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Gravity Separation of Ultrafine Iron Ore in the Reflux Classifier

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ABSTRACT
The recovery and concentration of ultrafine iron ore can provide significant economic benefits. Presently, there are limited options available, given the low settling rates achieved by conventional gravity separation, and the relatively poor performance of reverse flotation. The Reflux Classifier is a new water-based gravity separation technology which consists of a set of parallel inclined channels positioned above a vertical fluidised section. This arrangement promotes a powerful throughput advantage over conventional fluidisation, and a highly selective hydrodynamic basis for achieving sharp separations. A high shear rate develops within the inclined channels, which generates sufficient hydrodynamic lift to convey the lower density particles (even if relatively coarse) to overflow, while retaining the high density particles (even those that are ultrafine) for discharge to the underflow. The technology has previously been used around the world targeting particle sizes in excess of 0.1 mm. The present work, however, is concerned with density-based separations down to much finer particle sizes approaching 0.01 mm.

A major advantage of the Reflux Classifier technology is the achievement of simultaneous gravity separation and desliming via a single stage separation. A series of continuous experiments was conducted using an iron ore feed with head grade of 35 wt.% Fe\textsubscript{T} and a nominal top size of 0.106 mm with 59 wt.% being below 0.038 mm in size. At a low throughput of 1.5 t/(m\textsuperscript{2} h) the Reflux Classifier produced high grade products at a high recovery. For the entire feed, grades of 66.1 wt.% Fe\textsubscript{T} with Fe recoveries of 80% were achieved in a single stage separation. Within the 0.020-0.038 mm size fraction, grades of 68.8% were achieved with iron recoveries of 94.7%. Excellent recoveries of up to 57.0% were achieved for the -0.020 mm size fraction. The ability of the inclined channels to retain the fine dense material further enhances the effectiveness of the Reflux Classifier by creating an autogenous dense medium effect within the vertical section. This helps to elevate large gangue particles up into the overflow.

INTRODUCTION
The treatment of ultrafine minerals has been a major concern for the mineral processing industry for many years. Generally, particles having sizes less than 0.045 mm are lost to tailings streams, regardless of their grade. However, quite often this material contains high concentrations of valuable, well liberated material. The ability to recover and concentrate these particles could provide significant economic and environmental benefits for the industry.

Currently, limited options are available for processing ultrafine iron ore particles. Flotation of iron ore has been used in plants since the 1950s. The most widely used method is reverse cationic flotation, in which a cationic collector is used to float siliceous gangue material. However, it is well documented that the reverse cationic flotation method requires de-sliming, usually using hydrocyclones, to remove particles below 0.020 mm prior to flotation, resulting in significant losses of valuable mineral (Houot, 1983; Ma, 2012; Filippov, Severov & Filippova, 2014).

Gravity concentration methods have also been used for the beneficiation of iron ore. For instance, spiral separators have been used for treating iron ore particles with top sizes up to 2 mm. However, iron recovery
drops significantly for particle sizes below 0.075 mm in spiral separators due to low settling velocities and turbulence in the outer edge of the spiral (Hyma & Meech, 1989; Bazin et al., 2014).

A study conducted by Das et al (1992) investigated the ability of a hydrocyclone to process an iron ore slimes feed with 80 wt.% of the feed material having a size below 0.05 mm. In their work they obtained an optimum total iron grade of 64 wt.% and iron recovery of 49%. More recent studies have shown that for feeds with a top size of 0.11 mm, hydrocyclones can provide satisfactory desliming. However, in order to concentrate the ore effectively, they must be coupled with other processes such as spiral separators or high intensity magnetic separation (Srivastava et al., 2001; Donskoi et al., 2008).

The Reflux Classifier (RC), shown in Figure 1 is a relatively new water-based gravity separator that has already had considerable success processing material larger than 0.100 mm in various coal and dense mineral processing plants worldwide, operating typically at more than 20 t/(m²h). The system consists of a set of parallel inclined channels positioned above a vertical fluidised section. The inclined channels increase the effective settling area providing a significant throughput advantage compared to conventional fluidisation methods, the so-called Boycott effect (Boycott, 1920). The channels also promote density-based separation via the selective re-suspension and elutriation of low density particles (Laskovski et al., 2006; Galvin & Liu, 2011).

When operated on a continuous basis, feed enters the vertical section. As particles accumulate in the system, they start to be conveyed up into the inclined channels. High density particles settle onto the upward facing surface of a given channel and slide en masse back into the vertical section. High density material accumulates in the vertical section and exits via the underflow stream.

