COM 2013

Trends with Selection and Sizing of Large Flotation Circuits – What’s Available in the Market Place

Presented by Damian Connelly
Mineral Engineering Technical Services
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Key Attributes

Pragmatic, efficient, complete engineering through quality, personalised & exceptional service delivery

- Working globally since 1988
- Dynamic and innovative niche consultancy
- Dedicated team providing customised service
- Specialist in Mineral Processing & Engineering Projects
- Unique solution finder
> Current state of technology and flotation equipment

> Flotation cells have increased in size, cell layout, technology & design

> Key factors: ore type, retention time, grind size, reagent regime

> Change from Hough trough to tank cells up to $600m^3$

> Flash flotation, column cells, Jameson cells and in stream analysis

> Flotation control and simulation
Flotation Process

- Collectors
- Frothers
- Modifiers
- Depressants
- Activators
Recovery Response

Time Recovery Curve

Recovery (%)

0.0  10.0  20.0  30.0  40.0  50.0  60.0  70.0  80.0  90.0  100.0

0.0  5.0  10.0  15.0  20.0  25.0  30.0  35.0

Time (min)
Flotation Kinetics - Batch Flotation

\[ \frac{\text{slope at } t_1}{(R_\infty - R_1)^n} = \frac{\text{slope at } t_2}{(R_\infty - R_2)^n} = k \]

\[ -\frac{dC}{dt} = kC^n \]

> First Order Kinetic, \( n = 1 \)

\[ \left( \frac{C_0 - C_\infty - C + C_\infty}{C_0 - C_\infty} \right) = \left( \frac{C_0 - C}{C_0 - C_\infty} \right) = 1 - e^{-kt} \]

\[ R = R_\infty \left( 1 - e^{-kt} \right) \]
> k is a complex function involving:
  - Reagent concentrations
  - Particle and bubble sizes
  - Induction times
  - Flotation cell design
  - Rate of froth removal
  - Power input
  - Previous treatments

This will only be constant as long as these conditions remain constant

> For any given conditions, k is a quantitative measure of the probability of particles being recovered in the concentrate

> k can be used to compare different reagent conditions in the same cell, or different flotation cells treating the same pulp
First Order Kinetic Model

> Klimpel’s model: \[ R = R_\infty \left[1 - \frac{1}{kt} (1 - \exp(-kt))\right] \]

\(k\) = rate constant representing the largest allowable value of a rectangular distribution

Assumption: rate constant distribution is constant over a fixed interval

> Kelsall’s model: proposed a flotation model that incorporates two rate constants which describe fast and slow floating component

\[ R = (R_\infty - \phi)(1 - \exp(-k_F t)) + \phi(1 - \exp(-k_S t)) \]

where \(\Phi = \text{fraction of flotation components with the slow rate constant}\)
\(k_F = \text{fast rate constant (min}^{-1})\)
\(k_S = \text{slow rate constant (min}^{-1})\)
Limitations of Batch Flotation

> Rapid changing of concentrate trays in the early stages of the test

> Pulp level changing and inhibits the true measurement for the agitation and aeration characteristics

> Difficulty in denoting zero time

> Higher removal of active agent than pulp

> The solution: laboratory test should be conducted using a continuous cell and ideally in a minimum of 2 cells in series
Continuous Flotation

> Fractional recovery in a single cell, assuming all of the mineral is floatable

\[
k = \frac{\text{flotation rate (mass / unit time)}}{\text{mass of floatable material remaining in the cell}} = \frac{M_{SC}}{M_{ST}}
\]

\[
k \lambda = \frac{M_{SC}}{M_{ST}} \quad \lambda = \text{nominal residence time of the pulp in the cell (cell volume/volume flow rate of tailings)}
\]

\[
M_{SC} = \text{mass of solid in the concentrate} \\
M_{ST} = \text{mass of solid in the tailings}
\]

> Recovery from the feed to a cell:

\[
R' = \frac{M_{SC}}{M_{SF}} = \frac{M_{SC}}{M_{ST}} \cdot \frac{M_{ST}}{M_{SF}} = \frac{k \lambda}{1 + k \lambda}
\]
Continuous Flotation

Total recovery from N cells:

\[ R = R_1 + R_2 + R_3 + \ldots + R_N \]

\[ R = R_1 + R_1(1-R_1) + R_1(1-R_1)^2 + \ldots + R_1(1-R_1)^{N-1} = 1-(1-R_1)^N \]

\[ R = 1-(1+k\lambda)^{-N} \]
Effect of Cell Size and Number

> Consider a bank of 6 cells replaced by a single large cell of the same total residence time

> For 6 cells, recovery = 94%

> For a single large cell (same total volume), $\lambda = 6 \times 2 = 12$ min

> Recovery = $1 - (1+0.3 \times 12)^{-1} = 78\%$

> The difference in recovery is the result of a difference in the residence time distribution of particles in the bank which changes for more than one cell in series, though the mean residence time may remain the same
P(t) is the probability that a particle will have a residence time, t.

