Spiral concentrators have been used globally in various types of mineral beneficiation plants. Particles are introduced in a slurry form at the top of a spiral and gravitate in a radial formation around a central axis, separation occurring mainly on size and density. Spiral concentrators are primarily employed to process fine material (-1mm particle size). Over the last few years a "low-cut" spiral technology has entered the market.

The study entails a technology comparison using feed material sourced from two Exxaro coal mines.

The paper also demonstrates an alternate approach, for evaluating and comparing spirals, instead of using traditional washability measurements known to the coal industry.

The results show a similar separation performance for the two spirals up to a point, with the low-cut spiral demonstrating the ability to achieve lower cut-points by producing a cleaner coal product in a single pass.

INTRODUCTION

Spirals were introduced by Humphrey in the 1940’s (Thompson et al., 1990). During the 1980’s, there was an increased interest in recovery of fine coal (Holland-Batt, 1995). Spirals have since become an effective and low cost means of upgrading fine (-1mm) coal, treating material too coarse for flotation and too fine for dense media separation. In Southern Africa, spirals typically have EPM (Ecart Probable Moyen) values of about 0.15 and cut-point densities around 1.80 in most applications.

Spirals

Spiral concentrators are gravity separators usually separating particle sizes between 0.1 and 2 mm in a water carrier medium (Wills, 2007) (Holland Batt, 1995b). Developments over the years include; improved feed box and splitter designs, trough design, wash water addition, capacity improvements, re-pulpers and product boxes (Holland Batt, 1995b). The introduction of the low-cut spiral produced is a recent opportunity for fine coal beneficiation.
Feed is introduced at the top of the spiral usually containing between 15-45% solids and is allowed to flow downward. High density material reports to the center of the spiral, while material with a lower density reports to the outer wall of the spiral. Separation on a spiral is achieved through a combination of forces that act on particles as they move down the trough of the spiral. The main forces (among others) acting on the particles are gravitational, centrifugal and hydrodynamic drag. Apart from all forces acting on a spiral, other factors affecting performance are identified as shape of trough (including pitch and slope), number of turns, spiral diameter and height. The composition and properties of the slurry presented to the spiral also influence performance, namely percent solids by mass, particle shape, particle size distribution, density differential of particles to be separated, and mass/volumetric flowrate of the slurry.

Conventional spiral

The conventional spiral is the most commonly used spiral in South Africa for fine coal beneficiation. It is a 7-turn spiral equipped with one auxiliary splitter which was developed for difficult to wash coals. The conventional spiral has a cut point of around 1.8 (feed quality dependent).

Low-cut spiral

The low-cut spiral is a relatively new entrant in the South African market. It is a low density cut-point 8 turn spiral equipped with two auxiliary ruler slide splitters; the first one is located at spiral turn 4 and the second one is located at turn 6. The low-cut spiral is capable of lower than traditional cut-points achieving below 1.6 (feed quality dependent). The low-cut spiral is designed to produce a low ash product. Traditionally if one required a low ash product, hindered settlers such as teeter beds or reflux classifiers were looked at.

Aim of this study

The aims of the study were twofold:

- to produce the lowest ash product by both spirals in a single pass (10.5% for colliery 1 and 15% for colliery 2);
- to do a direct comparison at comparable mass yields of the conventional and low-cut spirals for applicability in Exxaro.

METHOD OF EVALUATION

For this study, traditional washability measurements were abandoned due to the feed material having long settling times making it difficult for traditional sink-float analyses to be performed. Fourie, 2007 provides a clear discussion of the Holland-Batt Equation that will be used in this paper for calculation of separation efficiency on a spiral.
Separation Efficiency

The separation of a desired aspect can be described by the cumulative recovery of that aspect versus the cumulative total mass recovery to product (yield) (see equation 1). Figure 1 will be used to explain this principle. The solid trapezoid shape referred to as the perfect separation and illustrated as the separation window (this specific example is of a feed material containing 32.3% ash). The dashed diagonal line defines no separation as mass is accumulated and can be used to depict splitting. The separation curve is indicated by the line labelled non-ash, is as constructed in this example, is everything that is not ash calculated as a percentage recovered as mass is cumulated to product.

