MODELING OF FINE COAL PROCESSING
IN A TEETER BED SEPARATOR

Avimanyu Das*, Vidyadhar Ari and Sujit Kumar Dey
MNP Division, National Metallurgical Laboratory, Jamshedpur, 831007, India
* avimanyu_das@yahoo.com

ABSTRACT

Beneficiation of fine coal using Floatex Density Separator (FDS) is investigated through experimental and computational approaches. Performance of the FDS is determined through detailed experimentation. The separation in the FDS is also described theoretically using a slip velocity correlation and steady state mass balance equations. The performance of the FDS is estimated by solving the resulting set of mathematical equations. The computed data are found to be in reasonable agreement with the experimental observations albeit with certain deviations. It is shown that at a low bed pressure the FDS acts as a size classifier. At an elevated bed pressure density based concentration is the dominant mode of separation. Low teeter water flow rate is inadequate for hydraulic transport of particles while too high a value leads to misplacement. It is shown that a slip velocity model based on modified Richardson and Zaki equation in which the dissipative pressure gradient is considered to be the primary driving force for separation predicts the performance more accurately than the other models.

INTRODUCTION

The Floatex density separator (FDS) is a teeter-bed based gravity separator which is used to separate different types of minerals based on their specific gravity. The solid particles settle against a rising current of fluidizing water. The settled particles form a bed at the bottom that acts as an autogeneous heavy medium. The bed is under teetering condition through which further settling of only heavy particles occur. The lighter ones are unable to penetrate this bed and are swept away by the rising water.

Richardson *et al.*[1] proposed an empirical slip velocity model to describe particle movement in sedimentation and liquid fluidization processes where slip velocity is defined as a function of void fraction and particle terminal settling velocity. Van Der Wielen *et al.* [2] proposed a steady state force balance model to estimate classification velocity of fluidizing particles. Galvin *et al.*[3] proposed an empirical slip velocity equation considering terminal settling velocity and density difference. According to them the model is applicable to particles of varying densities in homogeneous suspensions. Substantial work has been done to describe the particles separation in a liquid fluidized bed[4-6]. However, most of these are restricted to binary or ternary mixtures varying either in size or density. It is well established that in a teeter bed separator both density and size play significant roles[7-8]. The features of separation in FDS are studied through computational work and validated against experimental data.

MATHEMATICAL FORMULATION

The slip velocity approach suggested by Patwardhan and Tien[9], can be used in a modified form for the particle slip velocity in multi-solid system in which the solids differ in size as well as density:

$$V_{slip,ij} = U_{ter,ij} F(\varepsilon) G(\rho) \tag{1}$$

Where, V_{slip} and U_{ter} are the slip velocity and the terminal settling velocity of the particle, F(ε) is a function of bed voidage, i denotes the size class and j denotes the density class and G(ρ) accounts for the effect of the suspension.

The estimation of F(ε) and G(ρ) is quiet complex. Several empirical correlations are proposed by various researchers. Masliyah[10] proposed the functional form of F(ε) and G(ρ) for multi-particle system as follows:

$$F(\varepsilon) = \varepsilon^{n_{ij}-2} \tag{2}$$

$$G(\rho) = \frac{\rho_{ij} - \rho_{sus}}{\rho_{ij} - \rho_f} \tag{3}$$

Where, n_{ij} is the Richardson and Zaki index.

Van Der Wielen et al.[2] and Galvin et al. [3] proposed two other approaches for evaluation of these two functions. Thus, four different slip velocity correlations are chosen in the present study.

Steady State Mass Balance

The component-wise mass balance and the overall mass balance are expressed by the two relationships:

$$Ff_{ij} = Uu_{ij} + Oo_{ij} \tag{4}$$

$$F = U + O \tag{5}$$

where, F is feed mass flow rate, U is underflow mass flow rate, O is overflow mass flow rate, f_{ij}, u_{ij} and o_{ij} are the mass compositions of the feed, underflow and overflow, respectively. Simultaneous solution of the relevant slip velocity equation along with mass balance equations gives the composition and, hence, the size and density distributions of the overflow and underflow products. The estimation of required parameters including voidage and suspension density is discussed by Das et al. [11].

