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Segregation-Dispersion Model of a Fluidized Bed System Incorporating Inclined Channels Operated with no Shear Induced Lift

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Abstract: A segregation-dispersion model able to predict the coal and mineral separation achieved using a continuous steady state fluidized bed system incorporating inclined channels was developed. This system, referred to as a Reflux Classifier (RC), consists of a lamella settler and a fluidization section below. The feed suspension enters the unit, passing into the inclined channels, segregating onto the inclined surfaces, before sliding back towards the fluidization section. Lower density particles report to the overflow, and denser particles to the underflow. A significant breakthrough in the development of the RC was established in 2008 when closely spaced inclined channels were introduced (~6 mm), promoting a new laminar-shear mechanism. This arrangement led to the selective shear induced lift of low density particles, thus the separation performance increased significantly following 2008. This paper describes the first major step towards developing a segregation-dispersion model of the above mentioned system. As a first step, the effects of the laminar-shear mechanism in the inclined channels have been neglected, and therefore the results have been validated using the experimental work for widely spaced channels prior to 2008. A total of 35 species were used in the simulations, corresponding to 5 different sizes with 7 densities per size for a particle size range of -2.0+0.25 mm. Partition curves for particles of a given size have been determined, achieving excellent agreement with the published data in terms of D_{50} and Ep values. Thus, the basic framework for incorporating the effects of shear induced lift is now in place.

Keywords: fluidization, hindered settling, lamella settler, segregation-dispersion, shear induced lift.

1 Introduction

The Reflux Classifier (RC), consisting of a lamella settler and a fluidization section, has been used for size classification and recovery of valuable minerals, such as, coal and iron ore [1-6]. A schematic diagram of the reflux classifier is given in Figure 1. The RC works on the principle of the Boycott Effect [1, 2, 4-6], according to which, the lamella settler provides large settling area for the particles to settle down. Therefore, when a mixture of high and low density particles enter into the inclined section of the RC, the high density solid particles settle on the inclined channels at a higher rate than low density solid particles. Then, these denser particles slide backwards towards the fluidization section of the RC and discharge as bottom product, while, the low density particles move out from the RC through hydraulic conveying as a top product [1-3].

The development of the RC had a significant breakthrough in 2008 when closely spaced inclined channels (~6 mm) were introduced [7]. The introduction of closely spaced inclined channels caused a new laminar-shear mechanism that led to the selective shear induced lift of low density particles [7, 8]. Thus, the separation performance increased significantly following 2008.

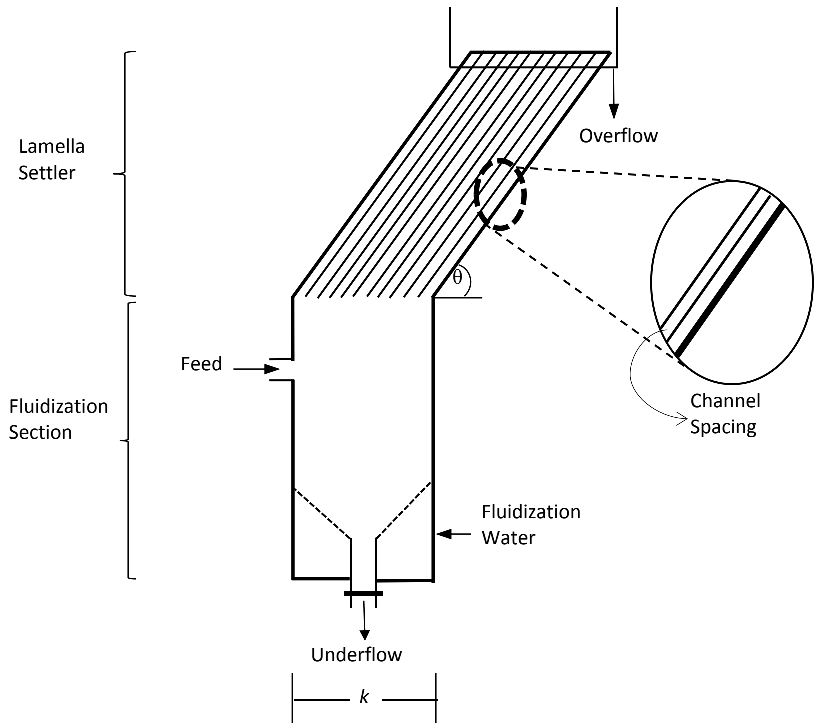

Figure 1. Schematic diagram of the Reflux Classifier.