Amariei et al. (2014) conducted a study using a pilot scale Reflux Classifier to process a fine iron ore feed with 80 wt.% of particles below 0.15 mm using a feed pulp density of 37 wt.%, a solids throughput of 8.9 t/(m² h) and a fluidisation rate of 4.4 m³/(m²h). The system performed well down to a particle size of about 0.045 mm, with the overall iron recovery typically exceeding well over 80% with iron grades typically well over 60 wt.%. A comparison with a float-sink test at 3300 kg/m³ also gave excellent agreement indicating that a very sharp separation was achieved.

The present work was aimed at extending the study of Amariei et al. (2014) using the Reflux Classifier to perform gravity-based separations to cover much finer sizes. Specifically, the throughput was significantly lower in order to maintain a laminar flow condition in the channels and retain ultrafine high grade particles. Performance was analysed based on comparison of the feed, reject and product streams. Samples were also collected along the height of the vertical section to provide insight into the internal functioning of the Reflux Classifier, the first time that these types of measurements have been performed on this system.

**THEORY**

A free-falling particle has a terminal free settling velocity when the downward gravitational force on the particle matches the buoyancy force and upward drag force created by the medium in which the particle is
settling. The terminal free settling velocity, \( u_t \), of an ultrafine particle with a particle diameter of \( d_p \) and a particle density of \( \rho_p \), settling in a fluid of density \( \rho_f \) and viscosity \( \mu \) can be predicted using Stokes law:

\[
    u_t = \frac{d_p^2 (\rho_p - \rho_f) g}{18 \mu}
\]

where \( g \) is the gravitational acceleration.

Particles in a narrow inclined channel only have a relatively short distance to fall before meeting the upward-facing surface, prior to sliding down the channel. The inclined channel provides an increase in the effective settling area over a vertical column with the same footprint, known as the Boycott effect (Boycott, 1920). The increase in effective settling area provides a throughput advantage, \( F \), which is defined as the ratio of the fluid superficial velocity in the vertical section, \( U \), to the terminal free settling velocity of the largest particle that can be conveyed through the channels to the underflow \( u_t \):

\[
    F_{\text{actual}} = \frac{U}{u_t}
\]

Inclined settling has been described using the kinematic approach of Ponder (1923), Nakamura and Kuroda (1937). The increase in horizontal projected area of the inclined surfaces leads to an increase in the particle segregation rate. As a result, the throughput advantage in the Reflux Classifier can be linked directly to the angle of inclination with respect to the horizontal, \( \theta \), and the aspect ratio \( L/z \), where \( L \) and \( z \) are the length and perpendicular widths of the channels respectively (Laskovski et al., 2006):

\[
    F_{\text{theory}} = 1 + \frac{L}{z} \cos \theta \sin \theta
\]

Equation 4 suggests that as the channel length increases and the channel width decreases the throughput advantage should increase indefinitely. However, in reality this is not the case. Particles that settle onto the upward-facing surface of the channels can be re-suspended due to fluid-shear at the channel surface. The segregation efficiency, \( \eta \), defines the ratio of the actual throughput advantage to the theoretical:

\[
    F_{\text{actual}} = \frac{U}{u_t} = \eta F_{\text{theory}} = \eta \left( 1 + \frac{L}{z} \cos \theta \sin \theta \right)
\]

Batch Reflux Classifier experiments were conducted by Laskovski et al. (2006) to establish a model for predicting the segregation efficiency. An empirical expression was fitted to the segregation efficiencies obtained in their work:

\[
    \eta = \frac{1}{1 + 0.133 \frac{L}{z} \cos \theta \text{Re}_t^{1/3}}
\]
where \( \text{Re}_t = \frac{\rho v d_p}{\mu} \) is the particle settling Reynolds number.

**EXPERIMENTAL**

A laboratory scale Reflux Classifier (RC100) was applied to the separation of hematite and siliceous gangue at ultrafine sizes. The system had a horizontal cross section of 0.1 m × 0.1 m, vertical section height of 1 m, and channel length of 1 m inclined at 70° to the horizontal, with a nominal channel spacing of 6 mm. The suspension density was measured using two pressure transducers positioned on the wall of the vertical section. A target suspension density, termed the set point, was chosen and a PID controller used to drive the underflow discharge rate accordingly. Ten sample points were installed on the side of the vertical section to allow internal sampling of the RC100.

