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Enhanced Recovery and Concentration of Positively Buoyant Cenospheres from Negatively Buoyant Fly Ash Particles using the Inverted Reflux Classifier

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Abstract

The enhanced separation of valuable positively buoyant cenosphere particles from negatively buoyant fly ash particles using an Inverted Reflux Classifier (IRC) was examined. The effect of the suspension density on the recovery and concentration was examined in the IRC by operating at different feed pulp densities ranging from 10 wt% to 46 wt%. Using a sufficiently high fly ash concentration, it was hypothesised that a powerful bulk streaming phenomenon develops (Batchelor, G.K., Van Rensburg, J., 1986, Structure formation in bidisperse sedimentation, J. Fluid Mech, 166, 379-407) within the inclined channels, driving the segregation between the positively and negatively buoyant species. With the feed flow rate, fluidization rate, and flow split to overflow and underflow fixed, the recovery of the cenospheres increased from 61.7% (at 10.1% solids) through to an optimum recovery of 89.9% (at 38.1% solids), before declining rapidly to a recovery of 60.2% (at 46.4% solids). The performance at the optimum of 38.1% pulp density was remarkable, with 3.1 t/(m² h) solids throughput, a single-stage cenosphere recovery of 89.9% and upgrade of 58.6, and throughput advantage over a conventional fluidized bed of 54. Detailed analysis indicated that the inclined channels produced an underlying throughput advantage of 18, with a further factor of 3 attributed to the bulk streaming phenomenon. The separations were also assessed in terms of the partitioning of the cenospheres between the overflow and underflow exit streams, with the sharpest size classification evident at the optimum feed pulp density, with the $d_{25}=31.5\text{ }\mu\text{m}$, $d_{50}=36.5\text{ }\mu\text{m}$, and $d_{75}=50.0\text{ }\mu\text{m}$. The separation was then investigated using different feed flow rates, providing the basis needed for ensuring optimum performance in future pilot scale investigation of this novel technology.

Keywords: dense medium, Reflux Classifier, positively buoyant, cenosphere, fly ash

1. Introduction

Even though some applications have been found for fly ash, on average about 60% of this material is still discarded to the surrounding environment of coal fired power stations (ADAA, 2005). This waste can be considered a resource if the valuable components of the fly ash can be recovered and concentrated. One of the most useful and valuable components is cenospheres, hollow spherical silica - alumina particles, exhibiting a very low bulk density, high strength and good insulation.

Wet gravity separation is the best method for separating positively buoyant cenospheres from fly ash given the significant difference between the densities of fly ash, cenospheres and water. However, being very fine and having a density close to the density of water, the cenosphere rise velocity in water is relatively low. Therefore a method to increase the segregation velocity of the particles is crucial. Boycott (1920) observed a significantly larger segregation rate in a tilted tube compared to vertical tubes, leading to the development of inclined settlers (Acrivos and Herbolzheimer, 1979; Leung and Probst, 1983; Masliyah et al., 1989). This phenomenon is also exploited via the Reflux Classifier system.

The Reflux Classifier, a combination of a system of inclined channels and a conventional fluidized bed, has been investigated extensively by Galvin and co-workers (Galvin, 2012; Galvin and Liu, 2011; Laskovski et al., 2006; Zhou et al., 2006) in a range of coal and mineral applications. More recently, Kiani et al., (2015) investigated the potential of an Inverted Reflux Classifier (IRC) (i.e. a Reflux Classifier placed in an inverted position) in concentrating and recovering positively buoyant cenospheres from fly ash. The present study builds directly on the previous research, utilizing a dense medium effect to promote an even more powerful overall separation.