COMPUTATIONAL

Richardson and Zaki index, terminal settling velocity of the particle and suspension density are computed first. The slip velocity is then estimated using relevant equation and is compared with the interstitial water velocity. If the slip velocity of a particle is equal to the interstitial teeter water velocity relative to the stationary observer, the particle has a zero velocity relative to that stationary observer and it is in equilibrium with external forces. This particle has equal probability to report to either in the overflow or the underflow. Particles having the slip velocity greater than the teeter water velocity report to the underflow, otherwise they report to the overflow. A user friendly computer code has been developed in VC++ for prediction of performance of the FDS.

EXPERIMENTAL

To study the effect of size distribution on the performance of the FDS, experiments are performed for two types of feed: a widely distributed feed (WSF) of -1.8 mm nominal size and an intermediate sized feed (ISF) of -1.18+0.15 mm size. Size distributions, size-wise ash distributions and washability analysis of the above feeds are obtained experimentally and are presented in Figure 1. The influence of bed pressure and teeter water flow rate was also studied by varying them and observing the response of the FDS. The experimental conditions are shown in Table 1.

Table 1. Test conditions selected for comparison

Test No.	Feed type	Teeter flow rate (lpm)	Bed Pressure (%)
T1	-1180 micron feed (WSF, 33.3% ash)	10	15
T2		10	25
T3	-1180 + 150 micron feed (ISF, 28.3% ash)	10	25
T4		14	25

COMPARISON OF MODEL PREDICTIONS

The details of the feed matrix used for interpolation are available elsewhere [11]. Comparison of the performance of FDS as predicted by the four different models with the experimental results is shown in Table 2. It may be seen from Table 2 that at low bed pressure all four models over predicted the yield for WSF. However, at high bed pressure the model predictions are comparable with the experimental results. Galvin, Masliyah and Van der Wielen models marginally under predicted the yield whereas Patwardhan and Tien model predicted slightly higher yield. At a low bed pressure, the bed formation is not complete. This prevents the formation of an effective heavy medium which leads to a very low yield value.

At a low teeter water rate, all models over-predict the yield for ISF. However, Galvin model offers the closest prediction under these conditions. At higher teeter water rate also all models over-predict the yield.

Under these conditions, Galvin model predicts a yield value which is very close to the experimental value and Patwardhan & Tien model predicts a value which is farthest from what is experimentally observed.

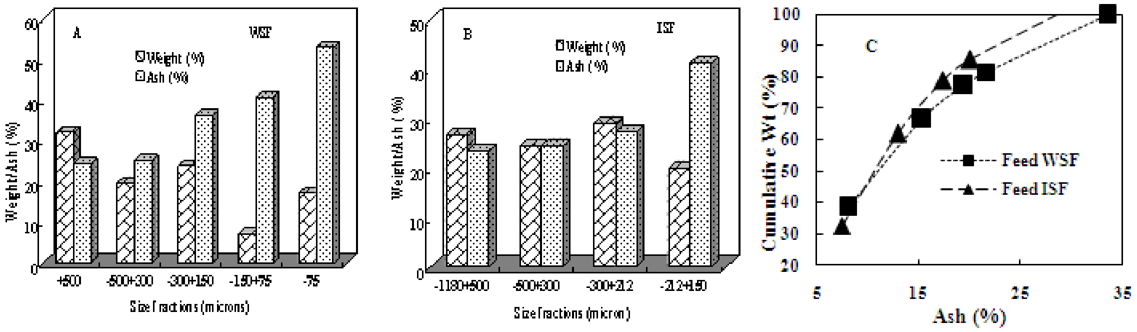

Figure 1. Size & ash distribution of feeds (A) WSF and (B) ISF and (C) Washability of the two feeds

It may be summarized from Table 2 that Galvin model gives good predictions except when the bed pressure is low. Masliyah and Van der Wielen models offer similar predictions under all conditions. Patwardhan & Tien model predicts much higher yield values than what is observed experimentally in all cases.

