Studies of the dynamic characteristics of plant circuits for the development of control strategies

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The dynamic behaviour of plant circuits and the available instrumentation determine the control strategies that are appropriate for the duty of the mineral separation plant. Although steady state modelling is appropriate to provide the main requirements of grade and throughput capability of a plant, it is the dynamic characteristics that determine the tolerance of the plant to disturbances and also its controllerability. This paper explores these issues with respect to the additional use of dynamic modelling to achieve these objectives.

Introduction

The overall performance of a wet gravity circuit during the design of a mineral sands wet plant has invariably been determined using a computer model to simulate the circuit. The separation parameters for each stage in the circuit are derived from laboratory-scale and/or pilot plant test work for a particular mineral or mineral suite. These parameters are then used in a model on a stage-by-stage basis with one stage feeding into the next, incorporating the relevant recirculating streams into the feed for each stage. The circuit performance is determined at various expected head feed grades and these data are then used to establish an operating control philosophy. The selection of the type and quantity of appropriate separation and material transport equipment to accommodate the expected stage loadings is also part of this process. Appropriate use of available actuators and sensors for key parameters would then allow automated control of the circuit.

A circuit design is generally constrained by the maximum feed rate (maximum rougher stage loading), or sometimes the tailings system handling capacity. Another constraint could be the maximum heavy mineral concentrate (HMC) production rate as determined by the downstream processing. The maximum feed rate or the tailings system capacity is particularly relevant for a low grade feed and determines the rougher stage capacity. The HMC production rate reduces the throughput when there is an abnormal high grade feed and determines the cleaner capacity stages.

It is usual to conduct simulations at the expected upper and lower bounds of the feed grade with a third simulation at the ‘average’ or design feed grade. In addition, multiple discrete simulations of possible operating scenarios of a circuit are required, but unfortunately are both time consuming and prone to some subjective interpretation, particularly of stage mass splits. The requirement allows the exploration of the potential controllerability of the circuit as well as the sensitivity to various disturbances. The most significant disturbances for a wet circuit are the feed rate of mineral and its grade.

In this paper, the concept of using a dynamic simulation of a wet gravity circuit is discussed, particularly the resultant ‘real’ life output of the simulation and the demonstrable effects of the derived operating philosophy via the performance matrix for a circuit.

Flowsheet and sample preparation

To enable the demonstration of the dynamic design approach of the this paper, a four-stage wet concentrator plant (WCP) will be used. The WCP flowsheet has a nominal required feed rate of 1 125 tph with a concentrate production rate constrained to a nominal 100 tph. The steady state and dynamic operation of the WCP will be demonstrated by determining the performance matrix with the feed grade as the major disturbance variable.

The basis of the simulations of the WCP flowsheet is the integration of stage by stage separation performance as determined by individually constructed release curves. These curves have been constructed from data collected from physical test work using full-scale separation equipment and a representative bulk sample of the expected feed material.

The rougher stage release curve is constructed from data gathered from test work conducted on material representing the expected/design rougher feed material. The feed material for this stage in the test work is prepared from the bulk sample by desliming and also the removal of oversize material. A bulk bleed-out is then conducted on the remainder of the sample at optimum conditions as determined by the initial test work. This then generates feed material for the subsequent stages in the flowsheet. The process is repeated with recirculating streams combined as appropriate to generate the stage-by-stage separation performance data for inclusion in the flowsheet simulation.

Circuit description

The flowsheet for the WCP used in this paper has four components, a rougher stage, a mid scavenger stage, a cleaner stage and a reclaimer stage that produces the final concentrate.

The rougher stage of spiral separators generates tailings, middlings and concentrate streams. The tailings stream is removed from the circuit. The middlings stream reports to a mid scavenger stage of spiral separators. The concentrate stream reports to a cleaner stage of spiral separators.
The feed for the mid scavenger stage is composed of the rougher middlings stream, its own middlings stream and the cleaner stage tailings stream. The tailings generated are directed to the tailings pumping system for disposal. The concentrate stream reports to the cleaner stage.

The feed for the cleaner stage feed comprises the rougher and mid scavenger concentrate streams, its own middlings stream and the recleaner tailings stream.

The recleaner feed is made up of the cleaner concentrate stream and its own middlings stream. The tailings stream reports to the cleaner stage, as indicated previously. The concentrate from the recleaner stage reports to the final concentrate sump.

It is clear from this description that the tailings from this circuit are removed only at the rougher and mid scavenger stage for the WCP flowsheet.

Release curves

The rougher stage data were collected from a series of tests conducted on a model HC1 R/S spiral separator using mineral sand material with 7% HM as feedstock. Mass and water flows for test streams were calculated from timed full stream samples, with each stream analysed for heavy mineral (HM) content. The HM analyses were determined by using heavy liquid separation analyses at a specific gravity of 2.85 g/cm³ using bromoform.