Richardson and Zaki (1954) have provided a description of the hindered settling that develops through an increase in the volume fraction of the solids. However, for systems involving particle species of different density there remains much ambiguity, especially in terms of the phenomenon known as phase inversion (Moritomi et al., 1986). Moreover, there is considerable complexity in suspensions containing positively buoyant and negatively

buoyant particles, producing enhanced rates of segregation (Fessas and Weiland, 1984, 1981; Weiland and McPherson, 1979; Whitmore, 1955). This phenomenon referred to as bulk streaming motion was thoroughly investigated and then reported to be largely dependent on the species size, density and their volume fractions in the suspension (Batchelor and Van Rensburg, 1986). The phenomenon was also investigated for a system containing both heavy and buoyant particles segregating within an inclined settler. Interestingly, there were no signs of the phenomenon for suspensions at a low total volume fraction of solids (Law et al., 1988).

We therefore hypothesize that in the present study the streaming structure formation, and in turn segregation between the two species might develop through an increase in the feed solids concentration of the fly ash. The dense medium produces a higher effective buoyancy driving force, promoting the upward movement of the cenospheres, although the higher effective viscosity should counter this effect to a degree. The overall enhancement should be promoted further by the segregation that develops within the inclined channels, reflecting the combination of the two effects. In this paper we investigate for the first time the segregation enhancement arising from the dense fly ash medium surrounding the cenospheres by examining the separation performance in the IRC as a function of the feed pulp density, at a fixed volumetric rate. Once optimised with respect to the feed pulp density, the operation is further explored as a function of the feed rate.

2. Theory

This section provides relevant background on the suspension hydrodynamics and the particle transport in the Reflux Classifier.

2.1 Hindered Settling

For spherical particles settling in the Stokes regime, the following explicit equation describes the terminal settling velocity (U_t) of the particles in the fluid. That is,

$$U_t = d_p^2(\rho_p - \rho_f)g/18\mu \quad (1)$$

where d_p and ρ_p are the particle diameter and density respectively, ρ_f and μ are the fluid density and viscosity respectively, and g is the acceleration due to gravity. For particles less

dense than water, the above equation generates negative values, consistent with an upward movement relative to the fluid.

In concentrated suspensions, the particles are no longer isolated and hence the above equation no longer applies. For homogeneous suspensions, Richardson and Zaki (1954) proposed the following empirical result to describe the hindered settling velocity. That is,

$$U_h = U_t \varepsilon^n = U_t (1-\varphi)^n \quad (2)$$

where ε is the voidage, φ the volume fraction of the solids and U_t the unhindered terminal settling velocity. Equation 2 can be modified to describe the slip velocity of a given species present in a suspension of identical particles or in a polydisperse suspension of particles of the one density. Where a suspension involves different particle densities the result is much more complex, requiring consideration of the suspension density (Asif, 1997). For cenospheres with a density of about 802 kg/m³ in a fly ash suspension of density 1214 kg/m³ (38% pulp density, with the fly ash density 1863 kg/m³), the effective density driving force in the concentrated suspension is 412 kg/m³, and about 198 kg/m³ in a dilute suspension. These data, derived from the conditions of this study, give a dimensionless density ratio of 2.1. However, the suspension viscosity, relative to the viscosity of the underlying liquid, increases by a similar factor, hence the pseudo fluid approach fails to account for any significant effect.

2.2 Bulk streaming motion

In suspensions containing both positively and negatively buoyant species, under the specific conditions leading to instabilities in the suspensions, the particles from each species gather together and form a chain of clusters moving as a bulk in the suspensions. Therefore the velocities of the species remarkably increase due to the significant convective effects of these clusters or streams. The instabilities are necessary for the development of the bulk streaming structure and segregation. Batchelor and Van Rensburg (1986) developed a regime map based around dimensionless quantities to describe the circumstances that would lead to the instabilities in the suspension. Four dimensionless parameters, the ratio of the species radii ($\lambda=a_2/a_1$), the ratio of the reduced density of the two species ($\gamma=(\rho_2-\rho_f)/(\rho_1-\rho_f)$), and the volume fractions of the two species (ϕ_1 and ϕ_2) were used to specify different two-component

suspensions. Here ρ_1 and ρ_2 are the densities of the two species, ρ_f is the density of the fluid, while 1 and 2 denote the two species. Possible instabilities in the suspensions containing both positively and negatively buoyant particles were examined for two different cases, providing two different regime maps (Batchelor and Van Rensburg, 1986). For the case study involving $\lambda=1$, $\gamma=-1$ and variable values of ϕ_1 and ϕ_2 , this work suggests the cenosphere concentration within the fly ash should be too low for instabilities to occur. However, in the vicinity of the downwards facing inclined surfaces much higher concentrations of the cenospheres should develop, hence the benefits arising from the associated instability of the suspension may be observed.