The introduction of closely spaced inclined channels improved the overall separation, reducing the dependence of the D_{50} on the particle size, and reducing the Ecart probable, Ep, of the RC [7-9]. The partition curves obtained after the inclusion of closely spaced inclined channels, published by Galvin et al. (2010) [7], were much sharper, as shown in Figure 2, and the effect of shear induced lift was quite significant. The induced lift caused particles having a large size and low density to lift inside the inclined channel and convey upwards to the overflow. While the small particles having high density managed to settle and slide backwards along the inclined channel wall towards the fluidization section of the RC. This phenomena improved the recovery of small dense solid particles to the underflow [7]. Figure 3(a-b) shows the plots of D_{50} and Ep values verses particle size, obtained after the introduction of closely spaced inclined channels. The RC with closely spaced inclined channel was termed the RC 2000 model [7].

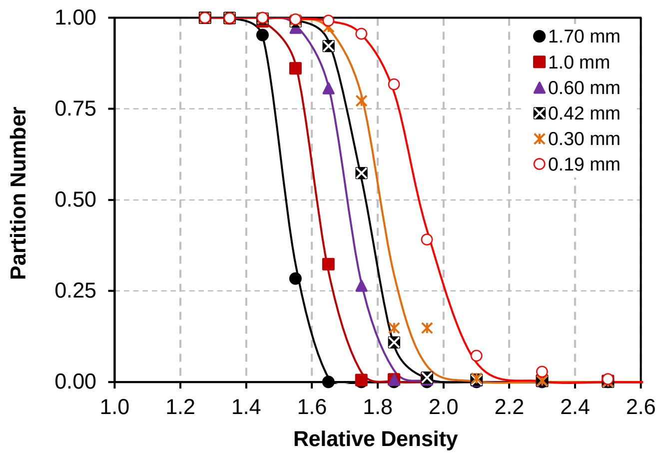

Figure 2. Partition curve from experimental results (Galvin et al., 2010).

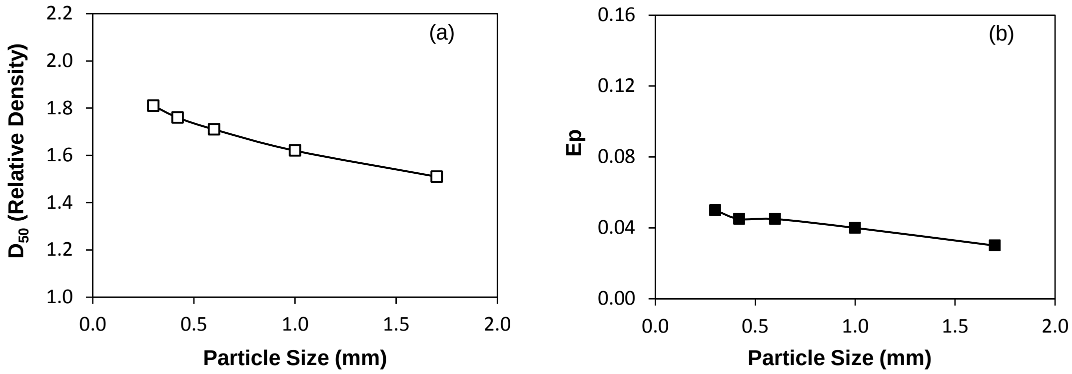

Figure 3(a-b). Experimental results Galvin et al., (2010). a) D_{50} as a function of particle size; b) Ep as a function of particle size, covering the size range -2.0+0.25 mm.

However, prior to 2008, the system was operated using a much wider channel spacing (~120 mm) [1-3, 5, 10, 11]. The model of the RC at that time was termed the RC 1800. Figures 4 and 5(a-b) represent the partition curves, D_{50} and Ep of the system prior to 2008, published in 2005 [10], respectively. The value of overall Ep for -2.0+0.25 mm was 0.15 in that case, proving that the partition curves were not very sharp. While, after the introduction of closely spaced inclined channel, the overall Ep for -2.0+0.25 mm improved to 0.05, which is considerably less than the results obtained in 2005 [7, 10].

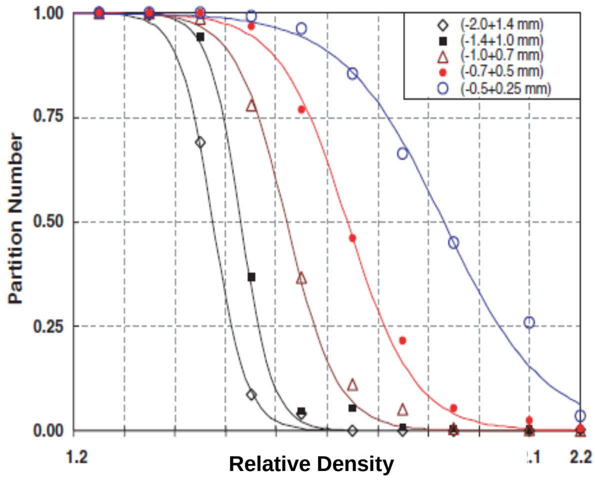

Figure. 4. Partition curves based on individual size fractions (source: Galvin et al., 2005)

