A simple process control model for spiral concentrators

by M.K.G. Vermaak*, H.J. Visser*, J.B. Bosman*, and G. Krebs*

Synopsis

Spiral concentration forms a crucial part of gravity separation circuits. The application of process models in the operation of gravity separation circuits offers significant benefits in recoveries and grade control. Significant strides in the modelling of spiral concentrators have been made during the last couple of decades. Despite these advances in modelling techniques and models, application in industrial processes is not fully optimized. The adjustment of splitter positions to accommodate changes in the feed parameters is impractical and difficult, resulting in losses. In this work an optical method is employed to detect the concentrate band position as a function of operating variables. As expected, the results indicate a strong influence of the solids content and total heavy mineral (THM) feed grade on the predicted gangue-mineral interface. Viscosity modifiers indicated the band position to be sensitive to viscosity and therefore the slimes content. Validation on an industrial sample indicated the possibility of using this model in feed-forward control application.

Introduction

Spiral concentrators are compact, cost-effective and generally efficient gravity concentration separators for a wide range of applications (for example, coal, beach sands, iron ore, chromite and tantalite). Recent research has resulted in the development of mathematical models to predict the performance of spiral concentrators with an important aim of control and optimization of spiral circuits[1–5]. Most of these models are fairly fundamental and sophisticated in nature and have seen only limited application in industry. This paper does not aim to add to the refinement of these models but focuses on the development of simple control functions and a digital image analysis technique for on-line control.

The control of spiral concentrators, to provide a concentrate with as little as possible fluctuation in grade and recovery while feed parameters are fluctuating, is difficult and has not been perfected. Large mineral processing plants consist of hundreds of spiral concentrators, and the adjustment of splitters is time consuming, impractical and is in many cases neglected. Spiral splitter adjustment has up to now been the only means to adjust recovery into the concentrate, middling, tailings and (in some cases) the slimes streams. An alternative approach is to adjust the position of the concentrate band instead of adjusting the splitter position. The radial position of the concentrate band is a strong function of the operating variables, i.e. solids content of feed, total heavy mineral (THM) feed grade and to a lesser extent volumetric flowrate[1,2]. On-line control whereby different feed parameters are controlled has not been developed and implemented for spiral concentrators. The aims of this project were to develop an optical technique to detect the mineral-gangue interface, and to identify transfer functions that may find application in the on-line control of spiral concentrators. The possibility of controlling product recovery and grade by adjusting feed parameters was investigated. In addition, this work investigates the effect of viscosity on the position of the separation band.

Experimental

Experimental set-up

Experiments were carried out on a closed-circuit test rig (see Figure 1) comprising a spindle pump, mouth-organ splitter, gravity distributor and a single-start Multotec SC22 heavy mineral rougher spiral. The gravity distributor was fitted with an overflow and orifice at the outlet to control the volumetric flow rate to the spiral concentrator. A pressure transmitter was connected to a DataTaker recorder to record the pressure variation throughout a test. Pressure was recorded to

* *Department of Materials Science and Metallurgical Engineering, University of Pretoria, Pretoria, South Africa.*

 Paper received May 2007; revised paper received Feb. 2008.

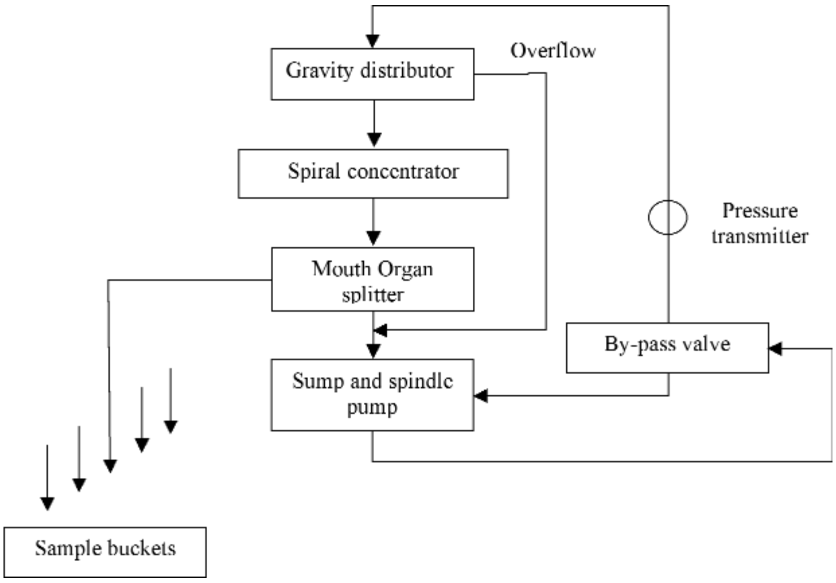

Figure 1—Schematic of the closed-circuit test rig fitted with a pressure transmitter

ensure that an acceptable pressure range (variations of less than 5 kPa were considered acceptable; a 5kPa pressure variation resulted in a less than 3 mm variation in the position of the concentrate band for 5 repeats) was maintained throughout the test to prevent surging and non-steady state conditions—measurements were taken after the pressure readings had stabilized. The sample was replaced after every experimental run. All tests were conducted as quickly as possible (usually within 5 minutes from the start of the experiment) after steady state conditions had been reached to minimize heat build-up due to pumping action in a closed-loop system.

