Prediction of Falling Solids Film Thickness near the Wall in Circulating Fluidized Bed Risers

V.V.Basava Rao*, T.Bala Narsaiaha and B.V. Reddyb

Abstract—**The solid particles distribution in circulating fluidized beds (CFB) has been extensively studied because of its importance in the design of CFB boilers and reactors. The previous studies report that in the circulating fluidized beds, the solids near the wall move down ward as a film with axial variable thickness. Therefore, it is very important to predict solids film thickness near the wall to estimate the heat transfer between a solid suspension in the bed and wall surface. In the present paper, an expression for the local solids film thickness has been suggested from the data of local solids flux measurements by using U-tube probe. The data measured in two laboratory scale CFB units which consist of 0.0508m diameter & 3 m height and 0.1016m diameter & 6m height. Sand (182 µm and 2560 kg//m3) and FCC particles (99 µm and 1600 kg/ m3) are used as bed material. The operating gas velocity and solid circulation rates are in the range of 1-6m/s and 5-125kg/m2-s respectively for the material considered. The R2 values for the correlation developed are 0.577 for literature data, 0.3904 for small column (0.0508m ID & 4m Height) and 0.886 for large column (0.1016m ID & 6m height).**

Index Terms—**Circulating Fluidized Bed, Dilute Core, Dense Annulus, Down Flowing Solids Clusters, Flow Structure, Film Thickness, Cross-sectional Average Voidage, Gas velocity & Solids Circulating Rate.**

I. INTRODUCTION

Circulating fluidized beds (CFBs) have been employed commercially in numerous gas–solid contacting processes such as combustors, coal gasifiers and catalytic reactors. Therefore, the gas-solid flow structure in the CFBs has got important role in understanding and design of these processes. The flow structure strongly depends on operating conditions such as gas velocity & solid circulation rate and bed geometry. Also it is possible to control the solid circulation rate in the circulating fluidized bed, therefore high concentration within the bed may result by promoting turbulent regime into the fast-fluidized bed regime. The solid in the fast-fluidized bed may typically occupy up to 20% of the bed volume and is in a state of extreme turbulence marked by refluxing of dense clusters. The flow structure for fast fluidization is summarized in Figure 1.

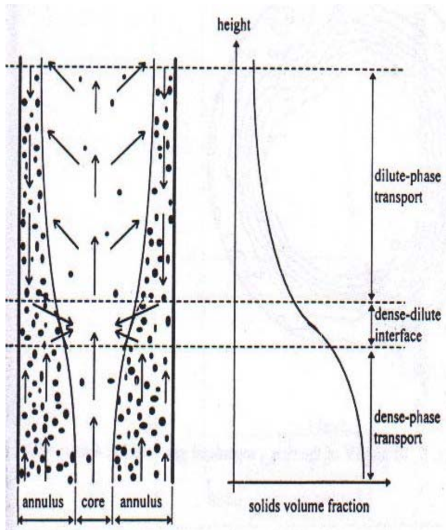

Figure 1: Flow structure of CFB (Core – Annulus)

Under S-shaped axial voidage profile conditions typical of fast fluidization, the core-annulus flow persists over the whole length of the riser with a solids film near the wall in which solids are continuously flow downward [1]. In the film, near the wall, the solids concentration may be quite high so that the instantaneous voidage can be equal to voidage at the minimum fluidization condition of the bed [2] and the flow structure in the film is not uniform in radial direction [3]. Such solid down flow has been observed by measuring the radial distribution [4], the radial distribution of solids flux [5] and the radial solids momentum distribution [6]. Further, the solid flow downward near the wall in the form clusters and flow up ward in the core as dilute suspension. Also, Berruti & Kalogerakis [7], Senior & Brereton [8], Harris & Davidson [9] assumed in their models a Core/annulus two-region structure in which solids flow in the riser consists of a dilute up-flowing suspension in the central core region, surrounded by dense wall where solids fall downward as clusters. The solids film thickness near the wall depends again on operating conditions and bed geometry of the CFB. This solid film plays a significant effect on heat and mass transfer predictions. In this article, an attempt has been made to characterize the flow structure in the film and model for estimating the film thickness.