Figure 1: Recovery of coal (100-ash) as a function of mass yield to product

Separation efficiency is being expressed as a percentage of the difference between the actual recovery and the no separation recovery, and the difference between the perfect recovery and the no separation recovery (also indicated in Figure 1). This translates to the following equation (Holland-Batt equation):

\[
\text{Separation Efficiency} = \frac{(\text{Recovery} - \text{Yield})}{(100\% - \text{Feed Grade})} \times 100
\]

Eq1

The separation efficiency curve is thus developed and is also shown in Figure 1.
To define recovery and yield we can use the example of carbon.

Recovery (expressed as a percentage) is calculated as mass of aspect (such as carbon) in product divided by the mass of carbon in feed.

Yield is expressed as a percentage of the mass of product over the feed mass.

The relationship between separation efficiency and feed rate can be depicted by a straight line, with a decrease in efficiency at higher flowrates when the feed density is kept constant. Previous work on flow profile by Holland Batt (Holland Batt, 1990) indicated that any increase in the feed rate to a spiral results in a greater part of the additional flow volume reporting to the outside of the trough.

EXPERIMENTAL PROCEDURE

Feed samples

Two test samples from two of Exxaro’s collieries of approximately 500kg each were used in this study. Colliery 1 sample was taken at the spiral feed distributor and Colliery 2 was sampled at the wet desliming screen undersize. Both samples were collected in December 2015.

The ‘as received’ samples were air dried and thereafter split using a vibratory rotary divider into approximately 20kg sub-samples for the spiral testwork. This was to ensure representative samples are available for the individual spiral concentrator tests. A head sample was also collected during the feed preparation.

Analytical methods

Ash

Ash analysis was performed by Exxaro Metallurgical Services according to internal standard procedures. The coal was pulverised in milling pots. A representative sample of approximately 1.0 g was used for the analysis ashed in a Lenton furnace at 1000°C. All product results were also analysed at CoalLab (Pty) Ltd for confirmation.

Particle size distribution (PSD)

PSD was conducted on both samples at Exxaro Metallurgical Services. Sieves were selected on Tyler series increments with a top size of 1800µm and a bottom size of 45µm.
Experimental set-up

Spiral test set-up

All tests were conducted in a closed-circuit test rig that consisted of a pump, variable speed drive, a mouth-organ pneumatically activated splitter, a distribution box and the relevant spiral. The exit stream from the distribution box returned to the sump and positioned in such a way that there is constant agitation in the sump. Figure 2 illustrates the plant setup for the testwork.

Water and feed material were added to the system. The setup used between 30 and 40 kg sample to reach the desired tonnages of between 1.5 to 2.5 t/h as required for the various tests. Once the desired parameters were reached, two or three samples were taken to check the stability and returned to the system. The conventional spiral was fitted with a 6 split mouth organ across the profile of the spiral and was sampled at once for the each test. The low-cut spiral was fitted with adjustable splitters and thus had to be sampled twice per test. The splitters were set as far as they could be adjusted so that the entire spiral profile was covered. After each sample set was taken, the system was topped up with feed material and water and checked for stability before the next sample was taken.

Figure 2: Photograph and schematic of the test Spiral set-up

Spiral products (for both low-cut and conventional) were prepared as follows, after the spiral testwork:

• Samples were dried and weighed to determine the actual dry t/h and % solids by mass (note that all samples were timed using a stopwatch); and
Dried samples were split using a vibratory rotary divider to obtain representative splits for laboratory analyses.

**Pre-test**

It’s important to note that a pre-test was carried out on both the low-cut and conventional spiral to determine the relationship between the splitter/auxiliary cutter position and ash quality. This was done so that the splitters or cutters are set to desired positions when the actual tests are run.

For the low-cut spiral, Table 1 shows the relationship of the reject ash quality as the cutter opening is increased. For both collieries the top cutter reject ash quality had marginal change and the top cutter was set at 45mm as indicated in Table 1. The measurement was taken from the centre column to the knife edge of the cutter. The bottom cutter showed a decrease in ash quality as the cutter was opened further. This cutter was also set at 45mm to align with the objective to produce a low ash product in a single pass.