Samples

Test work was performed using an artificial ore consisting of ilmenite and silica obtained from Richards Bay in KwaZulu-Natal on the South African east coast. The ilmenite and silica were sized to between 53 μm and 500 μm (the d_{50} of the ilmenite was close to 150 μm and silica close to 300 μm). The ilmenite and silica were combined in ratios that were close to the average Hillendale (Exxaro KZN Sands' heavy mineral treatment plant is situated near Empangeni in KwaZulu-Natal, South Africa) THM feed grade.

A slurry sample of deslimed spiral feed (300 kg at a feed grade of 5.6% THM) was obtained from Exxaro Sands' Hillendale plant for model validation purposes—the slimes fraction in the heavy mineral industry is defined as the smaller than 45 micron fraction.

Image analysis

The feed parameters (see Equation [1]) that were adjusted in order to quantify the effect on the separation efficiency were percentage solids, feed grade and volumetric flow rate (ranges investigated are shown in Table I). Table III summarizes the feed parameters tested for each experimental run.

Changes in these parameters were related to the position of the concentrate band on the spiral profile. An empirical model was developed using three-factor experimental design to relate the three different feed parameters to the gangue-mineral interface distance from the centre column. An optical method was developed, which provided a light intensity value based on the appearance of the minerals—a light intensity plot (see Figure 2) as a function of position provided the location of the ilmenite-silica interface; the light intensity

Table I

Range of feed parameters tested

Feed parameters	Range
Percentage solids	10–50 %
Feed grade	5–20 % THM
Volumetric flow rate	2.2–5 m^3/h

THM: total heavy minerals

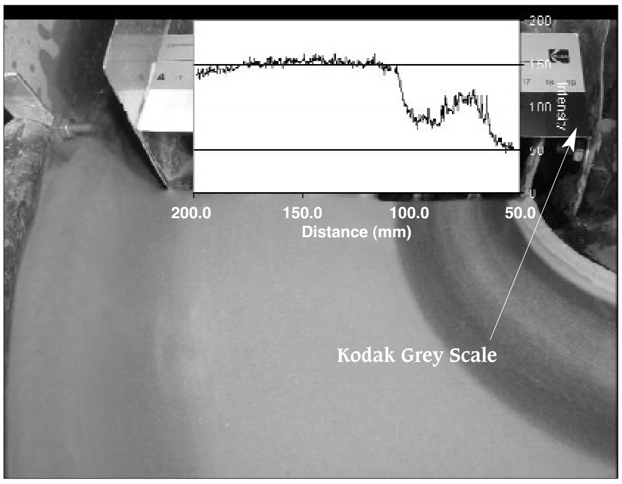

Figure 2—Light intensity plot from a line drawn across the flow profile

plots also provided an estimate of the mineral grade. The grey values of each test were calibrated against the standard Kodak Gray Scale (see Figure 2). Seven high resolution digital images of concentrate and tailings bands at the mouth-organ splitter were taken in quick succession in order to obtain an average value for the distance from the centre column to the silica-ilmenite interface. These distance measurements were done on the high resolution digital images by equating known lengths on the experimental set-up to lengths given in pixels from an image analysis program (ImageTool™). The advantage of the optical technique is that much higher resolution could be obtained compared to more traditional techniques[1,3,6]. The output of the optical technique could also be used to detect the radial position of the interface on line under plant conditions for low slimes concentration applications (typically between 2 and 5%)[7]. High slimes levels affect the fluid flow, settling of particles and carrying capacity of the spiral concentrator, resulting in heavy, valuable particles reporting to the discard streams. High slimes contents prevent visual inspections of a spiral concentrator in operation. Slimes also pose serious operating difficulties during thickening and tailings rehabilitations because of poor settling properties and because water is retained in the interlayer spacing of the clay minerals.

Sampling and sample analysis

The spiral was fitted with a mouth-organ splitter at the base of the profile (Figure 3). The splitter divided the flow on the spiral into eight streams. After the final picture was taken, a sample was taken for five seconds by switching the switch sampler to the sample buckets. Samples were weighed wet, dried, and then reweighed to evaluate the water and solids loading and performance.

The synthetic samples were analysed for ilmenite by performing repetitive magnetic separation tests at low feed rates using a Readings Induced Roll Magnetic separator. The accuracy of this analysis technique was checked with X-ray fluorescence analysis.