2.3 Reflux Classifier

A Reflux Classifier consists of parallel inclined channels mounted above a vertical fluidized bed. This system, which is now well established in the industry, provides a basis for understanding the hydrodynamics of the Inverted Reflux Classifier system being investigated here. The hydrodynamics of the Reflux Classifier have been examined previously by Laskovski et al., (2006). They based the theoretical throughput advantage on the projected area of the inclined channels, relative to the vessel area. That is,

$$F = 1 + (L/z)\cos\theta\sin\theta \quad (3)$$

where θ is the inclination angle with respect to the horizontal in degrees. L and z are the length of the plate and the perpendicular width of the inclined channels, respectively, both in meter. The actual throughput advantage is given by (U/U_t) , where U is the suspension velocity up through the vertical section, just prior to the inclined channels, and U_t the terminal velocity of the particle that has an equal tendency to either be retained within the system (and report to underflow) or elutriate to overflow. The actual throughput advantage, however, is often considerably lower than F . Hence, Laskovski et al., (2006) introduced a factor called the segregation efficiency given by,

$$\eta = (U/U_t)/F \quad (4)$$

Using Dimensional Analysis, they developed an empirical expression for the segregation efficiency,

$$\eta = 1/(1+0.133\cos\theta Re^{1/3} (L/z)) \quad (5)$$

where Re is the particle Reynolds number. Thus the actual throughput advantage is given by,

$$U/U_t = (1+\cos\theta\sin\theta (L/z))/(1+0.133\cos\theta Re^{1/3} (L/z)) \quad (6)$$

By taking the limit as the aspect ratio, L/z , approaches infinity, the actual throughput advantage asymptotes to,

$$U/U_t = 7.5 Re^{-1/3} \quad (7)$$

where U is the superficial suspension velocity within the inclined channels. As shown in our previous paper (Kiani et al., 2015), the Inverted Reflux Classifier provides significant advantages over the Reflux Classifier and conventional fluidized beds in separating positively buoyant particles, delivering very high grade due to the inverted fluidization, and a throughput advantage due to the system of inclined channels. The purpose here is to incorporate additional benefits arising from the strong dense medium of the fly ash, and associated bulk streaming that can develop for unstable suspensions consisting of positively and negatively buoyant particles.

3. Experimental

3.1 Equipment

An Inverted Reflux Classifier (IRC) was applied to the separation of cenospheres from fly ash. The system of channels was inclined at an angle of 70° to the horizontal, consistent with the standard Reflux Classifier. The channels had a length of 1 m and perpendicular spacing of 0.0095 m. Fluidization water, regulated by a rotameter, was introduced into a distribution chamber located at the top of the device, to wash fine gangue particles from the rising product. Two pressure sensors were installed in the vertical fluidized bed section, providing a measure of the suspension density of the system. A net positive pressure was maintained

using a stand-pipe arrangement, with a vented exit point located 1 m above the system. The system was operated by discharging some portion of the underflow tailings upwards through this vented exit point. This approach ensured the system remained full. A schematic representation of the experimental set-up is shown in Figure 1.

3.2 Methodology

The fly ash used in this study was sourced from an Australian coal fired power station. The grade of the cenospheres in the fly ash defined as the mass of the cenospheres divided by the total mass of solids was in the order of 1 wt%. Feed slurry, with a given pulp density, was prepared by mixing for several hours in the feed tank. The feed was sourced via a tube with its end point located 80 mm from off the bottom of the feed tank. The feed was supplied to the IRC via a peristaltic pump at an elevation 300 mm above the system of inclined channels.