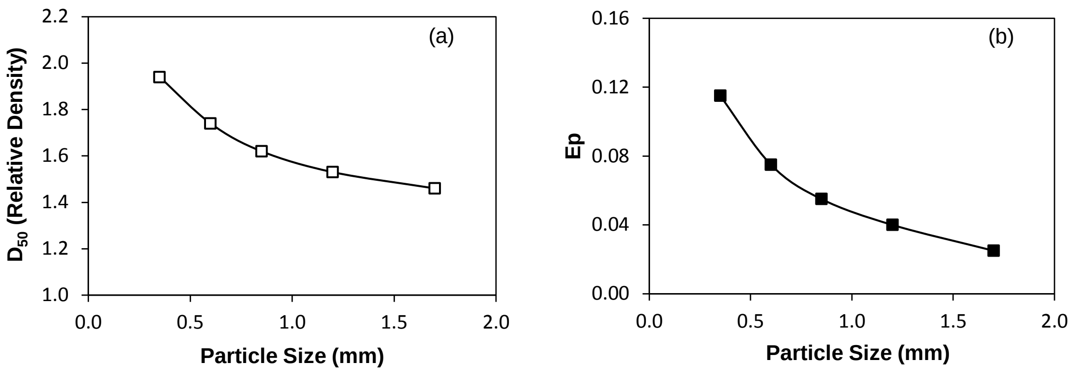

Figure 5(a,b). Experimental results Galvin et al., (2005). a) D_{50} as a function of particle size; b) Ep as a function of particle size, covering the size range -2.0+0.25 mm.

The main purpose of the present work is to modify the continuous segregation-dispersion model of the RC developed by Syed et al. (2015) [12] for multiple component systems in order to better explain particle segregation on the basis of density difference. In the continuous segregation-dispersion model of the RC [12], slip velocity model based upon the Richardson and Zaki model (1954) [13] was used to predict the movement of particle species in the RC. However, in this paper, we have considered the settling model of Asif [14] to investigate the segregation and dispersion of particle species having different densities and sizes at the same time. As a first major step, in the development of the RC model, the effect of shear rate on particle lift has been neglected. The simulation results are therefore compared with the experimental results of the work prior to 2008 which correspond to wide channels. The influence of shear induced lift will be the subject of a further publication.

2 Methodology

The continuous segregation-dispersion model of the RC is a volume flux based model is based on the Kennedy and Breton (1966) approach [12, 15, 16]. The net volume flux of the particle $\mathcal{N}_i$ relative to the column consists of a dispersion flux and a segregation flux [12-16]. It can be expressed mathematically as,

$$\mathcal{N}_i = \phi_i \nu_{pi} = - D_i \frac{\partial \phi_i}{\partial z} + \phi_i \nu_{seg,i} \quad (1)$$

where ν_{pi} is the velocity of the particle species *i* relative to the vessel, D_i the dispersion coefficient, $\nu_{seg,i}$ the segregation velocity and ϕ_i the volume fraction of the particle species. The terms $\partial\phi_i/\partial z$, $-D_i \frac{\partial \phi_i}{\partial z}$ and $\phi_i \nu_{seg,i}$ represent corresponding local concentration gradient, the dispersion flux and the segregation flux respectively.

The total volume flux through the system for a continuous process depends upon the zones below and above the feed points [12]. At the feed point and above, total volume flux through the system is given as,

$$\nu_{fs} + \mathcal{N}_f - \mathcal{N}_u = \nu_f \phi_f + \sum \phi_i \nu_{pi} \quad (2)$$

and below the feed point the total volume flux is given as,

$$\nu_{fs} - \mathcal{N}_u = \nu_f \phi_f + \sum \phi_i \nu_{pi} \quad (3)$$

where $\mathcal{N}_f$ is the total volumetric feed flux, $\mathcal{N}_u$ the underflow flux, ν_{fs} the fluidization flux, ν_f the interstitial fluid velocity and ϕ_f the volume fraction of liquid or the voidage. The superficial velocity ν_o entering into the inclined channel is assumed to have a parabolic shape and is expressed as,

$$\nu_o = \frac{3}{2} \nu_N \frac{d}{z} \left(2 - \frac{d}{z}\right) \quad (4)$$

where d is the particle diameter and ν_N is the total volume flux entering into the inclined channel as given by,

$$\nu_N = \nu_{fs} + \mathcal{N}_f - \mathcal{N}_u \quad (5)$$

Now, the local fluid velocity or interstitial fluid velocity into the inclined channel is obtained as,

$$\nu_f = \frac{(\nu_o - \sum \phi_i \nu_{pi})}{(1 - \sum \phi_i)} \quad (6)$$

Since the continuum model is a 2D model, the velocities of the particle species have components in x and y directions within the RC. In the inclined channel the x and y direction are taken as the normal and parallel directions to the surface of the channel, respectively.

