average solid holdup for varying viscosity of the liquid with auxiliary liquid velocity as independent variable for the given constant primary velocity is shown in Fig. 10 for sand–glycerol and Fig. 11 for glass bead glycerol system. With increase in auxiliary velocity solid holdup almost remains constant, on the other hand solid holdup is found to increase with increase in viscosity of the liquid. This is due to the fact that primary velocity dominates the auxiliary velocity which in turn entrains more solids out of the riser and hence less solid holdup is observed for low viscous solution.

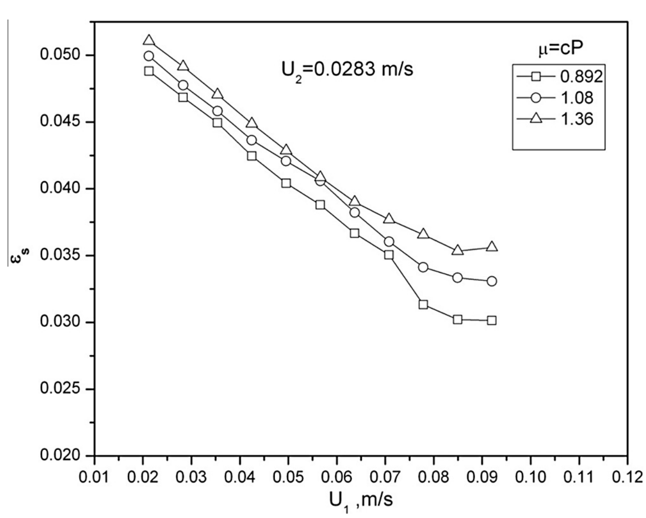

Figure 8 Effect of liquid viscosity on average solid holdup for sand.

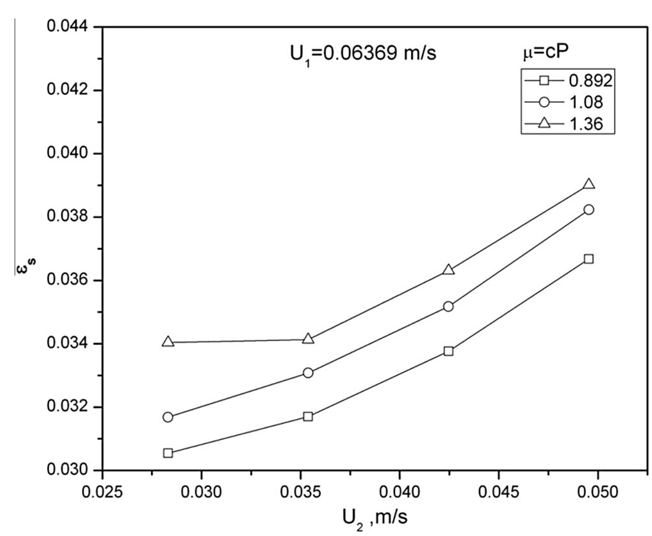

Figure 10 Effect of auxiliary velocity on average solid holdup for sand–glycerol.

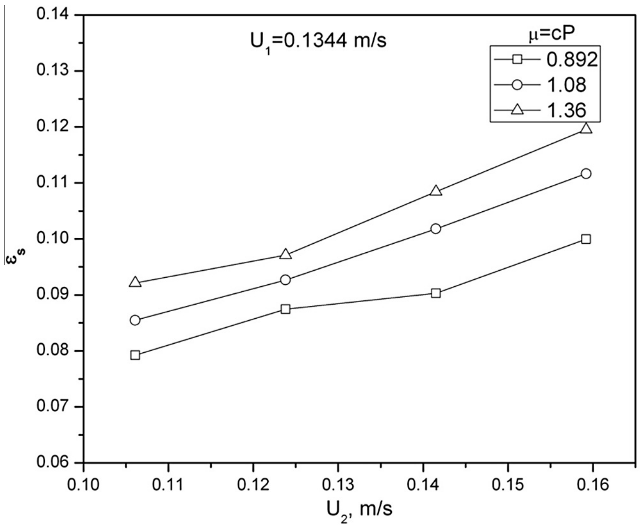

Figure 11 Effect of auxiliary velocity on average solid holdup for glass bead.