In initial stages of the CFB investigations, the mean bed void fraction was described as a function of the gas velocity and solid rate in the fluidization regime diagram. This mean bed void fraction was obtained by averaging over the entire volume of the CFB riser column, assuming no variation along the bed height. This school of thought considered that the clusters were distributed uniformly over the bed volume.

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Bolton & Davidson [10] and Rhodes et al [11] investigated the bed structure near the wall in the upper part of the laboratory scale CFB riser. They reported that the wall layer increases exponentially with distance from the top of the riser. This suggests that the wall layer grows in its thickness as it moves down. The observed thickness of the wall layer varied from several millimeters to several centimeters. Further, the voidage of this layer was experimentally estimated to be in the range 0.7-0.8. The fibre optic probe study of the CFB structure by Horio et al [12] confirms this, as well as the existence of clusters in the lean core with their size in the range of few millimeters, which remained constant throughout the column height. Briel et al [13], Rhodes [5], Miller & Gidaspow [14] and Zhang [15] investigated the influence of the suction velocity of the sampling probe and found that a non-isokinetic sampling fibre probe can be employed in CFB risers to measure the net solid flux and from that solid down flow film thickness near the wall can be measured. Bi et al [16] reported that wall layer thickness based on solids flux measurements tend to be larger and are more meaningful than those based on local particle velocity measurements. Therefore, in this article solids flux measurements have been carried out by using a U-tube non-isokinetic sampling probe.

TABLE 1: CORRELATION AVAILABLE IN LITERATURE

Investigator (s)	Correlations
Patience & Chaouki [17]	$\frac{\delta}{D} = 0.5 \left[1 - 1/\sqrt{1 + 1.1 Fr_D \left(\frac{G_s}{\rho_s U_g}\right)^{0.083 Fr_D}}\right]$
Werther [18]	$\frac{\delta}{D} = 0.55 \, \mathrm{Re}_D^{-0.22} \left(\frac{H}{D}\right)^{0.21} \left(\frac{H - z}{H}\right.$
Zhang et al [19]	$\frac{\delta}{D} = 0.05 \, D^{-0.26}$
Bai et al [3]	$\frac{\delta}{D} = 0.403 \, \varepsilon_s^{-0.7}$
Bi et al [16]	$\frac{\delta}{D} = 0.5\left[1 - \sqrt{1.34 - 1.30\, \varepsilon_s^{-0.2} + \varepsilon_s}\right.$
Wei et al [20]	$\frac{\delta}{D} = 0.5\left[1 - 0.2 \, \mathrm{Re}_D^{0.153} \, \varepsilon_s^{0.127}\right]$
Haris et al [21]	$\frac{\delta}{D} = 0.5\left[1 - 0.4014 \mathrm{Re}_D^{0.0585} \varepsilon_s^{-0.0247} \left(\frac{H-z}{H}\right)^{-0.}\right.$
Kim et al [22]	$\frac{\delta}{D} = 1.75 \left(V^*\right)^{0.21} \left(Fr_{dp}\right)^{-0.97} \left(\frac{\rho_s \varepsilon_s}{\rho_g \varepsilon}\right)^{0.16} (Fr_D$ when $V^* < 6.5$ $\frac{\delta}{D} = 0.53 \left(V^*\right)^{-0.32} \left(Fr_{dp}\right)^{-0.55} \left(\frac{\rho_s \varepsilon_s}{\rho_g \varepsilon}\right)^{-0.70} (Fr_D$: when $V^* \geq 6.5$

Literature Correlations on Solids Film Thickness near the Wall:

Considerable numbers of correlations have been reported in the literature for calculating solids film thickness near the wall. They are presented in Table 1. Parity plot with measuring data published in literature (Table 2) is shown in Figure 2.