The net fluxes of particle species relative to the vessel in the x and y directions in the fluidization and inclined sections are given as,

$$\mathcal{N}_{x,i} = \phi_i \nu_{p\_x,i} = - D_i \frac{\partial \phi_i}{\partial x} + \phi_i \nu_{seg\_x,i} \quad (9)$$

$$\mathcal{N}_{y,i} = \phi_i \nu_{p\_y,i} = -D_i \frac{\partial \phi_i}{\partial y} + \phi_i \nu_{seg\_y,i} \quad (10)$$

where $-D_i \frac{\partial \phi_i}{\partial x}$ and $-D_i \frac{\partial \phi_i}{\partial y}$ are the corresponding dispersion fluxes. The x and y components of the segregation velocity ($\nu_{seg,i}$) are given as,

$$\nu_{seg\_x,i} = \nu_{slip\_x,i} \quad (11)$$

$$\nu_{seg\_y,i} = \nu_{slip\_y,i} + \nu_f \quad (12)$$

where $\nu_{slip\_x,i}$ and $\nu_{slip\_y,i}$ are the slip velocity of particle species relative to the fluid in the x and y directions respectively.

When multicomponent systems consist of particle species having simultaneously different sizes and densities, in such a way that large particles are light and the small particles are heavy, segregation phenomena become more complex. For instance, such a situation may lead to a layer inversion phenomenon [14, 18]. The Richardson and Zaki (1954) slip velocity model [13], used in the continuum model of the RC [12] previously, cannot describe the layer inversion phenomenon. The Richardson and Zaki (1954) model [13] always predicts upwards movement of particle species having low terminal settling velocity and downwards movement of particle species having high terminal settling velocity [14, 17]. This is because in the Richardson and Zaki (1954) slip velocity model [13], shown in Eq. 13, the particle species have a common hindered settling factor, i.e. $(1-\phi_t)^{(n-1)}$. Hence, particle species having high terminal settling velocities will always have high slip velocities and will move in downwards direction. While, the particle species having low terminal settling velocities will have low slip velocities and will move in upwards direction [17].

$$\nu_{slip,i} = \nu_{ti}(1-\phi_t)^{n_i-1} \quad (13)$$

Asif (1997) [14] proposed a hindered settling model, which is a modified form of the Richardson and Zaki (1954) model [13]. The slip velocity is now a function of suspension density and is given as,

$$\nu_{slip,i} = \nu_{ti}\left(\frac{\rho_i - \rho_{sus}}{\rho_i - \rho_f}\right)^{n_i-1} \quad (14)$$

where ρ_i is the density of the particle species *i*, ρ_f the fluid density and ρ_{sus} the suspension density or bulk density of the bed.

The suspension density of the bed is given by,

$$\rho_{sus} = \sum \phi_i \rho_i + (1 - \sum \phi_i)\rho_f \quad (15)$$

The hindered settling factor, i.e. $\left(\frac{\rho_i - \rho_{sus}}{\rho_i - \rho_f}\right)^{n_i-1}$, in Eq. 14, is based upon suspension density of the particle species rather than the volume fraction of the particle species [14]. The model can be used to describe separation on the basis of density difference and layer inversion behaviour in the liquid fluidized beds with particle species having different density and size at the same time [14, 17, 19].

Therefore, when dense particle species reach a region of high concentration of low density particle species, the dense particle species experience less hindered settling effect relative to the low density particle species. Such situation causes the dense particle species to move in the downwards direction. On the other hand, when low density particle species reach in a region of high concentration of dense particle species, the low density particles experience a high level of hindered settling. This effect causes the low density particle species to move in the upwards direction [14, 18].

Now the x and y components of the slip velocity in the fluidization and in the inclined sections are calculated as,

$$\nu_{slip\_x,i} = \left[\nu_{t,i}\left(\frac{\rho_i - \rho_{sus}}{\rho_i - \rho_f}\right)^{n_i-1}\right]\cos\theta \quad (16)$$

$$\nu_{slip\_y,i} = \left[\nu_{t,i}\left(\frac{\rho_i - \rho_{sus}}{\rho_i - \rho_f}\right)^{n_i - 1}\right]\sin\theta \tag{17}$$