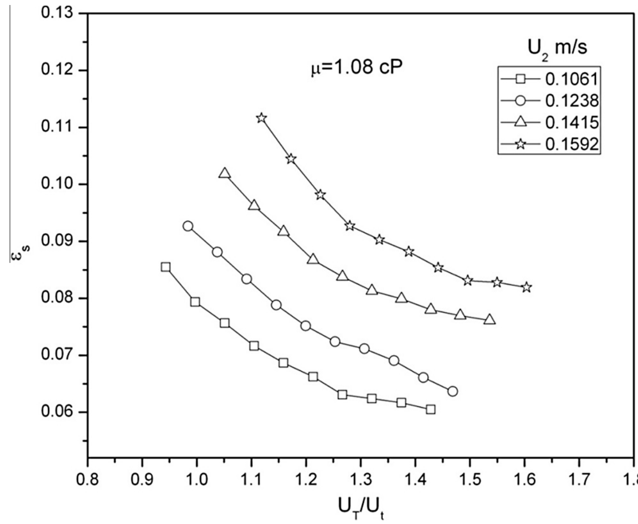

Figure 13 Effect of normalized liquid velocity on average solid holdup–glass bead.

3.2.4. Effect of solid holdup with solid velocity

The variation of average solid holdup with solid circulation rate and auxiliary liquid velocity in the LSCFB regime is shown in Fig. 12 for sand and in Fig. 13 for glass bead. It is noted that average solid holdup decreases with increase in solid velocity and it is higher for the higher auxiliary velocity at a given solid velocity. The solid holdup attains very low value at different solid velocities. The solid velocity at which solid holdup attains minimum, corresponds to $U_{s_{max}}$, which is higher for higher auxiliary velocity and for higher liquid viscosity. It shows the maximum solid velocity depends on auxiliary velocity as well as particle properties as it increases with increase in auxiliary velocity but decreases with size and density of particles

3.2.5. Effect of normalized total and auxiliary liquid velocities

The effect of liquid viscosity on the average solid holdup in terms of normalized auxiliary liquid velocity with normalized total velocity is shown in Fig. 14 for sand and in Fig. 15 for glass bead of liquid viscosity 1.08 cP. Average solid holdup decreased with increase in normalized total velocity as shown in Figs. 6 and 7 for total liquid velocity. With increase in normalized total velocity solid holdup decreased quickly up to U_T/U_t = 1.3 and later the reduction in solid holdup is gradual up to the ratio 2.1 for sand system. For glass bead system the decrease in average solid holdup is up to the ratio 1.2 and the gradual decrease in solid holdup was carried out up to U_T/U_t = 1.6.

3.3. Empirical relation and analysis

Even though several research studies have been reported in recent literature [15,16,22] for the estimation of solid holdup using water as the liquid phase, the availability of average solid holdup correlation using viscous liquids is limited and was reported by Vidyasagar et al. [18] and Lee et al. [21]. Hence

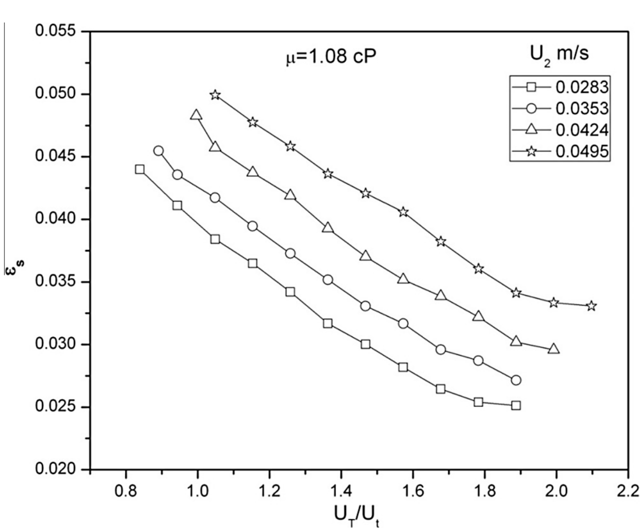

Figure 12 Effect of normalized liquid velocity on average solid holdup–sand.