When the fly ash entered the system there was a natural tendency for the positively buoyant cenospheres to rise upwards, while a significant proportion would have been entrained downwards with the rest of the fly ash, and into the inclined channels. Moreover, the downwards fluidization resulted in a downwards flow of wash water, and increased tendency for the ultrafine fly ash to convey towards the entrance of the inclined channels. Meanwhile, the washed cenospheres were permitted to discharge via the central overflow exit point.

The suspension of fly ash and cenospheres experienced a strong degree of segregation within the inclined channels, with the denser particles migrating towards the upward facing surfaces and the positively buoyant cenospheres migrating towards the downwards facing inclined surfaces. These cenosphere particles had a strong tendency to then return back towards the vertical section of the IRC, located above the inclined channels. Once steady state was reached, equally timed samples were taken from the product and the tailings streams in order to preserve the grade of the remaining cenospheres in the feed for future experiments.

3.3 Measurements

3.3.1 Sink - float experiments

All of the samples were analysed using the sink-float method via separating funnels as shown in Figure 2A. During the first few hours, the contents were disturbed in order to release entrained ultrafine dense particles in the layer of concentrated cenospheres. The dense fly ash component was discharged through the base of the funnel and into a bucket. Given some fine cenosphere particles were entrained by the fly ash to the sinks, a method was applied to recover these cenospheres. The material in the bucket was stirred very slowly allowing the settling of the heavy particles, leaving behind the entrained cenospheres as shown in Figure 2B. These were then returned to the separating funnel. By repeating this method several times, it was possible to achieve good reconciliation in the cenosphere material balance. The cenospheres and dense fly ash components were then dried and weighed, allowing the concentrations and recovery to be quantified.

3.3.2 The particle size distribution

Laser light scattering (Malvern Mastersizer 2000) was used to measure the size distributions of the cenospheres and fly ash solids present in the feed, product, and tailings. Mass balance reconciliation was used to make minor adjustments in the size distributions, and to in turn quantify the partition curves, and hence the nature of the size classification. This is a standard practice, utilizing a Simplex algorithm to achieve a least squares data adjustment according to material balance requirements and an objective function based on the data adjustment (Galvin et al., 1995). The particles exhibiting a 25%, 50% and 75% probability of reporting to the product are referred to as the d_{25} , d_{50} and d_{75} , respectively. The sharpness of the particle size separation can be described using the Imperfection, $I = (d_{75} - d_{25}) / (2d_{50})$ (Wills, 1997). Figure 3 illustrates a typical partition curve, showing the key parameters.

3.3.3 Fly ash properties

The sink-float method of separation was applied to the feed prior to commencing the first experiment, producing the positively buoyant cenosphere particles and negatively buoyant fly ash particles. Gas pycnometry was applied to each portion. The density of the cenospheres was found to be 802 kg/m^3 and the density of the remaining fly ash 1880 kg/m^3 , while the density of the overall fly ash, based on a separate sample of the feed, was 1863 kg/m^3 . Note that at a feed pulp density of 38.1%, the volume fraction of the solids is 0.248, hence the calculated suspension density is $0.248 \times 1863 + (1 - 0.248) \times 1000 = 1214.0 \text{ kg/m}^3$.

The size distributions of the cenospheres and fly ash solids in the feed, obtained by laser light scattering, are shown in Figure 4. The fly ash covers a broad range of particles size from 1 μm to about 200 μm , while the cenospheres size range is from about 20 μm to 200 μm .

4. Results and Discussion

The purpose of this research was to investigate the separation performance of the Inverted Reflux Classifier (IRC) on a fly ash feed sourced from a coal-fired power station. The primary goal was to establish the effect of the feed pulp density on the upgrade and the recovery of the cenospheres. The hypothesis was that there should be a strong enhancement in the performance when the concentrations of the positively and negatively buoyant particles reach a sufficient level. In principle, at a fixed volumetric rate, the separation performance should decline as the solids concentration increases due to the increased level of hindered settling. But if the conditions can yield the necessary instability necessary for streaming structures to develop in the suspension, then the performance should improve up to a point with increasing the solids concentration. The second objective was to explore the system performance at the optimum feed pulp density, varying the feed rate and overflow rate.