As material may moves out from the system as an overflow, a free boundary condition has been taken at the top (i.e. outlet) of the system. The dispersion flux was also taken as zero at the top of the system. Similarly, at the bottom the flux is equal to the underflow flux of the system. The boundary conditions are,

$$z = z_{max} \qquad \text{Free boundary, } D_i \frac{\partial \phi_i}{\partial x} = 0,\ D_i \frac{\partial \phi_i}{\partial y} = 0 \tag{18}$$

$$z = 0 \qquad \mathcal{N}_{y,i} = \mathcal{N}_u \tag{19}$$

The Particle Reynolds number, Re_t, was found using Zigrang and Sylvester (1981) equation [20]:

$$Re_t = \left[\left(14.51 + 1.83\left(g\times(\rho - \rho_f)\rho_f\right)^{0.5}\frac{d^{1.5}}{\mu}\right)^{0.5} - 3.81\right]^2 \tag{20}$$

where μ is the viscosity of the fluid. The particle terminal settling velocity was calculated using Eq. 21,

$$Re_t = \frac{\rho_f\, \nu_{t,i}\, d}{\mu} \tag{21}$$

A fixed value of exponent n, i.e. 3.2 based upon average values for system of particles (which can be considered as a fitted parameter), was taken in the simulations.

Partition curves on the basis of partition number, P, as a function of particle relative density, D, were obtained from the simulations. If the value of P is 0.5, it means that D_{50} is 0.5 or 50 %, whereas D_{50} represents the relative density of a particle species having 50% probability of reporting either to the overflow or the underflow. The data points have been fitted by using the function:

$$P = \frac{1}{1+\exp\left(-\frac{\ln 3\,(D_{50} - D)}{E_p}\right)} \tag{22}$$

where Ep is calculated as [21],

$$E_p = \frac{D_{75} - D_{25}}{2} \tag{24}$$

where D_{75} and D_{25} represent the relative density of the particle species that have 75% and 25% probability of reporting to the overflow respectively.

2.1 Simulation parameters

Simulations were performed for multiple particle species systems in the absence of shear induced lift in order to validate the experimental results for wide inclined channels prior to 2008. The dimensions of the system were taken as 1 m each for the height of fluidization section and length of the inclined channel. The vertical section has a cross sectional area of 6 mm x 6 mm. The channel spacing of the inclined section was found as ksinθ, where k is the width of the fluidized section (i.e. vertical section) and θ is the angle that the inclined channel forms with the horizontal. One inclined channel forming a 70^0 angle with the horizontal plane was considered in the simulations. The whole system was divided into 100 shells in y-direction and 11 elements in x-direction. Element number 1 is the nearest element to the inclined surface in the inclined channel while element number 21 is the nearest to the upper surface of the inclined channel. The fluidization region had a height of 1 m and the feed inlet point was taken at a height of 0.7 m (~shell no. 35). The inclined channel started from a height of 1 m above the bottom of the unit (~shell no. 51).

Simulations were performed for 35 particle species and the results were validated with the experimental results of Galvin et al. (2005) [10]. The particle size ranges considered were: -2.0+1.40 mm, -1.40+1.0 mm, -1.0+0.70 mm, -0.7+0.50 mm and -0.50+0.25 mm [10]. The properties of the particle species are given in Table 1. A fixed value of the exponent n, (~ 3.2) was taken in all the simulations.

Table 1: Particle properties

Particle size (mm)	Particle density (kg/m^3)	Particle Reynolds number	Terminal velocity (m/s)
1.70	1400	158.12	0.093
1.70	1500	181.31	0.11
1.70	1600	202.62	0.12
1.70	1700	222.33	0.13
1.70	1800	240.92	0.14
1.70	1900	258.41	0.15
1.70	2000	275.12	0.16
1.20	1400	81.72	0.068
1.20	1500	94.40	0.079
1.20	1600	106.0	0.088
1.20	1700	116.90	0.097
1.20	1800	127.10	0.10
1.20	1900	136.80	0.11
1.20	2000	146.00	0.12
0.85	1400	41.00	0.048
0.85	1500	47.74	0.056
0.85	1600	54.00	0.064
0.85	1700	59.82	0.070
0.85	1800	65.41	0.077
0.85	1900	70.61	0.083
0.85	2000	75.72	0.089
0.60	1400	19.60	0.033
0.60	1500	23.00	0.038
0.60	1600	26.20	0.044
0.60	1700	29.20	0.049
0.60	1800	32.14	0.054
0.60	1900	34.91	0.058
0.60	2000	37.50	0.063
0.35	1400	5.62	0.016
0.35	1500	6.71	0.019
0.35	1600	7.82	0.022
0.35	1700	8.81	0.025
0.35	1800	9.81	0.028
0.35	1900	10.70	0.031
0.35	2000	11.60	0.033

A total feed slurry flux of 0.016 $m^3/(m^2s)$ containing a total solid flux of 0.004 $m^3/(m^2s)$ with equal mass fractions of each species and water flux of 0.012 $m^3/(m^2s)$, was considered. The fluidization rate was kept at 0.005 $m^3/(m^2s)$ and the underflow flux was set at 0.004 $m^3/(m^2s)$ in the simulations. The results obtained from the simulations were used to produce partition curves and were compared with the experimental results of Galvin et al. (2005).