The mineralogical composition of the Hillendale samples was determined by performing quantitative X-ray diffraction analysis. Samples obtained from the mouth organ splitter were pulverized in a tungsten carbide milling vessel followed by a micronizing step in a McCrone micronizing mill. Samples were prepared for XRD analysis using the back loading preparation method and analysed using a PANalytical X'Pert Pro Diffractometer with X'Celerator detector and variable divergence and receiving slits with Ni filtered Cu-Kα and Fe filtered Co-Kα radiation. Phases were identified using X'Pert Highscore plus software. Quantification was done using the Rietveld method by Autoquan/BGMN software (GE inspection Technologies) employing the Fundamental Parameter Approach.

Viscosity investigations

The feed parameters (see Equation [3]) that were adjusted in order to quantify the effect on the separation efficiency were percentage solids, feed grade and viscosity (ranges investigated are shown in Table II).

The effect of viscosity (47.5–95.8 mPa.s measured at a shear rate of 22 s^{-1}) on the silica-ilmenite band position was determined by employing a viscosity modifier, i.e. carboxylic methylcellulose (CMC). Kawatra[8] discussed materials that were used to create artificial viscosity conditions. CMC was selected for its colourless nature (no interference with optical technique) and high solubility as well as the ease of measuring the viscosity at different concentrations. Viscosity measurements were performed by employing a Brookfield viscometer. CMC was found to be shear thinning and, as a result, all tests were conducted as quickly as possible after steady state conditions had been reached to minimize the effect of the spindle pump on the viscosity of the slurry. The first model developed in the absence of the CMC modifier indicated the volumetric flow rate to have a small effect on the band position (see Equation [1] later in this paper); the volumetric flow rate was hence not investigated further and kept constant during the viscosity investigations.

Results and discussion

The first approximation of the empirical model (see Equation [1]) managed to predict the actual output variable for more dilute flows (more dilute refers to the lower end of the percentage solids and feed grade conditions tested, as summarized in Table I; a predicted gangue mineral interface (M in Equation [1]) larger than 95 mm).

The first approximation of the empirical steady-state model was derived as follows:

$$M = 95.29 + 10.89x_1 + 12.75x_2 + 1.88x_3 - 1.60x_1x_2x_3 \qquad [1]$$

with M = distance from centre column to gangue-mineral interface (in mm)

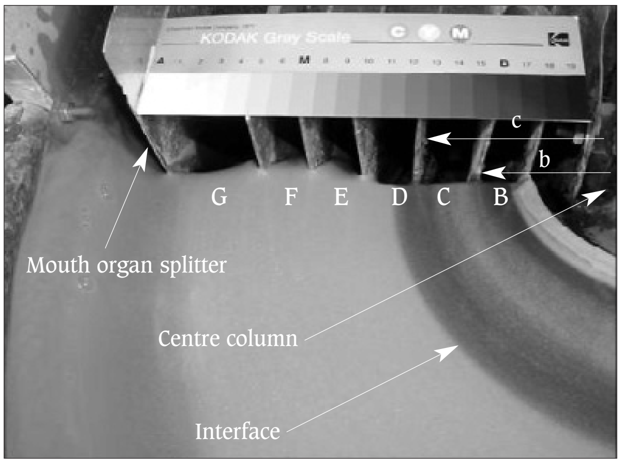

Figure 3—Gangue-mineral interface on the spiral profile. Measurements 'b' and 'c' present the radial position for the port B and C, respectively

Table II

Range of feed parameters tested

Feed parameters	Range
Percentage solids	10–50%
Feed grade	5–10% THM
Viscosity	47.5–95.8 mPa.s

Table III

Design matrix to test the range of the values of the variables shown in Table I as well as the measured band widths

Test run	Grade (%)	% Solids (m^3/h)	Flow rate width (mm)	Measured band
1	5	10	2.2	71.2
2	10	10	2.2	89.2
3	5	50	2.2	93.4
4	10	50	2.2	119.8
5	5	10	5	73.1
6	10	10	5	96.7
7	5	50	5	99.9
8	10	50	5	119.1
9	10	20	4.3	89.1
10	10	40	4.3	111.1
11	20	20	4.3	107.4
12	20	40	4.3	115.6
13	15	10	3.6	85.2
14	15	20	3.6	97.1
15	15	40	3.6	113.8
16	15	50	3.6	115.5

x_1 (grade, % THM), x_2 (% solids, mass basis) and x_3 (flowrate, m^3/h) are the three operating variables around which the three-factor experimental plan was designed, standardized according to Equation [2] (units as in Table I):

$$x_1 = \frac{(Grade) - 15}{10} \qquad x_2 = \frac{(\%Solids) - 30}{20} \qquad x_3 = \frac{(Flowrate) - 3.6}{2.5} \qquad [2]$$

The construction of the experimental design was based on the extreme highs and low of the variables being tested (see Table I). The variables in Equation [2] and [5] were coded in the following manner:

$$x = \frac{P - Q}{R} \qquad [3]$$

where P: design level of factor
Q: standard level of factor (mean of the maximum and minimum level)
R: distance of high or low level from standard level

The model coefficients indicate the weight of each variable or combination of variables. It is therefore clear that the output variable was most sensitive to fluctuations in feed grade and percentage solids. The model was adjusted for higher load conditions (a predicted gangue mineral interface (M in Equation [1]) larger than 95 mm) by means of mathematical manipulation. It was apparent that the model was underpredicting for higher load conditions, and the model is linearly corrected, as shown in Figure 4.