All experimental data points, including the operating conditions of each experiment, and also the mass balanced grade and recovery values were presented in Table 1. The inlet total mass of the slurry, solid fly ash, and cenospheres to the IRC compared to their outlet mass values were also presented in this table, demonstrating the consistency of the raw data. These data indicated a mere +/-2% discrepancy in most cases for the slurry and fly ash solids mass. However, owing to the small proportion of cenospheres in the separation process, and also difficulties in recovering all of the cenospheres in the sink and float technique, the discrepancy between the input and output for this component was higher at about +/-10%. This table also provided further details on the mass balance reconciliation.

4.1 The effects of the dense medium on the separation of positively buoyant cenospheres from fly ash in the IRC

In this section, the effect of the dense medium on the grade and the recovery of cenospheres in the IRC were investigated using different feed pulp densities (i.e. 10.1%, 19.2%, 30.7%, 38.1% and 46.4% by weight). The feed and fluidization water volumetric fluxes were kept constant in all experiments at an average of $7.18 \text{ m}^3/(\text{m}^2 \text{ h})$ and $0.87 \text{ m}^3/(\text{m}^2 \text{ h})$, respectively. In all experiments, almost 20% of the volumetric feed flux went to the product. As the difference between the product and the fluidization water volumetric fluxes were the same in all experiments conducted at different feed pulp densities, the product grade remained almost constant at about 70%. These results, shown in Figure 5, are consistent with the findings of the previous paper (Kiani et al., 2015) which showed the difference between the product and the fluidization water fluxes (i.e. P-W) as a significant factor in controlling the product grade. This factor, P-W, was about $0.62 \text{ m}^3/(\text{m}^2 \text{ h})$ in the present study. It is noted that the results of the previous paper, calculated using a width of 90 mm for the IRC, were adjusted here according to the more accurate width of 86 mm.

Figure 6 shows the cenosphere recovery as a function of the feed pulp density. In run 1, operating with a dilute feed (i.e. about 10.1 wt% pulp density), 61.7% of the cenospheres were recovered. By increasing the solids content of the feed to about 38.1 wt%, the recovery increased to 89.9%, an extraordinary result. In other words, the solids processing rate increased significantly, and in turn the separation performance increased significantly. However, when the feed pulp density increased to about 46.4 wt% the recovery dropped to just over 60%, revealing a clear optimum in the separation conditions. According to Figures 6, the optimum feed pulp density was found to be about 38%. In fact this optimum point reflects the dominant positive effects of the streaming phenomenon up to the pulp densities of about 38% and the dominant negative hindering effect of the suspension viscosity at higher pulp densities on cenospheres recovery.

As previously discussed, the rise velocity of positively buoyant particles can be increased *en-masse* if the streaming structure develops. This condition is most likely within the inclined channels where the cenospheres segregate strongly forming higher concentrations. Commencing off a low base, the cenosphere concentration increases with increasing feed pulp density, possibly reaching the critical value required for instability and hence formation of clusters. This cluster structure then results in a significantly larger entity and higher buoyancy driving force, increasing the cenosphere recovery. However the effect of the

suspension viscosity on hindering the cenospheres becomes dominant with increasing the feed pulp density further than a critical value, and hence the cenospheres recovery decreases.

4.2 Dense medium effects on the particles size classification in the IRC

In this section, the effect of the dense medium on the size classification of the cenospheres in the IRC is examined. Figure 7 illustrates the cenosphere size distributions of the feed, the underflow tailings, and the overflow product based on run 4 which was performed at about 38.1 wt% feed pulp density. As expected, the fine cenosphere particles are mostly present in the underflow tailings. This figure also shows that almost no cenospheres larger than 100 μm were lost in the tailings.