3 Results and Discussion

Figure 6 shows the partition curves obtained from the simulations. The partition curves are based upon individual sizes having different densities. The results obtained through simulations, shown in Figure 6, exhibit a very good agreement with the experimental results of Galvin et al. (2005) [10] shown in Figure 4. Figure 6 shows that the partition curves shift towards higher relative particle density as the particle size decreases, indicating that the D_{50} increases with a decrease in particle size. This fact qualitatively agrees with typically experimental observations [10]. Similarly, it was observed that the value of the inclination of the curves decreased as the particle size increased indicating an increase in Ep.

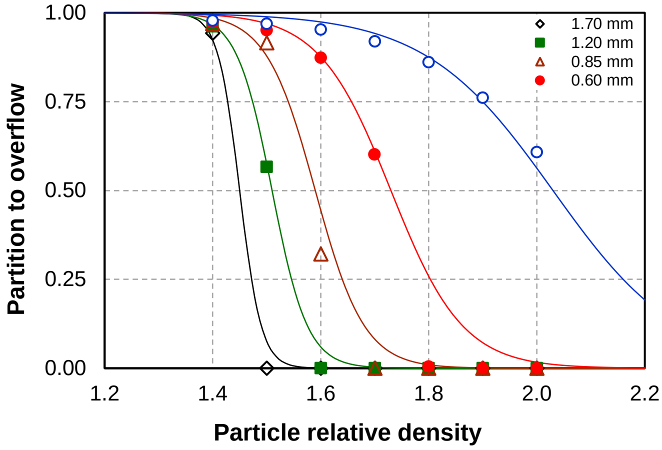

Figure 6: Partition curves obtained through simulations

Figure 7 shows the D_{50} values as a function of particle size and provides a comparison between the simulation results and the experimental results of Galvin et al. (2005) [10]. The dashed curve represents the experimental results while the continuous curve with circles depicts the simulation results. The simulation results showed very good agreement with the experimental results for the whole range of particle size.

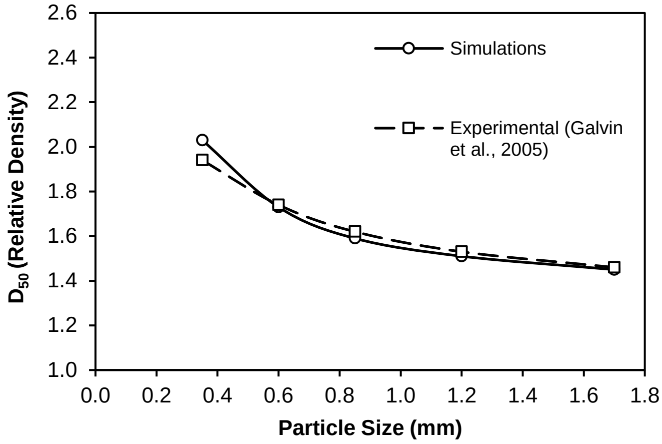

Figure 7: D_{50} as a function of particle size

Similarly, Figure 8 shows the comparison between the Ep values obtained from the simulations and the experimental results of Galvin et al. (2005) [10]. The Ep values are plotted as a function of particle size. The dotted curve in Figure 7 represents the experimental results and demonstrates that the value of Ep decreased with increase in particle size. A similar trend for Ep to that of the experiments was found through simulations and has been shown as smooth curve with circles in the Figure 8. The simulation and experimental results showed a very good agreement.

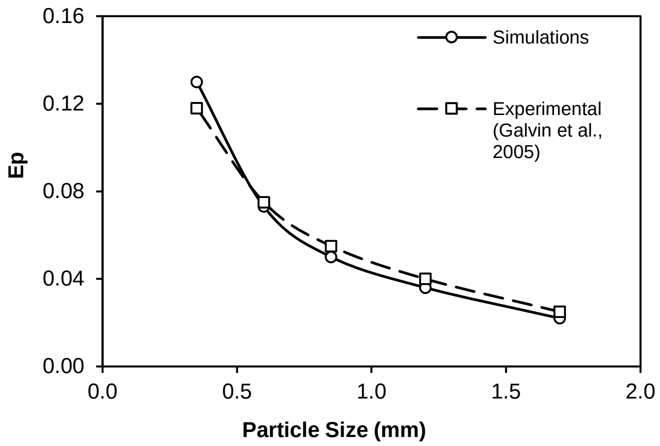

Figure 8: Ep as a function of particle size

Figure 9(a-c) shows the plot of total solid volume fraction as a function of height in the fluidization and inclined section of the RC for element numbers 1, 6 and 11 (Fig. 9 a, b and c, respectively). Figure 9(a-c) shows that the total solid volume fraction in the fluidization section remains same in all the elements, confirming that the suspension concentration in the fluidization section is uniform. In contrast, the total solid volume fraction showed some variations within the inclined channel. The concentration of solid particles is high in element no. 1 because most of the particles settled at the surface of the inclined channel and slid back towards the fluidization section of the RC. The total solid volume fraction in element numbers 6 and 11 is slightly smaller as compared to element number 1. However, the individual volume fractions of the particle species changed significantly with increase or decrease in the element numbers depending upon the type of particle species.