Figure 5 plots the actual and predicted radial position of the silica ilmenite-interface; a strong correlation is evident for the range of parameters tested. The small scatter in the data is related to the accuracy of determining the exact position of the interface, which can be strongly influenced by a thin layer of silica riding on top of the ilmenite concentrate. A similar observation is recorded elsewhere[3]. It is clear the model predicts the location successfully over the full range of the laboratory parameters.

This work demonstrates that the gangue-ilmenite interface can be measured by employing an optical method, and predicted with an empirical model. However, the optical technique measures only the uppermost layers of particles, and screening effects can be detrimental to the accuracy. Of the three controller input variables described by the model, the feed grade is expected to behave as a disturbance, given the variability in the dune compositions. One of the other variables can be manipulated to counteract the effect of the feed grade variations but this requires that the feed grade is accurately known; this implies feed-forward control rather than feed-back control. Feed-back control per se on a spiral

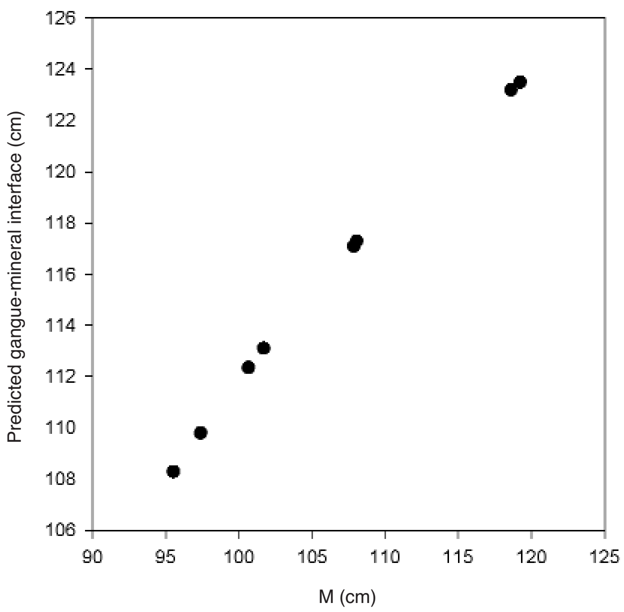

Figure 4—The predicted gangue-mineral interface as a function of the output of the empirical steady-state model

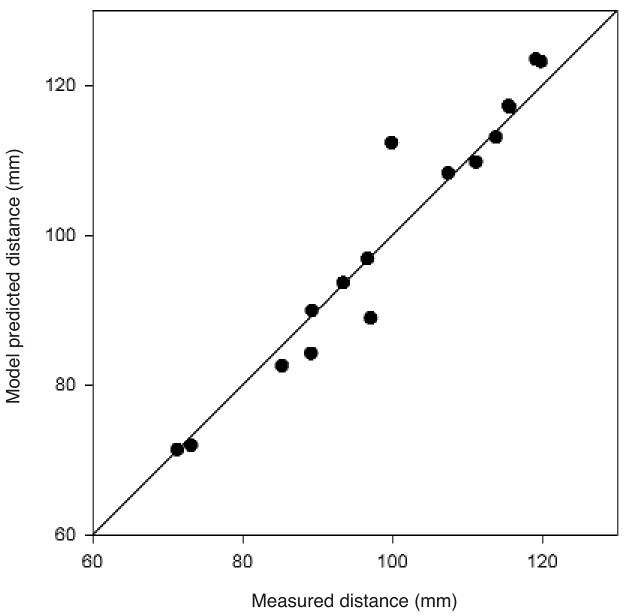

Figure 5—Radial position of the silica-ilmenite interface on the spiral-profile: model vs. experimental

plant can be difficult since the position of measurement and the time required to reach steady state conditions after a change need to be carefully taken into account. The change in the manipulated variable, for instance the solids content, can also have a dramatic effect on the overall mass balance of the plant, but the availability of a model (such as Equation [1]) allows this to be predicted.

Some of the heavy mineral deposits are known to contain high levels of slimes, and the performance of the spiral separators are adversely affected by the presence of slimes in the feed stream[9,10]. It is known that the heavy mineral slimes can contain up to 60% smectite clays; smectite clays swell in the presence of water and cations[11]. It is thus expected that the degradation of the slimes would adversely affect the rheology of the slurry by influencing the viscosity and in turn affect the radial position of the gangue-mineral interface. It was shown that the slimes content of the spiral concentrator feed should be reduced to around 10% to ensure good separation[10].