TABLE II: SOURCES OF DATA PLOTTED IN FIGURES 2 & 3

Author(s) Name	Riser dia meter [m]	Operating conditions		Solids Particles		Measuring Technique
		Ug [m/s]	Gs [kg/m²s]	dp [μm]	ρs [kg/m³]	
Gadjos & Bierl [23]	0.076	3.2	130	50	1600	Sampling Probe
Bader et al. [24]	0.305	4.6	147	76	1710	Sampling Probe
Hartge et al. [25]	0.4	2.9 – 3.7	30 – 29	85 & 120	1500 & 2600	Sampling Probe
Rhodes [5]	0.152	2.8	42	64	1800	Sampling Probe
Herb et al.[1]	0.15	2.4	20.5	88	1700	Sampling Probe
Miller & Gidaspow [11]	0.075	2.6 – 3.5	12 - 33	75	1654	Sampling Probe
Rhodes & Laussman [26]	0.152	2.8 – 4.0	30	75	2460	Sampling Probe
Bai et al[3]	0.066	2.0– 3.0	20– 88	51.9	1623	Momentum Probe
Zhou [27]	0.15*	5.5	40	213	2640	Sampling Probe
Zhang et al[9]	1.57*	6.3	20 - 54	330	2600	Sampling Probe
Issangya et al. [28]	0.076	7.8	126	67	1600	Momentum Probe
Wei et al. [20]	0.186	2.4– 5.75	46– 185	54	1398	Sampling Probe
Van der Meer [29]	0.14	1.3	2.8	55	1500	Sampling Probe
Issangya [30]	0.076	4.5- 7.5	38- 250	67	1600	Momentum Probes
Rhodes et al. [31]	0.09	4.0	150	100	2650	Momentum Probe
Zhang, et al. [32]	0.102	2.6- 4.4	17- 35	172	1647	Sampling Probe
Karri & Knowlton [33]	0.20	5.8	49- 195	175	2643	Sampling Probe
Karri & Knowlton [34]	0.30	4.9	586	67	1714	Sampling Probe
Liu [35]	0.076	6.0- 8.0	200- 455	67	1600	Optical Probe
Malcus et al. [36]	0.14	4.7	148	89	1740	Sampling Probe
Karri & Knowlton [37]	0.20	3.7	50	67	1200	Sampling Probe
Kim et al [22]	0.203	5.0- 8.0	22- 345	70	1700	Momentum Probe

*Square Cross-Section Risers

Figure 2 shows that all correlations presented in table 2 for the published data (table 1) are no way fitting accurately. Patience & Chaouki's [17] correlation fails to predict the variation of solids down flow film thickness with axial position in the riser. Werther's [18] correlation accounts for axial variation of the film thickness, but it does not include the effect of solids circulation rate and cannot predict the increase of film thickness with elevation in the risers with strong exit restriction.

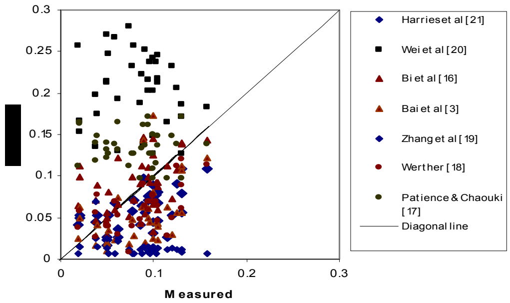


Figure 2: Comparison of published correlations with literature data

Further, Bi et al [16] developed a correlation based on available solids flux measurements from literature. It predicts the solids film thickness to riser diameter ratio as a function of only overall voidage and accounts for the effects of solids flux and axial position on the film thickness. But it fails to predict thickness when ε < 0.80 and most of the risers the average solids holdup at axial positions will be more than 25%.

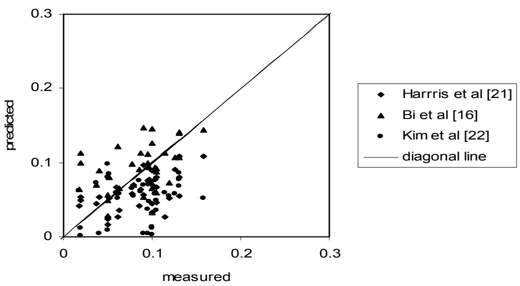


Figure 3: Comparison recently published correlations with measured data

Harris et al [21] also calculated maximum relative error for published experimental results by using these correlations and found them to be between 150% -275%. Further, they concluded that the solid down flow film thickness does depend on local flow structure of the riser and operating conditions. Recently, Kim et al [22] have observed that the thickness of solids down flow film reaches maximum with increasing height and it disappears locally with increasing solids mass flux at a constant gas velocity. Figure 3 shows the variation of predicted values with published thickness values. It can be felt that the variation is still much and better correlation is to be required to predict solids down flow film thickness. It is also felt that the gas-solid flow structure near the wall is more affected by clustering flow and those parameters are to be included in the correlation. Therefore, the present article is aimed to incorporate the cluster properties in the correlation.