Similarly, once the required feedstock was created from processing the bulk feed sample, release data were generated using a model HC1 spiral separator for the scavenger stage and the model HG10 spiral separator for each of the cleaner and recleaner stages.

By using the procedures just outlined the resultant heavy mineral distributions and grade versus mass yield to concentrate (release and grade) curves are shown in Figure 1. The HM release curves were generated using in-house propriety software that fitted appropriate functions to the test work data generated from laboratory separation of the prepared bulk heavy mineral sand.

Modelling

An HM content-based model can now be constructed for the circuit. The performance of each individual stage was determined by applying the relevant HM release curve normalized to that particular stage’s feed grade (HM content).

In order to automate the model for the mass split for each stage product, the feed grade to that particular stage was used to determine the yield to the concentrate for the same stage. The procedure used consisted of the determination of a setting that would be consistent with the operation of the spiral separator at or just before the peak separation efficiency point (as indicated on Figure 1 and Figure 2).

The separation efficiency curve, shown in Figure 2, is a mathematical derivation of the release curve. The separation efficiency can be defined as the proportion of the original mineral that has been recovered in the concentrate in pure form. This is equivalent to the recovery with ‘dead flux’ removed and ‘normalized’ with respect to the feed grade. The formula for the separation efficiency curve is shown below.

\[ SE = \frac{\text{recovery} - \text{yield}}{1 - \text{feedgrade} / 100} \]

The mass yield to the middlings split was then determined by selecting a point on the separation efficiency curve at or after the peak separation efficiency point for the remainder of the stream content, namely for the calculated stream content after the concentrate had been removed (as indicated on the original separation efficiency curves in Figure 1 and Figure 2).

Dynamic modelling

The example being used for this paper has a design feed grade of 10% HM and production constraints of a maximum of 1 125 tph rougher feed with a maximum concentrate production of 100 tph. Using these parameters the design performance of the circuit can be simulated. The results of such a simulation using these data are shown in Table I.

The resultant mass balanced stream data, from the simulations, are used to determine the equipment quantity and pumping requirements. Generally the extremes of the expected feed grade are then used in simulations to investigate the effect on the circuit performance and its
mass balance. In this case 6.5% and 15% HM were used for these limits. Table II and Table III show the circuit performance at these limits. Note that at the maximum feed grade, the throughput, is reduced in order to limit the HMC production rate to the design maximum HMC production rate of 100 tph.

The data shown in Tables I, II and III have traditionally been used to establish the circuit performance matrix as well as the operating strategy for the rougher feed rate reduction with increasing feed grade. While this has been the standard method in the flowsheet development process, the circuits’ non-linear response to varying feed grades is not adequately described. A ‘dynamic’ model has consequently been developed to investigate the circuit response to stream loading as the feed grade changes.

In order to achieve a real life simulation-the grade is changed randomly within certain constraints and the various stream parameters recorded while the circuit attains its new balance. The feed grade is then changed again and the process repeated several thousand times. Figure 3 shows typical output data. The feed grade, HMC output and HM performance (HMC grade and recovery) are plotted as a function of time. For the WCP simulations under consideration the feed grade had minor variations from one interval to the next (up to ±10% relative variation). The circuit performance for the range of feed conditions simulated is shown in Figure 4.

It is apparent that for this particular circuit and using the particular material characteristics of the feedstock, that the expected HMC performance will be greater than 94% HM at an overall recovery of greater than 92%. In particular, the HM recovery will increase from 89.5 to 90.7% when the HMC grade varies from 94.5 to 96%. The actual amount of HMC grade variation depends on the feed grade. The scatter in HMC grade and recovery determined from the simulation, as has been demonstrated here, can be used to establish a statistical-based performance guarantee.

Spiral start numbers are also determined using the design simulation procedure. During the dynamic simulation the stage-by-stage loadings are monitored. Typical spiral loading data are shown in Figure 5. These loading results verify that the spiral models selected are maintained at or below their maximum allowable loadings. The results also verify that both equipment numbers and the control strategy of limiting the rougher feed rate for the constrained HMC production rate for the expected range of potential feed grades is justified.
Figure 3. Dynamic simulation showing HMC production rate, grade and recovery with feed grade variation.

Figure 4. Circuit performance versus feed grade.