For the conventional spiral one movable splitter was adjusted to determine the relationship of the reject ash quality at that point versus the splitter position. This relationship is shown in Table 2. For colliery 1 there was a marginal decrease in ash quality as the splitter was adjusted into the slurry. For colliery 2 there was a marked decrease in ash quality discarded at the splitter. In keeping with the objective with a low ash product this splitter was set at 280mm as illustrated in Table 2.

**Table 1 : Low-cut spiral upper and bottom splitter reject ash versus splitter position relationship used to set splitters during the actual comparison tests.**

<table>
<thead>
<tr>
<th>Splitter position ID</th>
<th>Distance from centre column to cutter edge (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Upper splitter</strong></td>
</tr>
<tr>
<td>1.1</td>
<td>15</td>
</tr>
<tr>
<td>1.2</td>
<td>25</td>
</tr>
<tr>
<td>1.3</td>
<td>35</td>
</tr>
<tr>
<td>1.4</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td><strong>Bottom splitter</strong></td>
</tr>
<tr>
<td>2.1</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>25</td>
</tr>
<tr>
<td>2.3</td>
<td>35</td>
</tr>
<tr>
<td>2.4</td>
<td>45</td>
</tr>
</tbody>
</table>
Colliery 1 – use 45mm for both splitters

Colliery 2 - use 45mm for both splitters

Table 2: Conventional spiral upper and bottom splitter reject ash versus splitter position relationship used to set splitters for actual comparative tests.

<table>
<thead>
<tr>
<th>Splitter position ID</th>
<th>Distance from trough to splitter edge (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper splitter</td>
</tr>
<tr>
<td>1.1</td>
<td>210</td>
</tr>
<tr>
<td>1.2</td>
<td>230</td>
</tr>
<tr>
<td>1.3</td>
<td>250</td>
</tr>
<tr>
<td>1.4</td>
<td>280</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

Feed samples

Both feed samples were well prepared with more than 98% by mass passing 1.8mm and were relative well deslimed at less than 1% -45 µm. The D50 was approximately 430 and 380 µm for Colliery 1 and 2 respectively, as can be seen in Figure 3.

The feed Ash for Colliery 1 including all reconstituted spiral test feed results were between 32 and 33% by mass. For Colliery 2 the feed ash including reconstituted feed data from all the individual spiral tests was between 23 and 25% by mass.
Comparative test conditions

Throughput measured as dry t/h was the variable in the comparative tests. Table 3 indicates the dry t/h and their respective mass % in slurry required to achieve what is termed as acceptable feed conditions for good separation. The good separation zone is also illustrated in Figure 4 where a scatter plot of the desired conditions, actual measured conditions and the zone considered as good separation conditions. Test 3 for colliery 1 was excluded due to the measured % solids being outside the acceptable targeted % solids for this study.

Table 3: Low-cut and conventional spiral test conditions

<table>
<thead>
<tr>
<th>Spiral Tests</th>
<th>Feed Rate (t/h)</th>
<th>% Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>Test 2</td>
<td>2.0</td>
<td>30</td>
</tr>
<tr>
<td>Test 3</td>
<td>2.5</td>
<td>34</td>
</tr>
</tbody>
</table>
Figure 4: Scatter plot of volumetric throughput as a function of dry solids flowrate for the actual measured test conditions against the desired test points in the range for good separation. One data point out of range and excluded.
Colliery 1 comparative spiral results

Product grade versus recovery

It is clear from Table 4 that at 1.5 t/h and 25% solids, the grade recovery lines of the two spirals are similar however the conventional spiral did not allow any splits in a single pass to produce an ash product less than 15%. The low-cut spiral allowed less yield at ash qualities less than 15%. This observation is similar for all three tests performed.