II. Experimental Aspects

A Schematic diagram of the experimental set-up is shown in Figure 4. Two similar set-ups are used for the experimental work. One consists of 0.0508m ID and having a height of 3m. Another is 0.1016 m ID and 6m height. Both the set-ups are made up of Transparent Perspex to make naked eye observations. They are assembled with a solid collecting system which consists of Cyclone separator & Bag filter. Air at a controlled rate is allowed to enter through the bottom of solid transport section, so as to maintain the solid in a state of fluidization. The aerated solids are easily fed into the riser column through a solids transport line. A butterfly valve is arranged in the transport column to measure the solids circulation rates at various gas velocities.

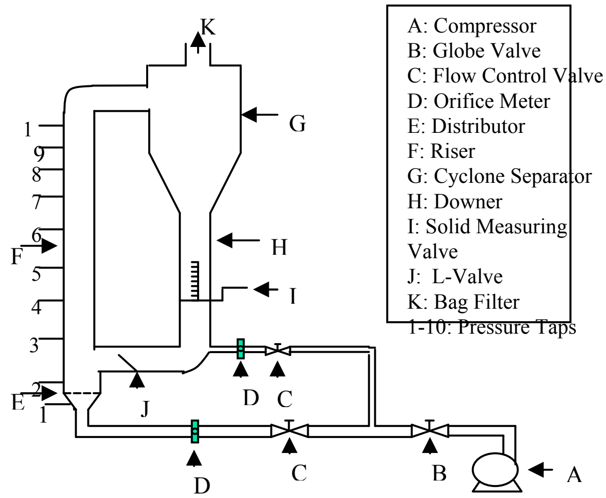


Figure 4: Schematic Diagram of Experimental Set-up

While determining the radial flux profile, a sampling probe (U-bend type) of 4mm internal diameter has been used. This probe is similar to the one employed by Yan et al [38]. The U-tube probe used in experiments is shown in Figure 5.

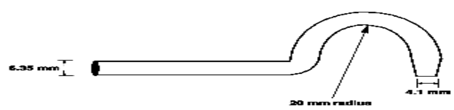


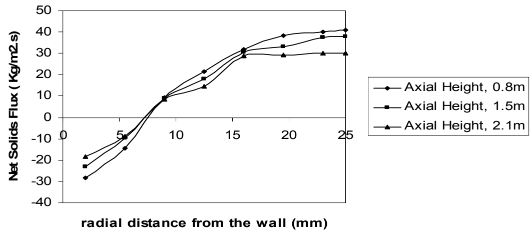
Figure 5: Schematic diagram of the U-tube probe used for collecting samples

Samples were collected at eight radial distances in the case of 0.0508m ID riser column and 13 radial locations in the 0.1016m ID riser column. Probes are used at riser heights of 0.8, 1.52 and 2.1m (measured from distributor) in 0.0508m ID column. The corresponding heights in 0.1016m ID column are being 1.2, 1.85 and 3.2m. Several readings have been taken at different radial and axial positions of the riser column so as to find the solids flux variations.