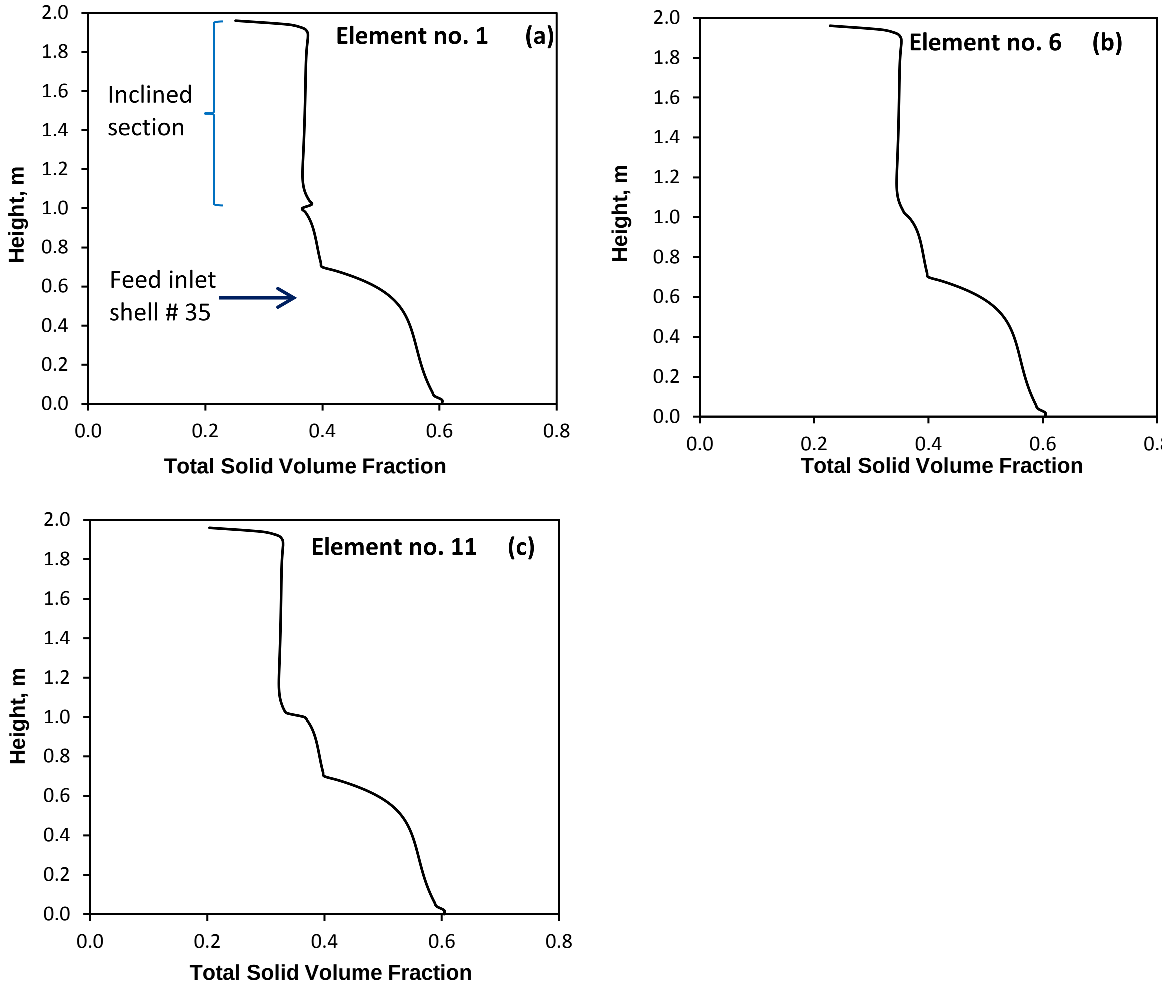

Figure 9(a-c): Total solid volume fraction vs height of the RC

3.2 Analysis of separation size D_{50}

Figures 10 and 11 show the solid volume fraction distribution for particle with sizes of 0.60 and 0.85 mm, respectively. The data correspond to the steady state which was obtained approximately in 50 min. The dashed line curves shown in both Figures 10 and 11 indicate the particle species whose density is closest to the D_{50} whose values are 1.73 and 1.59, respectively.