An iron ore feed having a head grade of 35.9 wt.% Fe\(_T\), a nominal top size of 0.106 mm with up to 59.4 wt.% of the feed mass being below 0.038 mm in size, was prepared in a 400 L mixing tank to a pulp density of 40 wt.% solids. This feed was pumped into the vertical section, 0.6 m above the distributor at a rate of 2.4 m\(^3\)/(m\(^2\)h), and at a low solids throughput of 1.5 t/(m\(^2\)h). A fluidisation rate of 0.90 m\(^3\)/(m\(^2\)h) was used.

Once the suspension density reached the set point value, the underflow valve opened and adjusted its position according to the PID controller. After a period of approximately 3 h, at which time it was assumed the system had reached steady state, simultaneous samples of the underflow and overflow were taken over a time period of 30 min. Internal samples of the vertical section were then taken starting from the highest sample point and moving down to the lowest. Finally, a 10 min feed sample was collected.

The average volumetric flux of the overflow was 3.84 m/h. Correcting for the plate thickness, this rate corresponds to a channel velocity of approximately 4.10 m/h, giving a channel Reynolds number of 13, clearly in the laminar regime. For a pure hematite particle with a density of 5200 kg/m\(^3\) and diameter 0.010 mm, the terminal setting velocity is 0.824 m/h and for a “pure” gangue particle with density of 2600 kg/m\(^3\) of the same size the terminal settling velocity is 0.313 m/h. And under hindered settling conditions the velocities are even lower. If a conventional fluidised bed was used, all of these particles would be conveyed into the overflow. However, with the inclined channels in place, it is possible to retain high density 0.010 mm particles in the unit resulting in their removal via the underflow.

**RESULTS AND DISCUSSION**

A program of work was conducted applying the Reflux Classifier to the processing of an ultrafine iron ore feed with an aim to obtain high recoveries down to particle sizes of 0.010 mm. This paper presents the detailed results from one of these steady-state experiments. A more comprehensive research article will be published in a journal covering the remaining work.

Samples of the Feed, Underflow and Overflow were sieved into 9 size fractions, each of which were assayed using x-ray fluorescent (XRF) spectroscopy to determine their total iron content (Fe\(_T\)). The results of this analysis are shown in Table 1. The feed had a head grade of 35.9 wt.% Fe\(_T\). The nominal top size was 0.106 mm with 59 wt.% of the feed mass being below 0.038 mm in size.
The average grade of the underflow and overflow were 66.1 wt.% FeT and 12.6 wt.% FeT respectively. This separation corresponds to an overall Fe recovery of 80.2% (44.8% yield). The Reflux Classifier achieved Fe recoveries greater than 87% across all size ranges greater than 0.020 mm, an exceptional result. Focussing on the -0.020 mm size fraction, it can be seen that an underflow grade of 65.5 wt.% FeT was obtained compared with 32.0 wt.% FeT in the feed, at a Fe recovery of 57.0%. If this -0.020 mm material had been removed prior to processing, as would have been the case in reverse cationic flotation, the maximum Fe recovery would have been limited to only 70.9%, compared to the 80.2% that was achieved in this study. Hence, the ability of the Reflux Classifier to recovery material below 0.020 mm significantly improves the overall performance.

Figure 2 shows Fe recovery versus size curves from the data in Table 1 compared to those obtained by Ameriei et al. (2014). The overall trend is similar, showing high recoveries in the intermediate sizes and a drop in recovery for the finest particles. In this work it can be seen that for particle sizes in the range 0.020-0.050 mm higher recoveries were achieved than in the work of Ameriei et al. (2014). The significant improvement in the recovery in the present work is a consequence of the much lower solids throughput, in particular the lower volumetric loading. Thus the channel flow velocity was significantly lower in the present work.

Ten samples of the lower fluidized bed were also collected down the height of the vertical section. These samples were wet split at 0.038 mm and further sieved, then the density, \( \rho_i \), of all size fractions were measured using gas pycnometry. The grade of each sample was then estimated, based on the application of a binary mixture of pure hematite with density of \( \rho_H = 5200 \text{ kg/m}^3 \) and “pure” gangue material (primarily silica, SiO\(_2\)) with a density of \( \rho_G = 2600 \text{ kg/m}^3 \):

\[
\text{Grade (wt.\% FeT)} = 69.9 \times \left[ \frac{\rho_H}{\rho_i} \left( \frac{\rho_G - \rho_H}{\rho_G - \rho_H} \right) \right]
\]  

The total solids, hematite and gangue volume fractions were then determined to describe the concentration profile in the vertical section of the Reflux Classifier. Figure 3 shows the variation of hematite and gangue volumetric concentrations for the total sample and -0.038 mm size fractions along the height of the vertical section.