Table 2. Comparison of overall performance with various model predictions

Test No.	Experimental Yield (%)	Yield (%) predicted by various correlations			
		Galvin	Maslyah	Van Der Wielen	Patwardhan & Tien
T1	27.36	41.52	39.47	38.96	44.20
T2	70.99	65.75	66.77	66.59	79.22
T3	52.33	59.02	66.31	66.24	66.24
T4	66.26	69.50	74.73	73.70	80.14

At high bed pressure, the Galvin, Masliyah and Van der Wielen models lead to under prediction for feed WSF. However, they provide an over prediction for feed ISF. These might arise since the size distribution for feed WSF and ISF are different. Bed voidage with feed WSF is less than that with feed ISF.

Size and Density Distributions

Some of the size and density distribution data are presented in Figures 2-3. Very little density separation for feed WSF at low bed pressure (15%) and 10 lpm teeter water flow rate (Figure 2) is observed. At low bed pressures, no autogeneous heavy medium is formed and the mode of separation is primarily size based. The predicted density distributions show a reasonable agreement with the experimental density distribution.

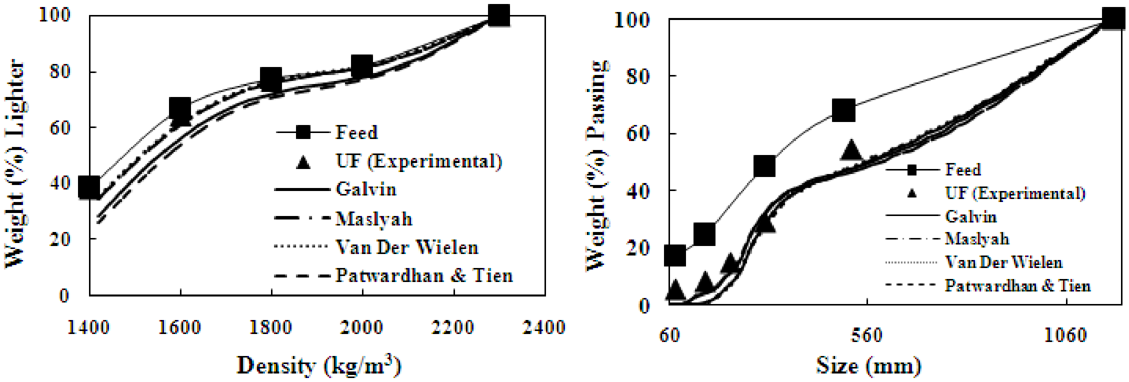

Figure 2. Comparison between experimental & predicted density and size distribution of underflow product using different slip velocity approaches at 10 lpm TWFR and 15% BP for feed WSF.

For size distribution of underflow product at 15% bed pressure and 10 lpm teeter water flow rate with feed WSF (Figure 2), the large difference between the feed curve and experimental size distribution curve signifies that at a low bed pressure, a good size separation is obtained. Very close agreement between the experimental result and model prediction is observed under these conditions.

As the bed pressure increases the effective density of the autogeneous heavy medium in the FDS also increases triggering the onset of density based separation at some point. Density based separation increases with increasing bed pressure while size based separation diminishes. Hence, the underflow product becomes enriched with heavier and larger particles (Figure 3) as the bed pressure increases. Thus, a gap between the size distribution of the underflow product and feed is expected at lower bed pressures while at higher bed pressure such a difference is visible in the density distribution of the underflow and feed. The trend of predicted density and size distribution by all four models follow the experimental density and size distribution pattern, respectively. Thus, all four models may be applied to predict the density and size distribution of the products albeit with varying accuracy.