A three-factorial experimental design (see Equation [4]) was employed to investigate the effect of solids concentration, feed grade and viscosity on the position of the gangue-mineral interface (See Table IV).

The volumetric flow rate was kept constant. Increasing the volumetric flow rate has an insignificant effect on the inner part (area close to the centre column) of the flow profile (see also the small coefficient of the flow rate in Equation [1]). The bulk of the additional flow reports to the outer wall of the spiral concentrator; this phenomenon was confirmed by depth profiling[1].

$$M_1 = 78.51 + 7.912x_1 + 10.489x_2 - 6.162x_4 + 5.31x_1x_2x_4 \quad [4]$$

with

M$_1$ = distance from centre column to gangue-mineral interface (in mm)

x_1 = grade (% THM), x_2 = % solids (mass basis) and x_4 = viscosity (mPa.s) are the three operating variables around which the three-factor experimental plan was designed, standardized according to Equation [5] (units as in Table II):

$$x_1 = \frac{(Grade) - 7.5}{2.5}, \quad x_2 = \frac{(\%Solids) - 30}{20}, \quad x_4 = \frac{(Viscosity) - 69.8}{25.9} \quad [5]$$

Both models indicate the dominant effect of the solids content on the gangue-mineral interface position, thus creating a powerful control variable. In contrast to the control variables in Equation [1], viscosity has a negative correlation with the radial band position; the radial bandwidths decrease with an increase in viscosity. Figure 6 shows the effect of viscosity on the radial position of the mineral-gangue interface (all other operating variables were kept constant). The strong effect is evident in the decrease of the radial bandwidths. This demonstrates clearly that the steady-state transfer functions are strongly dependent on the slurry viscosity.

Generally, the flow patterns on a spiral profile consist of primary component (downwards) and a secondary (transverse) component. Holland-Batt[1] indicated that the near-column zone is controlled by the secondary flow pattern because the rising flow component of this flow pattern controls the size of the particle that can be lifted off the spiral profile. As a result the grade is controlled by the rising velocity component of the secondary flow pattern since at any given size the lower density particle is more likely to be lifted from the spiral profile. As expected, the size of a particle (d_h) that can just settle under the influence of gravity is dependent on the viscosity of the carrying fluid (see Equation [6])[1]:

Table IV

Design matrix to test the range of the values of the variables shown in Table II as well as the measured bandwidths

Test run	Grade (%)	% Solids	Viscosity (mPa.s)	Measured band-width (mm)
1	5	10	47.5	61.9
2	5	10	69.8	59.9
3	5	10	95.8	60.3
4	5	30	47.5	75.6
5	5	30	69.8	56.8
6	5	30	95.8	57.5
7	10	10	47.5	89.3
8	10	10	69.8	68.1
9	10	10	95.8	61.0
10	10	30	47.5	88.3
11	10	30	69.8	84.9
12	10	30	95.8	82.6
13	10	50	47.5	98.4
14	10	50	69.8	97.8
15	10	50	95.8	97.0
16	5	50	47.5	89.1
17	5	50	69.8	83.7
18	5	50	95.8	71.5

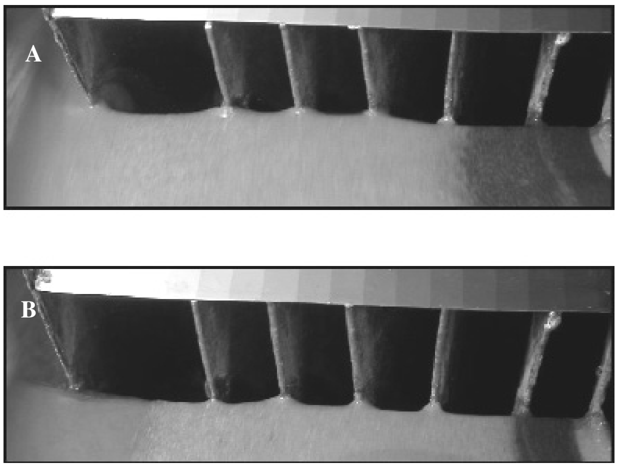

Figure 6—Visual observation of the absence and presence of viscosity modifiers on the radial position of the mineral-gangue interface. (A) No (CMC present. B) CMC present—medium viscosity of 48 mPa.s.

$$d_h = \left(\frac{18 \cdot \eta \cdot \omega}{(\rho_s - \rho_l) g \cdot (1 - C_v)^{4.6}} \right)^{0.5} \qquad [6]$$

with

ρ_s = density of particle (g/cm^3)
ρ_l = density of fluid (g/cm^3)
C_v = volumetric fraction of solids
d_h = vertical cut-size of particle (μm)
η = viscosity (P)
ω = vertical velocity component of fluid velocity (cm/s)

Equation [6] assumes perfectly round particles and fully laminar flow conditions. The viscosity negatively affects the size of a dense particle that can be lifted off the spiral profile (for the same rising velocity) and as a result the recovery of fine particles is expected to decrease in the near-column zone with increased viscosities. The less efficient separation would result in more coarse silica reporting with the ilmenite and also riding on top of the ilmenite, resulting in a smaller observed bandwidth.