Figure 5. Stage by stage spiral loading.
During a simulation run other parameters such as stage-by-stage feed density and feed volume are also monitored. These are shown in Table IV. These data are used to design the pumping systems for the flowsheet. A particular feature of the operating strategy used in this case is that the volume flow rate to the rougher, cleaner and recleaner stages was maintained at a constant level, thereby simplifying these pumping duties. The scavenger stage feed volume was varied according to demand; nevertheless its pumping volume remained reasonably stable within a ±50 m³/h range. The stage feed density changes to maintain the volume loading was found to be within usual spiral operating range.

The influence of a more significant variation in feed grade is simulated with the feed grade varied by up to ±20% relative. This results are shown in Figure 6. In this case the significant instantaneous variation in feed grade is translated to large variation in HMC output rate; however, the overall circuit performance is comparatively constant over time. The result is shown in Figure 7.

### Table IV
Various circuit parameters monitored during the simulation

<table>
<thead>
<tr>
<th>Item</th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed grade (%)</td>
<td>6.5</td>
<td>10.9</td>
<td>15.0</td>
</tr>
<tr>
<td>New feed rate (tph)</td>
<td>769.6</td>
<td>1005.5</td>
<td>1125.0</td>
</tr>
<tr>
<td>HM in HMC (%)</td>
<td>94.3</td>
<td>95.5</td>
<td>96.1</td>
</tr>
<tr>
<td>HM Rec’y (%)</td>
<td>89.5</td>
<td>90.2</td>
<td>90.7</td>
</tr>
<tr>
<td>Con rate (tph)</td>
<td>69.5</td>
<td>101.2</td>
<td>113.9</td>
</tr>
<tr>
<td>Rougher loading (tph/start)</td>
<td>5.3</td>
<td>7.0</td>
<td>7.8</td>
</tr>
<tr>
<td>Scavenger loading (tph/start)</td>
<td>1.8</td>
<td>2.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Cleaner loading (tph/start)</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Reclaimer loading (tph/start)</td>
<td>1.2</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Rougher feed density (%)</td>
<td>39.8</td>
<td>48.2</td>
<td>52.3</td>
</tr>
<tr>
<td>Scavenger feed density (%)</td>
<td>19.0</td>
<td>22.2</td>
<td>24.5</td>
</tr>
<tr>
<td>Cleaner feed density (%)</td>
<td>21.9</td>
<td>25.9</td>
<td>28.5</td>
</tr>
<tr>
<td>Reclaimer feed density (%)</td>
<td>22.8</td>
<td>30.9</td>
<td>34.0</td>
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<tr>
<td>Rougher feed volume (m³)</td>
<td>1440.0</td>
<td>1440.0</td>
<td>1440.0</td>
</tr>
<tr>
<td>Scavenger feed volume (m³)</td>
<td>808.1</td>
<td>849.4</td>
<td>906.9</td>
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<tr>
<td>Cleaner feed volume (m³)</td>
<td>864.0</td>
<td>864.0</td>
<td>864.0</td>
</tr>
<tr>
<td>Reclaimer feed volume (m³)</td>
<td>216.0</td>
<td>216.0</td>
<td>216.0</td>
</tr>
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</table>

Figure 6. Dynamic simulation showing HMC production rate, grade and recovery with feed grade variation of up to 20%

Figure 7. Circuit performance versus feed grade at high feed grade variability
In this case the expected HMC performance will indicate a grade of greater than 94% HM, as before, at an overall recovery of greater than 89% (89.5 to 90.8), showing a slight increase in recovery, but a significant increase in recovery variability. These data highlight the significant effect that increasing feed grade variability has on the circuit performance.

The options for control are:

• Use the dynamic simulator to explore different circuit options and determine which is best dynamically
• The dynamic performance, shown in this paper, indicates a need for improved feed control using a more consistent feed rate and/or more consistent % HM. These objectives may be achieved by increasing the feed buffering capacity and/or feed blending prior to the supply to the rougher stages of the plant
• Together with appropriate sensors, control the intermediate stages to a more stable criterion within the limits of intermediate buffering capacity.

Conclusions
The use of the dynamic simulation of the wet plant flowsheet has given the process engineer the ability to test and examine the results of operating the wet plant with a particular control strategy. The output gives an excellent visualization of the controllerability of the plant.

The effect of feed grade variability on circuit performance can be clearly demonstrated and it provides more significantly improved insight than steady state simulations of the circuit performance. For the wet circuit example used in this paper, the instantaneous or dynamic behaviour showed a significant drop in performance when the expected feed variation changed from low to moderate. Further refinements to the simulator are needed to add a more user friendly interface with a set of ‘standard’ control strategies that can be run for direct comparison of their influence on circuit performance.

A further benefit of the development of a ‘real-time’ simulator would be to assist in the training of plant operators, allowing future ores to be ‘processed’ and the prediction of relevant operating parameters prior to the plant mining in that area.

References