It’s important to note that the low-cut spiral produced the lowest ash grade of 10.3% with a mass yield of ~36%. While the lowest ash grade produced by conventional was 15.1% with a mass yield of ~65%. For the low-cut spiral as feed rate increased, the product ash content increased from 10.3% to 12.7% as the feed rate increased from 1.5 to 2.5t/h (mass yield of ~36%-45%). For the conventional spiral the change in ash content was 15.1 to 16.1 % ash as feedrate increased from 1.4 to 1.9t/h at mass yield of 65.6 to 66.4 %).
Table 4: Cumulate ash grade versus mass yield to product for the low-cut and conventional spiral comparative tests on Colliery 1 feed material.

<table>
<thead>
<tr>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Excluded</td>
</tr>
</tbody>
</table>

Separation efficiency

Higher separation efficiencies are observed for the low-cut spiral (Figure 5). A higher separation efficiency value is better since separation efficiency takes into account recovery, yield and feed grade. Figure 6 demonstrates the impact of higher separation efficiencies with the low-cut spiral having lower ash in final product at 65% yield when comparing at an equivalent dry throughput.
Figure 5: Separation efficiency versus throughput (dry t/h) for the conventional and low-cut spiral at a product yield of 65% for colliery 1 material.

Figure 6: Product ash quality versus throughput (dry t/h) for the conventional and low-cut spiral at a product yield of 65% for colliery 1 material.
Colliery 2 comparative spiral results

Product grade versus recovery

A variation in re-constituted feed assays is observed for all three tests with the conventional spiral receiving a slightly lower ash content in feed (24-25% ash for the low-cut and 23-24% ash for the conventional) as shown in Table 5. This translates to a gap between the two series lines (especially pronounced for test 1 and 2). Both spirals were operated at maximum splitter allowances. The conventional spiral had a lowest yield of ~76% with ash grade in product of 16.5%. It is important to note that low-cut spiral produced its lowest ash grade of 13.5% with a mass yield of ~30%.

Table 5: Cumulate ash grade versus mass recovered to product for the low-cut and conventional spiral comparative tests on Colliery 2 feed material.
Separation efficiency

Considering there was a difference on the head grade results of the two spirals, no separation efficiency results for colliery 2 are discussed in this paper.

CONCLUSIONS AND RECOMMENDATIONS

From the conditions tested and the results obtained, on a technical basis, the following is concluded:

- The low-cut spiral has the ability to produce a “low” ash product.
- Separation efficiency as calculated by the Holland-Batt equation is now demonstrated as a tool to compare spirals in a coal application and can be used in conjunction with or alternative to the widely used EPM and organic efficiency.
- For colliery 1
  - The low cut spiral was able to achieve a low ash product of 10.3% ash. This was only at 1.5t/h. As feedrate was increased to ~2 and ~2.5t/h, the resulting product ash increased to 11.4 and 12.7% ash respectively.
  - At yields above 65% by mass and a higher ash product, both spirals performed similar although the low-cut was able to process higher throughputs. When analyzing the data at equivalent feedrates (dry t/h) the low-cut spiral had higher separation efficiencies resulting in comparatively lower ash in product.
- For colliery 2
  - The low-cut spiral was able to achieve a low ash product. The same observation as that of colliery 1 is also observed with an increase in yield and product ash quality as feedrate is increased (ash% in product from 13.6 to 17% and mass yield ~30 to ~58%).
  - Feed grade of both spirals tests differed by up to 2%. When comparing the two spirals at a mass yield of 75% the trends look similar and can be inferred
to be similar due to the parallel trend lines (Table 5). The gap is attributed to difference in feed grade.

- No separation efficiencies were done because feed grade is one of the components when calculating separation efficiency.

It is recommended that:

- Further work be for colliery 2 at the same head grade and compared to the results of colliery 1 for confirmation.
- A total cost of ownership be done when choosing a spiral in a conventional application; and
- A double-stage spiral study be done for low ash products to improve yield on the low-cut spiral and to compete with hindered settling technologies such as the reflux classifier and teeter bed separators.

REFERENCES


Holland-Batt, A.B., 1995b. Some design considerations for spiral separators, Minerals Engineering, Lake Tahoe,