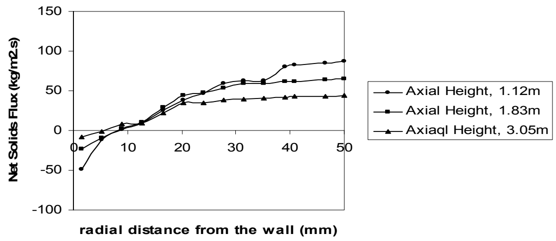
At chosen radial position, the upward and downward samples are collected by pointing the U-bend probe down stream and up stream respectively. The iso-kinetic samples were collected at fixed suction rates. Further, during the operation, a tendency towards plugging has been observed, particularly at low gas velocities and small suction flow rates. To avoid this difficulty, higher gas suction flow rates are maintained. Some difficulties were experienced in collecting samples at the wall of the riser column because of downfall of solids (which chokes the tip of the probe). To compensate the experimental errors, the readings were repeated at least three to four times at different conditions and average values are considered.

III. Results and Discussion

Figure 6 shows that as axial height increases, the radial solids flux is go on decreasing at the constant gas velocity and solid circulation rate. This is evident to have less entrained solids at the top of the column. However, nearing to the top exit the solid concentration increases and also it is expected that the solid down flow layer near the wall increase.

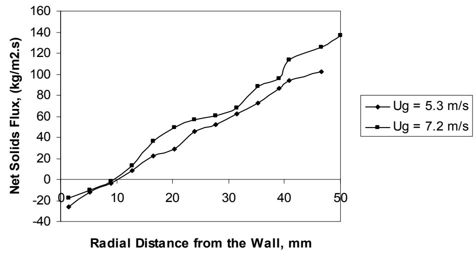


(a) D=0.0508m, H=3m, d_p=182μm, ρ_s=2550 kg/m^3, U_g=3.72 m/s and G_s= 38.2 kg/m^{2}s

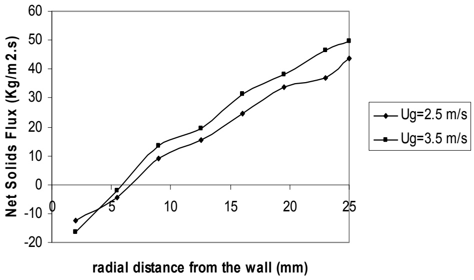


(b) D=0.1016m, H=6m, d_p=99μm, ρs=1600 kg/m^3, U_g=3.5 m/s and G_s= 34.7 kg/m^{2}s

Figure 6: Effect of axial height on radial solids flux profile



(a) D=0.1016m, H=6m, d_p=182μm, ρ_s=2550 kg/m^3, z=1.12m and G_s= 54 kg/m^{2}s

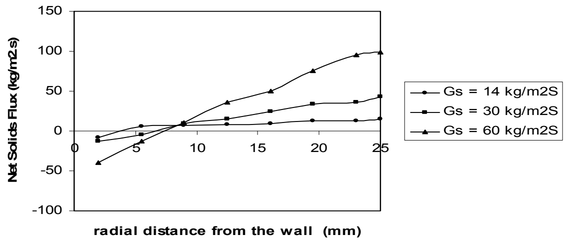


(b) D=0.0508m, H=3m, d_p=99μm, ρ_s=1600 kg/m^3, z=0.8m and G_s= 30 kg/m^{2}s

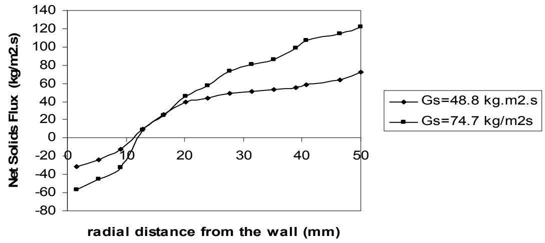
Figure 7: Effect of gas velocity on radial solids flux profile

Further, at a particular axial position and fixed solid circulation rate the radial solids flux profile variations with gas velocity is shown in figure 7 and it can be observed that the radial solids flux increases with increasing gas velocity.

The effect of solids circulation rate on radial solids flux profiles is also shown in figure 8. When the solid circulation rate increases the radial solids flux also increased with more solids flowing down near the wall. It means that the solid down flow film thickness can increase with solids circulation rate.