From Figure 3, it can be seen that above and around the feed height there is little variation in the volumetric concentrations of each species. However, below the feed point, there is a gradual increase in hematite concentration and a decrease in gangue concentration, approaching the bottom of the vertical section. At approximately 0.17 m, an obvious change occurs whereby the +0.038 mm hematite becomes much more concentrated. This corresponds directly to a decrease in concentration of siliceous gangue material at this level. In this zone of high hematite concentration there are several factors promoting the transport of gangue upwards. First, a dense medium effect is established forcing the low density large gangue particles out of this zone. Secondly, within the more concentrated bed, the fluidisation water experiences an increase in velocity due to narrower void spaces. This causes the -0.038 mm gangue particles to be washed out of this zone. In a conventional fluidised system, the -0.038 mm hematite should also be lost to the overflow.
However, these particles are recovered by the system of inclined channels, returning the particles to the vertical section. As their concentration increases within the vertical section, dispersion drives them downwards until their concentration is the same at all positions. Ultimately these dense ultrafine particles report with the coarser particles to the underflow.

Using the density and volumetric concentrations of each species, a suspension density was determined at each elevation of the bed. Figure 4 shows an essentially constant suspension density of approximately 1930 kg/m³. Approaching the base of the vertical section, at approximately 0.19 m, there is a sharp increase in suspension density. This increase directly corresponds to the increase in +0.038 mm hematite at this point. Coupling the suspension density in Figure 4 with the concentration data seen in Figure 3, it appears the system has distributed the material so as to minimize the potential energy. The suspension density established in the bed aids the transport of low density material upwards and high density material downwards. At the base of the vertical section, the suspension density almost reaches 2600 kg/m³, the density of the siliceous gangue matter. Considering these results in combination with the upward movement of fluidisation water, it is not surprising the concentration of gangue material in the vertical section is minimized.

**CONCLUSIONS**

An iron ore feed with a head grade of 35.9 wt.% FeT and a nominal top size of 0.106 mm was processed in a laboratory-scale Reflux Classifier at steady-state, the aim being to obtain high recoveries down to particle sizes below 0.020 mm. At a throughput of 1.5 t/(m² h), an overall Fe recovery of 80.6% was achieved with a grade of 65.4 wt.% FeT. For particle sizes below 0.020 mm, 57.0% Fe recovery was obtained with a grade of 65.5 wt.% FeT. This is a significant result when considering that the most common method for treating iron ore fines is reverse cationic flotation which would require the removal of particles below 0.020 mm before flotation.

This is the first published research on the internal behaviour of the Reflux Classifier. Above and around the feed point, volumetric concentrations of all species at steady-state are fairly uniform. This is likely due to turbulent mixing resulting from feed entrance effects, upward fluid flux, and the return of high density particles sliding back down the channels. Moving down the vertical section, hematite concentration increases slightly whilst gangue concentration decreases. At approximately 0.19 m from the base of the vertical section, a significant increase in +0.038 mm hematite occurs. This increase corresponds directly to a decrease in concentration of both -0.038 mm and total gangue. At this point, there is also a sharp increase in the suspension density, promoting the transport of gangue material upwards.

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REFERENCES


FIGURE CAPTIONS

FIGURE 1 – Schematic of the Reflux Classifier.

FIGURE 2 – Total iron size-recovery curve for this work and the Sample B Test 1 results from Ameriei et al. (2014).

FIGURE 3 – Volume concentration profiles of hematite (a) and gangue (b) for the -0.038 mm size fraction and total solids.

FIGURE 4 – Suspension density versus height in the vertical section.

TABLE CAPTIONS

TABLE 1 - Raw Sieve and XRF data for Feed, Product and Reject samples from continuous RC100 experiment.
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# TABLE 1 - Raw Sieve and XRF data for Feed, Product and Reject samples from continuous RC100 experiment.

<table>
<thead>
<tr>
<th>Size Fractions (mm)</th>
<th>Feed Mass (%)</th>
<th>Feed Grade (wt.% FeT)</th>
<th>Overflow Mass (%)</th>
<th>Overflow Grade (wt.% FeT)</th>
<th>Underflow Mass (%)</th>
<th>Underflow Grade (wt.% FeT)</th>
<th>Iron Recovery (%)</th>
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