The slimes present in industrial samples, even after desliming, prevents the visual detection of the concentrate band; as a result, the verification of the model on industrial samples was performed by analysing (employing quantitative XRD analysis) the splits produced by the mouth organ splitter. Figure 7 plots the average grade (% THM) of each port of the mouth organ splitter as a function of the radial concentrate band width (see measurement 'b' and 'c' in Figure 3; the measurement of the bandwidth was taken from the exact same reference point (the centre column) as the optical technique described earlier). The resolution of the bandwidth by employing the mouth organ splitter is unfortunately fixed by the width of each port; this precludes detailed comparison with the analytical technique. The resolution of the mouth organ could be enhanced by installing more product ports; this would, however, affect negatively the spiral flow patterns in close proximity of the mouth organ splitter inlet. Also plotted in Figure 7 are the model predicted mineral-gangue interface positions as calculated for each experimental run (% solids, volumetric flowrate and feed grade). A total of six tests was performed by varying mainly the flow rates and solids content; the head grade of the sample could not be varied and was fixed between 4 and 6 per cent. Figure 7 indicates that the model-predicted mineral gangue interface is in good agreement with the port where a sharp change in grade was observed (port D). Symbol 'd' in Figure 7 represents the test where a very low solids loading (22% by mass) and low grade (close to the bottom limit of the model) was employed; the model is very sensitive to this combination.

The difference in grade between port C and D was used to test the model predictions in more detail. Figure 8 (a) plots the assumed sigmoidal concentration variation of THM as a function of the radial concentrate bandwidth; it was found that the experimental data fit a sigmoidal equation well (see Figure 8 (b)). The sigmodial equation can be presented by: $y = 1/(y_0 + a/(1 + e^{-(x-x_0)/b})^c)$. Figure 8 indicates that the average THM grade of port D is higher for simulation L (a = 1.407; b = 3.689; c = 0.345; x_0 = 142.158; y_0 = 0.0121) than simulation K (a = 1.662; b = 5.288; c = 1.085; x_0 = 127.072;

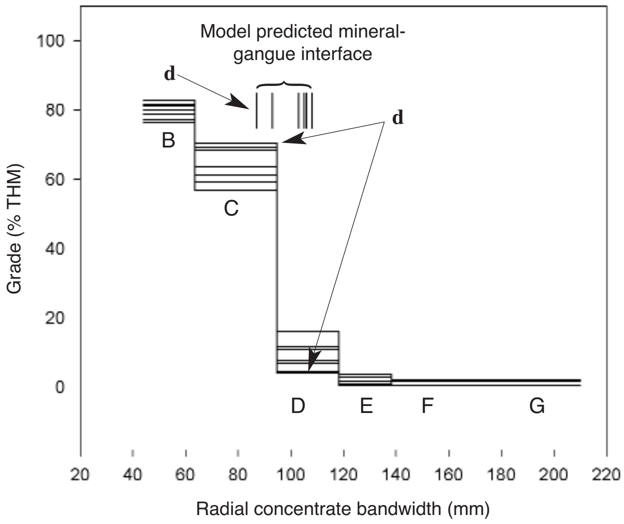

Figure 7—Grade as a function of the radial concentrate bandwidth. The model-predicted mineral gangue interface values are also indicated. The symbols B-G represent the ports shown in Figure 3. Symbol 'd' represents the test performed at a 22% solids loading and low THM grade

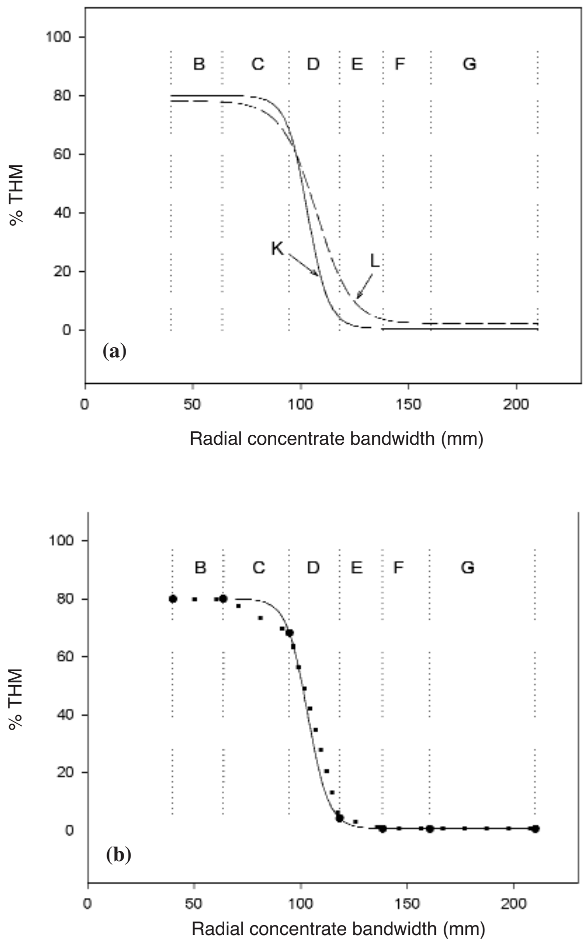

Figure 8—(a) Simulated distributions of the THM grade as a function of the radial position and (b) THM grade distribution of a typical experimental run (dotted line) as well as simulated distribution (solid line). The sample ports of the mouth organ splitter as a function of position are also indicated