(a) D=0.0508m, H=3m, d_p=99μm, ρ_s=1600 kg/m^3, z=1.5m and U_g= 2.5 m/s



(b) D=0.1016, H=6m, d_p=182μm, ρ_s=2550 kg/m^3, z=1.12m and U_g= 4.7 m/s

Figure 8: Effect of solids circulation rate on radial solids flux profile

Thus, the down flow solids film thickness depends not only on all the operating conditions but also on local position in the riser near the wall. Further, it is visually observed that the solids film near the wall is very much influenced by turbulence with formation & deformation of clusters and film thickness is time dependent. Therefore, it is felt that the cluster characteristics only decide the thickness of solids down flow near the wall in the CFB riser.

A. Downward Film Flow Structure:

Analysis of the microstructure of the gas-solid suspension has identified collections of solid particles grouped together in the form of “cluster(s)”. Many of the investigators observed these clusters mostly in the vicinity of the riser wall but also identified in the riser core. The formation of particle clusters in the riser near the wall makes the flow very complex. Clusters at the wall of a riser have been observed to from, descend, break-up, travel laterally from the annulus to the core and then be re-entrained in the upward flowing core [Horio et al, [39]. In this manner, they contribute to the internal solids mixing process within a riser. Typical downward velocities in the vicinity of the wall in the riser lie in the range 0.5 – 2 m/s. Radial and axial variations have been observed in cluster size, shape, voidage (solid concentration) and velocity. Soong et al [40] proposed a definition based upon the experimental technique that the solid volume fraction in a cluster must be significantly greater (three times the standard deviation) than the time averaged solid fraction at that local position.

Harris et al [41] have characterized the cluster properties and proposed the following equations;

B. Cluster Voidage:

$$\varepsilon_{cl} = \frac{0.58\,\varepsilon_s^{1.48}}{0.013 + \varepsilon_s^{1.48}} \qquad (1)$$

C. Cluster Size:

$$d_{cl} = \frac{\varepsilon_s}{40.8 - 94.5\varepsilon_s} \qquad (2)$$

D. Cluster Descending Velocity:

$$U_{cl} = 0.75\sqrt{\frac{\rho_s}{\rho_g} g\, d_{cl}} \qquad (3)$$

Therefore, we strongly believe that the down flow solids film thickness depends on these parameters. So, the dimensionless down flow solids film thickness is a function as shown below;

$$\frac{\delta}{D} = f(U_{cl}, d_{cl}, \varepsilon_{cl} \,\&\, U_{slip}) \qquad (4)$$

By applying dimensionless analysis, the following equation has been developed.

$$\frac{\delta}{D} = C\left(\frac{U_{cl}}{U_{slip}}\right)^{n_1} (Fr_{dcl})^{n_2} (\varepsilon_{cl})^{n_3} \qquad (5)$$

E. Estimation of Solids Down Flow Film Thickness:

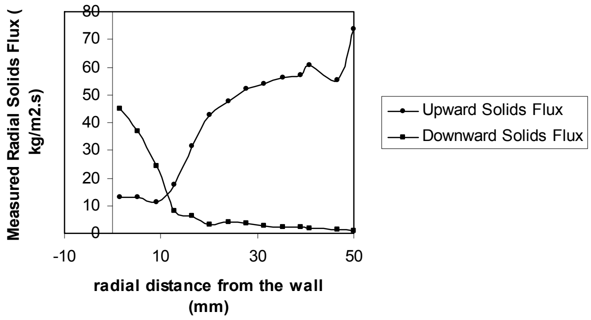
The measured upward and downward solids flux at various radial positions are shown in Figure 9, The down ward solids mass flux is more near the wall and it decreases with radial position in the riser. It can be seen in Figure 9 that the down flow solids flux approaches zero as radial position reaches to centre of the riser. Where as the upward solids mass flux increases with radial position and reaches to maximum at the center. But at one radial position the upward and downward solids mass fluxes intersects. That radial position is termed as solids down flow film thickness, where the net solids mass flux is zero. In figure 9, the solids down flow film thickness can be estimated as 0.125 mm.