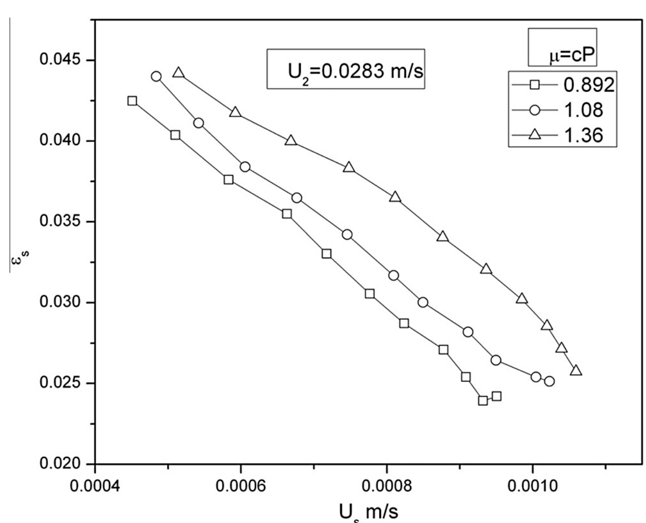

Figure 14 Effect of solid velocity and viscosity on solid holdup for sand.

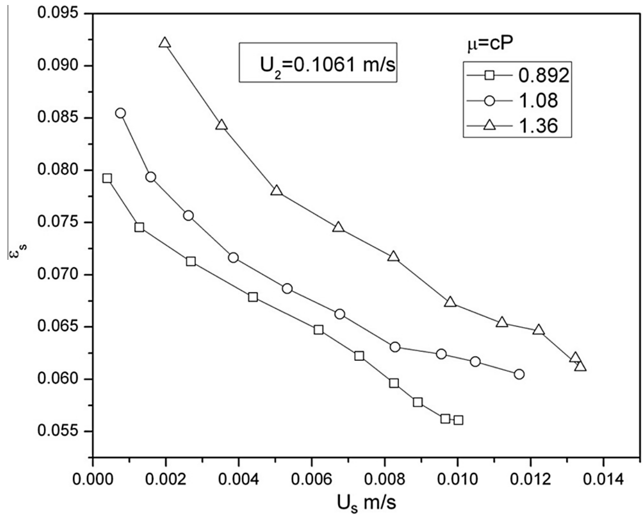

Figure 15 Effect of solid velocity and viscosity on solid holdup for glassbead–glycerol.

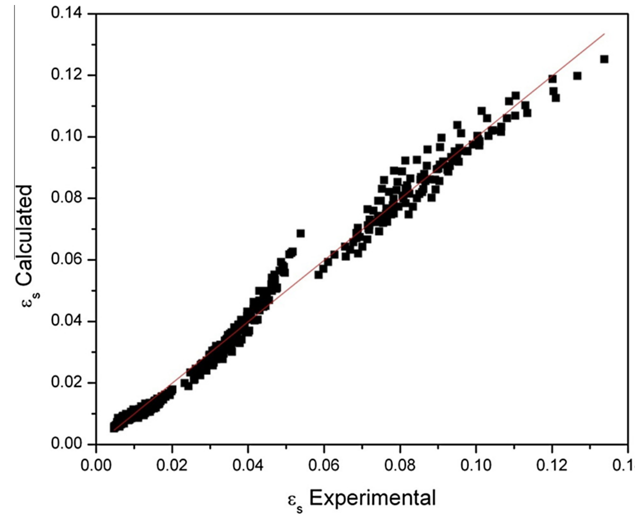

Figure 16 Comparison of experimental and predicted average solid holdup.