$y_0 = 0.0125$). Consequently the difference in grades between ports C and D is larger in the case of simulation K; a larger grade difference is therefore associated with a lower average grade in port D.

A concentrate band falling just inside port D would yield a low average grade while a band falling close to the interface between ports D and E would yield a higher average grade. Therefore following the difference in grade between ports C and D enhances the resolution of the data. Figures 9 and 10 plot the difference in grade values (THM, ilmenite, rutile and zircon) as functions of the predicted mineral-gangue interface. The clear monotonic relationship, especially for ilmenite and THM, is evident in Figure 9, indicating a strong relationship between the predicted and actual band position. A similar strong relationship is also evident for zircon, indicating that the model should be valid in predicting the position of zircon on the spiral profile. In contrast, rutile shows a weaker relationship, indicating a slightly lower predictive power for rutile. Rutile is less dense than ilmenite and zircon and as a result the grade of rutile in port B is strongly dependent on the operating conditions. For example, symbols 'e' and 'f' in Figure 11 represent the experimental runs with the smallest and second smallest predicted band-width, resulting in the largest and second largest difference in rutile grade between port B and C; it is expected that the more dense ilmenite and zircon forced more rutile to report to port C. Interestingly, the absolute value of the difference in rutile concentration (between port B and C) is consistent, for all the experimental runs, with the radial position of the mineral-gangue interface. Observed losses of rutile in the streams E-F could also be attributed to the weaker relationship observed.

The results suggest that the model is successful in predicting the position of the mineral-gangue interface for the majority of the total heavy mineral constituents and could therefore be employed for control purposes.

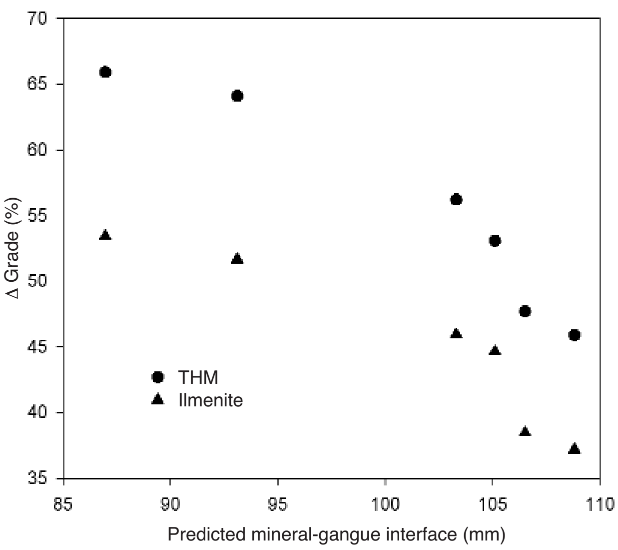

Figure 9—The change in grade (port C relative to port D) of THM and ilmenite as functions of the predicted mineral-gangue interface position for an industrial heavy mineral sample

Conclusions

A process control model for spiral concentrators was proposed. The physical distance of the mineral-gangue interface was successfully detected by means of digital image analysis and expressed as a simple function of the most important operating variables. CMC added as viscosity modifier to simulate the effect of slimes decreased the concentrate bandwidth significantly. A method was developed for deposits containing low slimes contents (dredged deposits) by which the radial position can be determined on line under plant conditions. The model was tested on an industrial heavy minerals sample, from which no mineral-gangue interface could be detected optically due to the presence of slimes, by the process of sampling and

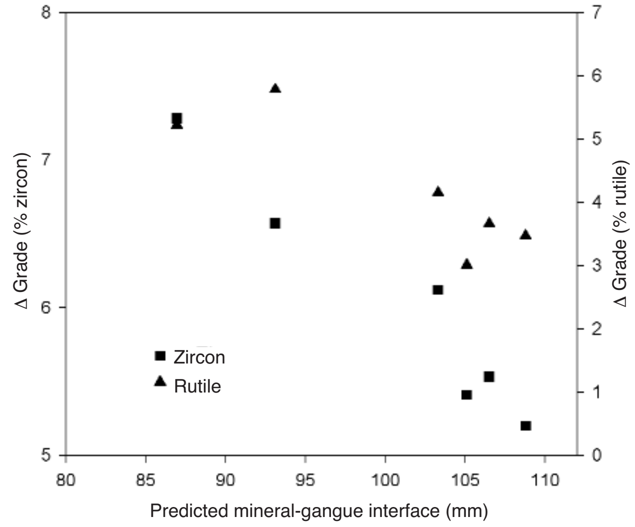

Figure 10—The change in grade (port C relative to port D) of zircon and rutile as functions of the predicted mineral-gangue interface position for an industrial heavy mineral sample