F. Correlation for Solids Down Flow Film Thickness:

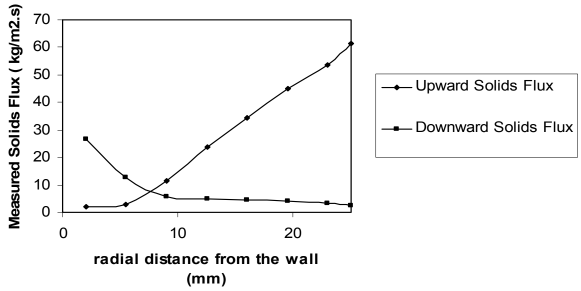
The data, in the similar manner, were estimated at various solids circulation rate and gas velocities for different axial heights in both the 0.0508ID and 0.1016ID columns. From these data, the following correlation was developed by using non-linear regression analysis;

$$\frac{\delta}{D} = 0.0625 + 0.025\left(\frac{U_{cl}}{U_{slip}}\right)^{0.3142} (Fr_{dcl})^{0.097} (\varepsilon_{cl})^{0.1145} \qquad (6)$$

Figure 10 shows the comparison between predicted and measured values of the thickness of solids down flow film near the wall in the riser of circulating fluidized bed. It can be seen that the correlation fits with good agreement with 15% error.



(a) D=0.1016m, H=6m, d_p=182μm, ρ_s=2550 kg/m^3, z=1.12m , U_g=4.7 m/s and G_s= 49 kg/m^{2}s



(b) D=0.0508m, H=3m, d_p=182μm, ρ_s=2550 kg/m^3, z=1.5m , U_g=4.7 m/s and G_s= 49 kg/m^{2}s

Figure 9: Estimation of solids down flow film thickness

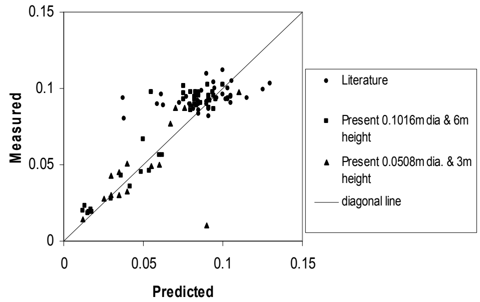


Figure 10: Comparison plot for correlation

IV. Conclusions

The flow structure in the down flow solids film is strongly influenced by clustering phenomena and cluster properties (i.e. size, voidage, descent velocity etc.). Therefore, the film thickness depends on cluster size, cluster voidage, cluster descent velocity at operating conditions. To estimate this film thickness, a new correlation has been developed based on cluster properties by using dimensionless analysis.

Further, the U-tube probe has been used to study the radial solids flux variations in 0.0508m ID and 0.1016m ID risers at various heights in the experiments. Form these radial solid flux variations, the film thickness near the wall in the both risers has been estimated. The measured data along with published data have been used to correlate the equation by non-liner regression analysis. The predicted correlation fits well within 15% error. This correlation shows better agreement with all the data shown in Table 2.

Nomenclature

dp : Sauter mean particle diameter, μm
D : Riser diameter or hydraulic diameter, m
Fr_D : Froude number based on riser diameter $(U_g/(gD)^{0.5}$

Fr_{dp} : Froude number based on particle diameter $(U_g/(gdp)^{0.5}$
Fr_{dcl} : Froude number based on cluster diameter $(U_g/(gd_{cl})^{0.5}$
g : Acceleration due to gravity, m/s^2
G_s: Solid circulation rate, kg/m^2s
H : Riser height, m
Re_D : Reynold's number ($D \rho_g U_g / \mu_g$)
U_{cl} : Cluster velocity, m/s
U_g : Superficial gas velocity, m/s
U_{slip} : Slip velocity, m/s
V^* :Dimensionless slip velocity

$$\left[\frac{\rho_g^2}{g\mu_g(\rho_p-\rho_g)}\right]^{1/3}\left[U_g-\frac{G_s\varepsilon_g}{\rho_p\varepsilon_s}\right]$$

z : axial height above the distributor in the riser, m

Greek letters

δ : Solids down flow film thickness, m
ρ_g : Gas density, kg/m^3
ρ_s : Solids density, kg/m^3
μ_g : Gas viscosity, kg/ms
ε_{cl} : Voidage in the cluster
ε_g : Cross-sectional averaged voidage
ε_s : Cross-sectional averaged solids concentration

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