the important available correlations (Table 2) established for water and viscous liquids were examined with present data available at different concentrations of glycerol. Zheng and Zhu [22] and Rao [16] proposed correlations in terms of dimensionless solid circulation rate, liquid velocity and dimensionless particle diameter. Natarajan et al. [15] proposed a correlation including the variables, liquid velocity (auxiliary and Primary), total velocity and Galileo number. Vidyasagar et al. [18] proposed the following correlation including primary and auxiliary velocity both in dimensional and dimensionless form to calculate average solid holdup in terms of solid inventory and liquid viscosity (see Table 3).

$$\varepsilon_s = 0.02(U_{11})^{-0.99}(U_{12})0.31(L_0)^{0.51}(\mu_l)^{-0.19} \quad (5)$$

$$\varepsilon_s = 0.22\left(\frac{U_{11}}{U_t}\right)^{-0.99}\left(\frac{U_{12}}{U_t}\right)^{0.31}(L_0)^{0.51}\left(\frac{\mu_1}{\mu_w}\right)^{0.055} \quad (6)$$

To estimate the solid holdup for viscous solutions in liquid solid circulating fluidized bed, performance equation was developed considering primary velocity, secondary velocity that induce solid flow, viscosity of liquid and buoyancy component. Hence a new empirical correlation is proposed in the present study to estimate average solid holdup in terms of input operating variables, dimensionless number which includes particle characteristics and flowing liquid viscosity.

Table 3 Summary of previous work: correlation and variables covered.

S. no.	Authors	Correlation	Variables				
			Solid phase	Liquid phase	Dp (mm)	ρ_s (kg/m^3)	ρ_l (kg/m^3)
1	Zheng and Zhu [22]	$1-\varepsilon=\left\{\frac{}{0.25}\frac{(\overline{G}_s)^{0.8}}{(\overline{U}_l)^{0.8}}\right\}$	Glassbeads	Water	0.508	2490	1000
2	Rao et al. [16]	$\overline{\varepsilon}_s=0.505\left\{\frac{(\overline{G}_s)^{0.17}}{(\overline{U}_l)^{0.53}(\overline{d}_p)^{0.37}}\right\}$	Plastic beads	Water	5	1080	1000
			Glass beads		6	2500	
			Ceramic beads		2.3	1850	
			Granite beads		3.1	2560	
3	Natarajan et al. [15]	$\varepsilon_s=0.058\left(\frac{\Delta\rho}{\rho_l}\right)^{-0.05}Ga^{-0.06}\left(\frac{j_a}{j_f}\right)^{0.72}$	Bluestone	Water	0.33	2850	1000
			Sand		0.55	2774.6	
			Silica gel		0.55	1060.8	
			Cation resin		0.655	1325	
					0.55		
		$\varepsilon_s=0.146\left(\frac{\Delta\rho}{\rho_l}\right)^{-0.05}Ga^{-0.06}\left(\frac{j_a}{j_l}\right)^{1.25}$			0.46		
4	Vidyasagar et al. [18]	$\varepsilon_s=0.02\ U_{11}^{-0.99}\ U_{12}^{0.31}L_o^{0.51}\mu_1^{-0.19}$	Glass bead	Water	1.36	2468	1000
				10 vol% Glycerol			1022
				20 vol% Glycerol			1050
		$\varepsilon_s=0.02\left(\frac{U_{11}}{Ut}\right)^{-0.99}\left(\frac{U_{12}}{Ut}\right)^{0.31}L_o^{0.51}\left(\frac{\mu_1}{\mu_w}\right)^{0.055}$		40 vol% Glycerol			1110
5	Lee et al. [21]	$\varepsilon_s=0.783(U_L)^{-0.100}(G_s)^{0.164}(d_p)^{0.302}(\mu_L)^{-0.036}$	Glass bead	Water	1	2500	1000
				CMC 0.1 wt%	1.7		1001
				CMC 0.2 wt%	2.1		1002
				CMC 0.3 wt%	3		1003