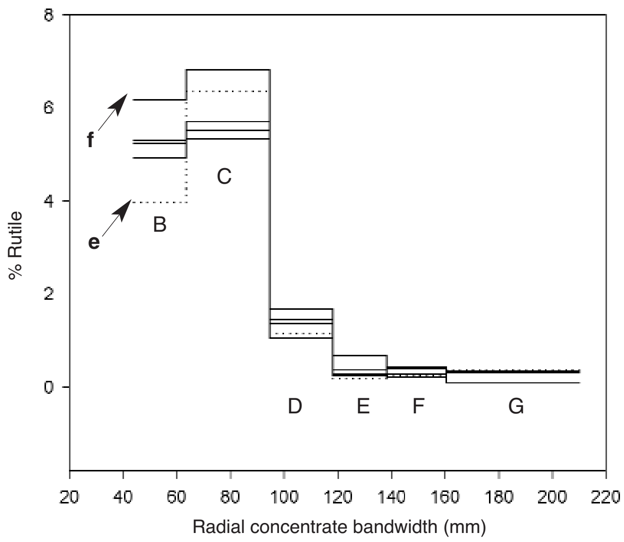

Figure 11—Grade of rutile as a function of the radial concentrate band-width. Symbols 'e' and 'f' represent the tests performed at a 22% and 31% solids loading, respectively. Low THM grades were employed in both experimental runs.

Transaction Paper

analysis of mouth-organ generated samples. The predicted position of the concentrate was in good agreement with the port where a sharp change in grade was observed, suggesting the possible use in process control purposes.

Acknowledgements

A part of the work featured in this article was first published in the *Proceedings of the Heavy Mineral Conference*[12]. The permission of the organizing committee to republish in the current format is acknowledged with gratitude. The paper has been subjected to a separate peer review for the purposes of this publication and has been refined to conform to the norms for scientific peer reviewed publication. The authors gratefully acknowledge the financial support of Multotec process equipment and Exxaro Sands and Richards Bay Minerals for supplying the mineral samples.

References

1. HOLLAND-BATT, A.B. Spiral separation: theory and simulation, *Transactions of the Institute of Mining and Metallurgy* (Section C: Mineral Processing and Extractive Metallurgy), 1989, vol. 98, pp. C46–C60.
2. HOLLAND-BATT, A.B. Interpretation of spiral and sluice tests, *Transactions of the Institute of Mining and Metallurgy* (Section C: Mineral Processing and Extractive Metallurgy), 1990, vol. 99, pp. C11–C20.
3. LOVEDAY, G.K. and CILLIERS, J.J. Fluid flow modelling on spiral concentrators, *Minerals Engineering*, 1994, vol. 7, pp. 223–237.
4. LI, M., JANCAR, T., HOLTHAM, P.N., DAVIS, J.J., and FLETCHER, C.A. Approaches to the development of coal spiral models, Kawatra, S.K. (ed.), *High efficiency coal preparation: An International Symposium*, Society of Mining, Metallurgy and Exploration, Littleton, Co., 1995, pp. 335–345.
5. KAPUR, P.C. and MELOY, T.P. Spirals observed, *International Journal of Mineral Processing*, 1998,vol. 53, pp. 15–28.
6. HOLLAND-BATT, A.B. and HOLTHAM, P.N. Particle and fluid motion on spiral separators, *Minerals Engineering*, 1991, vol. 4, pp 457–482.
7. JOUBERT, D. Personal communications, 2007.
8. KAWATRA, S.K., BAKSHI, A.K., and MILLER JR, T.E. Rheological characterization of mineral suspensions using vibrating sphere and a rotational viscometer, *International Journal of Minerals Processing*, 1996, vol. 44–45, pp. 155–165.
9. ABELA, R. The effect of the slimes content on the rougher spiral circuit in a heavy mineral sands operation, SAIMM, *Proceedings of the Heavy Mineral Conference* 2003, 2003, pp. 1–8.
10. BROWN, R. Slimes Effect on Spiral Efficiency, Report on the Cooljarloo North Mine, 2001.
11. MORKEL, J. and VERMAAK, M.K.G. The role of swelling clay in kimberlite weathering, *Mineral Processing and Extractive Metallurgy* (Trans. Inst. Min. Metall. C), 2006, vol. 115, no. 3, pp. 150–154.
12. STEINMULLER, A. Development and application of simple process models for spiral concentrators, SAIMM, *2005 Heavy Minerals Conference Proceedings*, 2005, pp. 167–172. ◆