The partition to product versus the size of the cenospheres was obtained using the cenosphere size distributions in all three streams. Figure 8 shows the partition curves for different feed pulp densities. The partition curve at the optimum feed pulp density (38.1% by weight) is clearly the sharpest, while the poorest occurs at the highest feed pulp density of 46.4% solids. Table 2 shows the corresponding values of the d_{50} and Imperfections. The theoretical throughput advantage based on the system geometry and particle Reynolds number at the d_{50} size, calculated using Equation 6, is shown. These values take into account the thickness of the plates, which limit the flow area by 7%. The actual throughput advantage derived from the experiments is also shown. Neglecting the expected errors, the discrepancies between the theoretical and actual throughput advantages are largely attributed to a concentration induced enhancement arising from the positively buoyant cenospheres which concentrate near the downward facing inclined surfaces, within an environment of negatively buoyant fly ash particles.

Consider now an analysis at the optimum feed pulp density of 38.1% solids, with the d_{50} equal to 36.5 μm . The state of the suspension within the inclines can be estimated using the tailings pulp density (40.3% solids) and the density of the solids in the tailings (1880 kg/m^3), corresponding to a volume fraction of 0.264. The density of the cenospheres within the inclined channels should be well represented by the feed value, 802 kg/m^3 . Thus the terminal velocity of the d_{50} particle is 0.52 m/h, with corresponding Reynolds number equal to 0.0052. The hindered settling velocity based on Equation 2 is 0.13 m/h using $n=4.5$. Using the

tailings flux of about $7 \text{ m}^3/(\text{m}^2 \text{ h})$ to denote the superficial velocity through the system of inclined channels, the throughput advantage becomes $7/0.13=54$, a remarkably large value. This result is significantly higher than the value predicted using Equation 6, given by $U/U_t=18$. The ratio, $54/18=3$, denotes the concentration induced enhancement.

Figure 9 shows the concentration induced enhancement as a function of the feed pulp density. The result expected for stable suspensions is given by the horizontal dash line at 1.0. The result obtained at a feed pulp density of 19.2% solids involved an actual throughput advantage of 15, while the theoretical value predicted by Equation 6 is 16, giving a concentration induced enhancement of 0.93, close to 1.0. The errors here are considerable given the reliance on the Richardson and Zaki equation for describing the hindered settling of the cenospheres within the fly ash. The error bars shown are based on the results calculated using the d_{25} and d_{75} values from the partition curves of Figure 8. The true error should be well within this range. Hence we conclude the strong concentration induced enhancement is a real and significant effect. The error bars are amplified by the low hindered settling velocities that arise at the highest concentrations.

4.3 Enhanced throughput at the optimum feed pulp density

In this section the effect of a higher volumetric feed flux of about $10.5 \text{ m}^3/(\text{m}^2 \text{ h})$ was examined at the determined optimum feed pulp density of 38.1 wt%. This work was motivated by the need to maximize the solids throughput, while ensuring sufficient recovery. Thus, in this set of experiments, the feed solids mass flux was set higher at $4.7 \text{ t}/(\text{m}^2 \text{ h})$ while the fluidization water flux was kept constant at about $1.05 \text{ m}^3/(\text{m}^2 \text{ h})$. Figure 10 shows the effects of different product fluxes on the product grade and recovery. By increasing the product flux from $0.74 \text{ m}^3/(\text{m}^2 \text{ h})$ to $1.95 \text{ m}^3/(\text{m}^2 \text{ h})$, the product grade decreased from 89.7 to about 20.8. However the recovery increased from 36.4% to about 79.7%. This Figure provides a good basis for choosing the best operating condition for a one-stage or a multi-stage process. A product rate given by 20% of the feed volumetric rate delivers a recovery higher than 80%, while the product grade is less than 20%, hence multi-stage processing becomes necessary at this higher throughput for achieving satisfactory grade.

4.4 Effect of the feed throughput at the optimum feed pulp density

In this section, the performance of the IRC in separating cenospheres from fly ash at the optimum feed pulp density was examined using different feed flow fluxes, and then compared to the results obtained in the previous work (Kiani et al., 2015). The fluidization water flux was constant at about $0.87 \text{ m}^3/(\text{m}^2 \text{ h})$ for all experiments in this section. The ratio of the product volumetric flux to the feed volumetric flux was kept constant in all of the experiments, at about 20%. By decreasing the feed flux, the cenosphere grade in the product increased, due to the desliming achieved by the fluidization. Again, the main parameter governing the product grade is the value of P-W, the difference between the product and the fluidization water flux. Figure 11 compares the product grade achieved in this study with those in the previous paper, while the product rate relative to the feed rate, and fluidization water flux were almost the same in both studies.