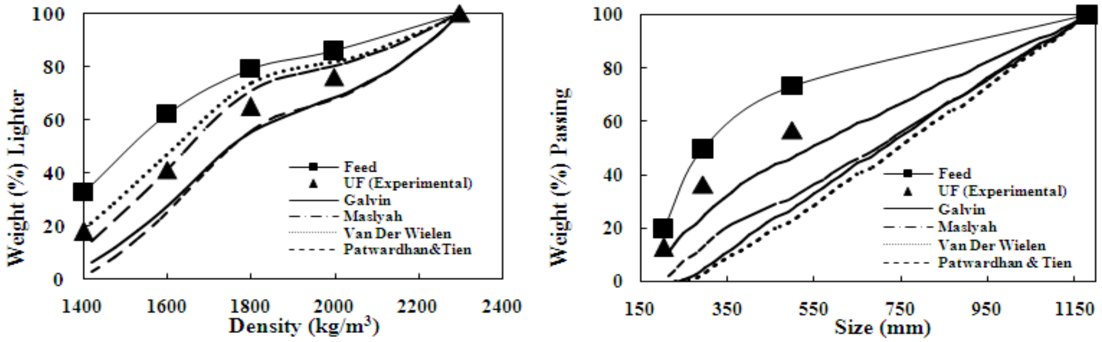

Figure 3. Comparison between experimental and computed density and size distribution of underflow product at 14 lpm TWFR and 25% BP for feed ISF.

Performance Prediction

Predicted performances for the FDS for beneficiation of coal fines of feed WSF are presented in Figure 4. From this figure it may be seen that at low bed pressure the FDS is unable to produce clean coal having ash less than about 28%. Feed WSF contains higher amount of fine particles (-150 micron) having high ash content. The separation is mainly size based at low bed pressure. With increase in bed pressure the total upward force exerted on the particle by the fluid increases. This increased upward force helps in carrying larger and lighter particles having lower ash content to the overflow. Further increase in bed pressure increases the density and viscosity of the separating medium which helps to transport larger and heavier particles to the overflow. This results in an increase in the ash content of the overflow product. Thus, the ash content of overflow product for feed WSF goes through a minimum (Figure 4).

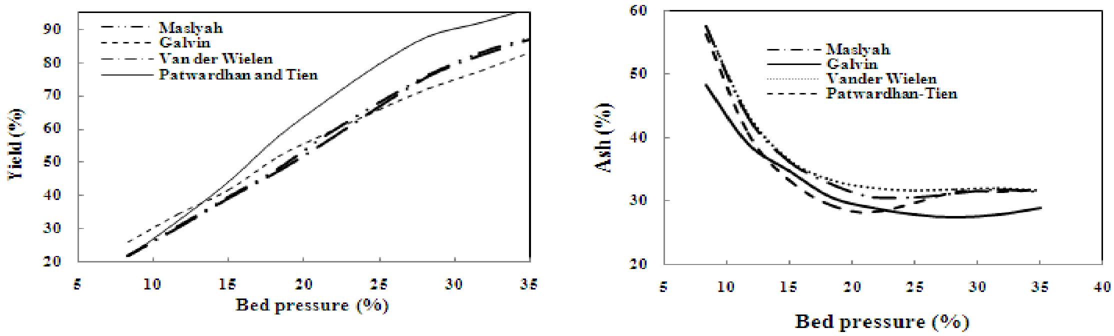

Figure 4. Performance prediction using different slip velocity models for feed WSF at 10 lpm teeter water flow rate as a function of bed pressure.

An increase in teeter water flow rate also increases the upward force resulting in enhanced hydraulic transport. Therefore, for feed ISF, clean coal yield increases with increase in teeter water flow rate (Figure 5). The clean coal grade (ash content) becomes poorer with a higher yield as the teeter water flow rate increases (Figure 5). At a very high teeter water rate, the clean coal grade expectedly stabilizes close to the feed grade as the hydraulic transport becomes the only mode of separation under these conditions.