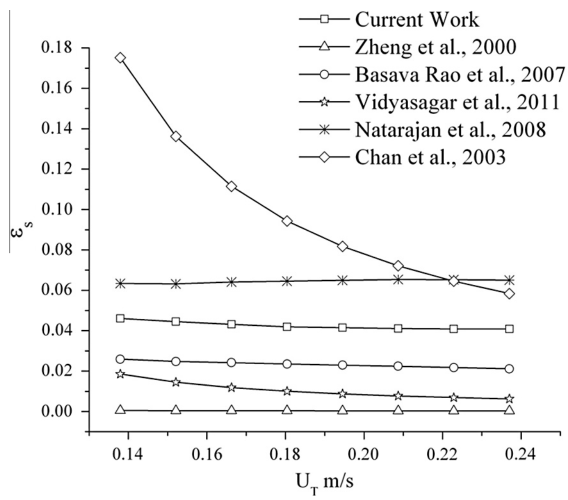

Figure 17 Comparison of predicted average solid holdup with various models for sand–glycerol (1.36 cP).

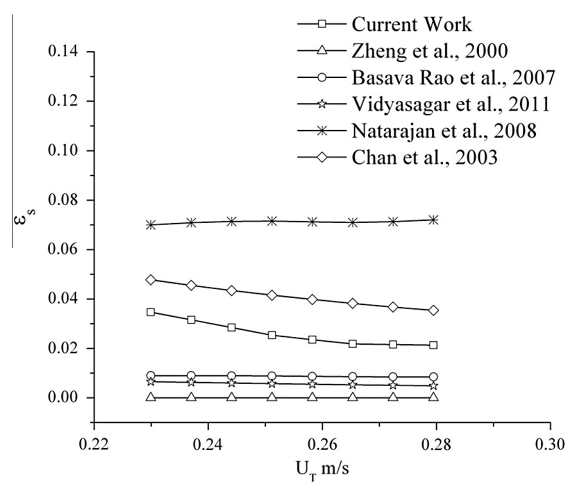

Figure 18 Comparison of predicted average solid holdup with various models for glass bead–glycerol (1.36 cP).

$$\varepsilon_s = 0.01375\left(\frac{\Delta\rho}{\rho}\right)^{1.080} Ga^{0.186}\left(\frac{U_2}{U_t}\right)^{0.942}\left(\frac{\mu_l}{\mu_w}\right)^{1.03} \tag{7}$$

The solid holdup predicted using Eq. (7) is compared with experimentally determined average solid hold and is shown in Fig. 16. It was observed that the performance of the equation was found to be good with a RMS deviation, ±20%. Hence these correlations can be used to predict average solid holdup covering wide range of particle properties, liquid velocity and viscosity within the LSCFB regime. Average solid holdup is calculated using the correlations reported in literature, for the present operating variables and plotted against total liquid velocities, and shown in Fig. 17 for sand–glycerol system for liquid viscosity of 1.36 cP and Fig. 18 for glass bead–glycerol of viscosity 1.36cP. For a given auxiliary velocity (0.084 m/s) it is observed from the figures that all correlations follow a same trend of decrease in solid holdup with increase in total velocity which validates the experimental data reported.

4. Conclusion

The average solid holdup in a liquid solid circulating fluidized bed was examined for two different particles with different viscous liquids at varying primary and secondary velocity. Average solid holdup ε_s was found to decrease with increase in primary or total velocity and found to increase with increase in secondary velocity for liquids of all viscosity due to more entry of solids into the riser which resulted in higher solid holdup. Axially homogenized distribution of the bed voidage is observed through the LSCFB riser and the axial effect was verified with different liquid viscosity and its uniformity with the auxiliary liquid velocity. The study also identified that solid holdup decreased with increase in solid velocity and ε_s found to be increase with viscosity. A performance equation is developed to predict the average solid holdup covering different operating conditions with an RMS error of maximum ±20% and it satisfactorily compared with the experimental results.

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