As shown in Figure 12, increasing the feed flux, with the product to feed flux ratio fixed, led to a rise in the recovery of the cenospheres, but at much higher feed fluxes, the recovery decreased. This interesting trend was comprehensively discussed in the previous paper (Kiani et al., 2015). The recoveries obtained at the optimum feed pulp density in this study are higher than those reported for the feed pulp density ranging from 30-35 wt% in the previous paper (Kiani et al., 2015), where the grade of the cenospheres was much lower at 0.51%. Arguably the improvement here was also due to the higher grade of cenospheres in the feed.

4.5 Grade-Recovery curve

The grade-recovery curve provides useful insight into the performance of the IRC under different operating conditions. Figure 13 presents the grade-recovery curves at different feed throughputs. As shown, the curves of the runs conducted at about 40 wt% feed pulp density with a grade of about 1% cenospheres are generally higher, indicating a better separation performance at the optimum pulp density and the higher grade of cenospheres in the feed. As expected, a better separation is achieved at a lower feed throughput.

5. Conclusions

In this paper the enhanced separation of positively buoyant cenospheres from negatively buoyant fly ash was studied using the Inverted Reflux Classifier at different feed pulp densities. It was concluded that increasing the feed pulp density led to an enhancement in the

separation performance due to a higher effective buoyancy driving force, and possibly the formation of hydrodynamic structures and bulk streaming of the cenospheres within the inclined channels. Specifically, the recovery of the cenospheres increased to an optimum recovery of 89.9% and upgrade of 58.6 when the feed pulp density increased to 38.1%, before declining at higher feed pulp densities. Detailed analysis indicated that the inclined channels produced an underlying throughput advantage of 18, with a further factor of 3 attributed to the bulk streaming phenomenon, resulting in an overall throughput advantage of 54 compared to a conventional fluidized bed. The optimum performance was also evident in the partition curves used for describing the cenosphere size classification. Under these optimum operating conditions the system was further explored in order to establish the conditions for a future pilot scale study.

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Figure Captions

Figure 1. A schematic representation of the experimental set-up.

Figure 2. (A) Sink and float analysis using a separating funnel, (B) Entrained cenospheres recovered from the sinks fraction.

Figure 3. A typical partition curve showing the d_{25} , d_{50} and d_{75} .

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Figure 9. Concentration induced throughput advantage of the Inverted Reflux Classifier. The curve is based on the d_{50} values while the error bars denote values ranging from the d_{25} to the d_{75} . The dash horizontal line denotes the base-line for the Inverted Reflux Classifier. At a feed pulp density of 38.1% the theoretical throughput advantage over a conventional

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Figure 10. Separation of cenospheres from fly ash at the optimum feed pulp density by discharging different product fluxes (based on the reconciled results).

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Figure 12. The effect of the feed flux on the cenosphere recovery, at the optimum feed pulp density of about 40% (based on the reconciled results).

Figure 13. The grade-recovery curves for experiments conducted at different feed volumetric fluxes, ($\text{m}^3/(\text{m}^2 \text{ h})$). The study by Kiani et al was based on 7.0-7.7 $\text{m}^3/(\text{m}^2 \text{ h})$, pulp density of 30-32%, and feed grade 0.51%. All other data are based on the present study involving a pulp density of 38.1 to 41.5% solids, and feed grade of about 0.81 to 1.08%.

List of Tables

Table 1. Detailed experimental data points reconciled by the error minimization technique. (Note that the total volumetric flow rate values are based on the raw data).

Table 2. I , d_{50} values, theoretical and actual throughput advantage for the experiments with different feed pulp densities (based on the reconciled results).