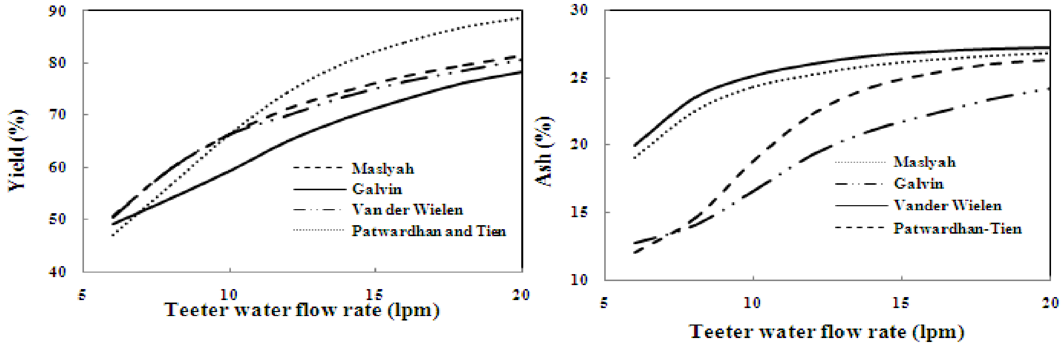

Figure 5. Performance prediction using different slip velocity models feed ISF at 25% bed pressure as a function of teeter water flow rate.

SUMMARY AND CONCLUSIONS

Separation process of FDS is described mathematically using simple slip velocity model. Effects of two operating parameters, viz. the bed pressure and teeter water flow rate on FDS performance have been studied through simulation. The effect of feed size distribution is also studied. It is observed that a closely sized feed from which ultrafines are removed, enhances the concentration performance of the unit by reducing the size effect. It may be said that the correlation proposed by Galvin et al., in which dissipative pressure gradient is considered to be the major driving force for separation regardless of its origin, offers better performance predictions than the other three correlations.

REFERENCES

(1) Richardson, J. F. and Zaki, W. N., Sedimentation and Fluidization: Part I, *Trans. Inst. Chem. Engr*., 32, 1954, 35-53.

(2) Van Der Wielen, L. A. M., Van Dam, M. H. H., and Luyben, K. Ch. A. M., On the relative motion of particle in a swarm of different particles, *Chem. Eng. Sci*., 51, 1996, 995-1008.

(3) Galvin, K. P., Pratten S. J., and Nguyen Tran Lam G., A generalized empirical description for particle slip velocities in liquid fluidized beds, *Chem. Engg. Sci*., 54, 1999, 1045-1052

(4) Epstein, N., Teetering, *Powder Technol*., 151, 2005, 2-14.

(5) Asif, M., The complete segregation model for liquid fluidized bed: formulation and related issues, *Powder Technol*., 140, 2004, 21-29.

(6) Rasul, M. G., Rudolph, V., and Carsky, M., Segregation in binary and ternary liquid fluidized beds, *Powder Technol*., 126, 2002, 116-128.

(7) Galvin, K. P., Pratten, S. J., and Nicol, S. K., Dense medium separation using a teetered bed separator, *Miner. Engg*., 12(9), 1999, 1069-1081.

(8) Sarkar, B., Das, A. and Mehrotra, S., P., Study of separation features in floatex density separator for cleaning fine coal, *Int. J. Miner. Proc*., 86, 2008, 40-49.

(9) Patwardhan, V. S. and Tien, C., Sedimentation and liquid fluidization of solid particles of different sizes and densities, *Chem. Engg. Sci*., 40(7), 1985, 1051-1060.

(10) Masliyah, J. H., Hindered settling in multi-species particle system, *Chem. Engg. Sci*., 34, 1979, 1166-1168.

(11) Das, A., Sarkar, B. and Mehrotra, S. P., Prediction of Separation Performance of Floatex Density Separator for Processing of Fine Coal Particles, *Int. J. Miner. Proc*., 91(1-2), 2009, 41-49.