Figure 10 shows that the particle species with density of 1700 kg/m^3 has the largest presence in the system as it is the particle species closest to the D_{50}. The particle species with density of 1800 kg/m^3 also exhibits a high concentration in the system as compared to the other particle species. However, the particle species at 1800 kg/m^3 density has a higher concentration in the fluidization section of the RC and its concentration dropped with increase in height in the inclined section, showing that most of it was discharging from the system as underflow. As expected, the lighter density particle species have lower concentrations in the fluidization section and higher concentrations in the inclined channel, as compared to higher density particle species and therefore, they are going out from the system as an overflow.

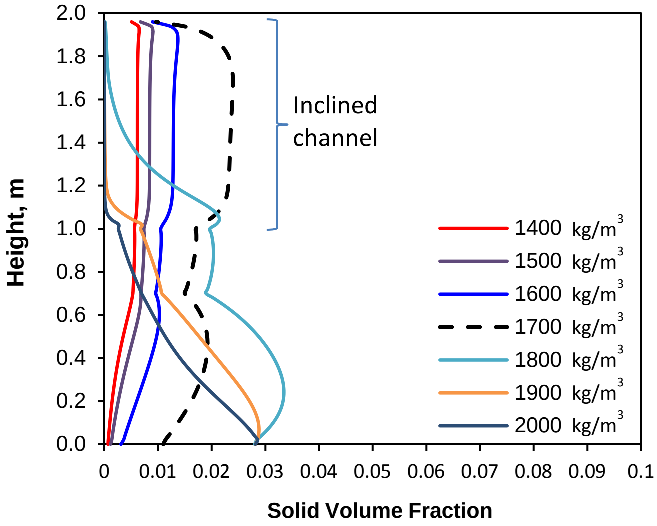

Figure 10: Individual solid volume fraction of particle size 0.60 mm in the RC

Figure 11 shows that the particle species with a density of 1600 kg/m³ has the largest presence in the system in both the fluidization and inclined sections of the RC. The particle species with density 1600 kg/m³ has equal probability to go either as overflow or discharge from the bottom of the RC as underflow. In contrast, the particle species of density 1700 kg/m³ shows the higher concentration in the fluidization section of the RC and its concentration dropped with increase in height in the inclined section. Similarly, particles species with lower density (<1600 kg/m³) have higher concentration in the inclined section of the RC as compared to denser particle species.

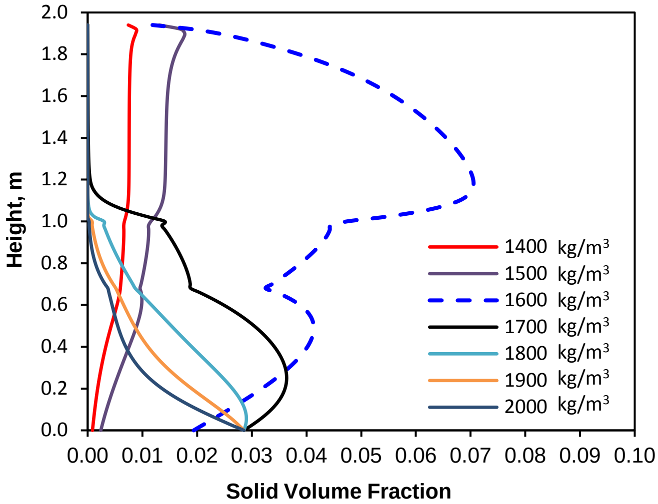

Figure 11: Individual solid volume fraction of particle size 0.85 mm in the RC

The above discussion clearly shows that the particle bed was mainly comprised of particles whose densities are close to the D_{50} of the system.

4 Conclusions

The simulation results show that it is possible to accurately predict the coal and mineral separation performance of the Reflux classifier under the conditions of wide channels (prior to the developments of 2008). The experimental particle size distribution was approximated by a set of 35 particle species having different sizes and densities. The computer model incorporated the hindered settling model of Asif as a way to consider the hindered settling dependence on the particle suspension density. The simulation results show an excellent agreement with the experimental results, by accurately predicting the D_{50} and Ep values of a multicomponent system.

Computer simulations also enabled us to monitor the total and individual solid volume fraction within the RC. It has been observed that particles, whose densities are close to the D_{50} values, show a continuous presence in the fluidization and inclined sections of the RC, and form the major part of the suspension within the system.

Thus the basic framework for incorporating the effects of shear induced lift in the segregation-dispersion model of the RC is now in place and in this way show the full capacity of the Reflux classifier to beneficiate different mineral feeds.

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