For a single cell, most particles exit the cell immediately.

At extended times there are still some particles exiting the cell.
Flotation rate of particles with varying feed floatability

Flotation response = particle characteristic x cell characteristic

\[ k = P S_B R_F \]

where

- \( P \) = a parameter related to ore floatability
- \( S_B \) = the bubble surface area flux \( (=6J_C/d_{32}) \)
- \( R_F \) = a froth recovery factor

The bubble surface area flux is defined as the total surface area of bubbles available in the cell per unit cross-sectional area of cell per unit time and hence will depend on the bubble size and velocity.
The bubble surface area flux is defined as:

\[ S_B = \frac{6J_G}{d_{32}} \]

where \( J_G \) = the superficial gas velocity, m/s and \( d_{32} \) = the Sauter mean bubble diameter, m

The Sauter mean diameter is the diameter of a bubble having the same specific surface (volume per unit surface area) as the whole bubble size distribution. That is:

\[ d_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \]

where \( n_i \) = number of bubbles of diameter \( d_i \)
The Sauter diameter is measured by a bubble size analyser such as the University of Cape Town Bubble Size Analyser or from digital images such as the McGill Bubble Size Analyser.
UCT Bubble Size Analyser

Scuddles Mine

Source: JKTech, 2013
The superficial gas velocity is measured by capturing a volume of bubbles for a set time in a tube of fixed cross-sectional area.

Source: Gupta, A. & Yan, D., 2013
Superficial Gas Velocity

> Superficial gas velocity ($J_G$) is a measure of the aeration ability of a cell and is directly related to the flotation kinetics

> If the superficial gas velocity is too high:
  - The entrainment of gangue material into the froth phase may become excessive
  - Reduces the froth stability
  - Decreases the concentrate grade

> Measuring the superficial gas velocity at various locations across the cell cross-sectional area gives a good indication of how well the air is dispersed in the cell
Gas Hold-up

> Gas hold-up ($\varepsilon_g$) measures the volume fraction of air contained within the pulp phase of the flotation cell.

> Generally increasing the gas content within the cell results in:

  - More bubbles per unit volume and hence more available surface area for particle-bubble interactions to occur, producing improved kinetics in the pulp phase.
  - There is a maximum value of gas hold-up before the cell capacity is limited, resulting in reduced residence time.

Source: JKTech, 2013
The froth recovery factor, $R_F$, is defined as the efficiency with which the particles arriving at the froth/pulp interface reach the concentrate.

This is dependant on the residence time of air in the froth, which is determined by froth depth:

- Froth depth = 0 \quad R_F = 100%  
- Very deep froth \quad R_F \text{ (and } k \text{)} = 0

$R_F$ is the ratio of the overall rate constant and the collection zone rate constant and lies between 0 and 100%.

Other factors affecting the froth recovery factor are:

- The air flow rate
- Impeller design
- Cell design
- Impeller speed
- Frother type and concentration
Ore Floatability

> The ore floatability, $P$, is affected by the ore mineralogy, particle liberation and particle size, reagent coverage of the particle surface and the pulp chemistry.

> For a given froth recovery factor, a plot of rate constant versus bubble surface area flux gives a straight line, of slope $= P$. 
JKSimFloat is a general purpose computer software package for the simulation of flotation plant operations.
Steps

1. Determine Surface Area Flux, \( S_B \) eg. Using \( J_G \) and Sauter diameter measurements
2. Determine \( R_F \) and \( \text{ENT} = \text{Recovery by entrainment}/\text{Recovery of water} \)
3. Assumes 10% of feed goes to concentrate
4. Estimate water flow in concentrate and hence water and solid flow in tail
5. Estimate residence time by:
   \[
   \lambda = \frac{V(1 - \varepsilon_g)}{Q_{\text{tails}}}
   \]
   where \( \varepsilon_p = \text{gas hold-up} \)

6. Calculate \( k_i \) the rate constant for each particle class and hence \( R_i \) the recovery for each particle class
   \[
   R = \frac{PS_B R_F \lambda}{1 + PS_B R_F \lambda}
   \]
   Recovery in tails is calculated by difference

7. Calculate proportion of each component in tail recovered to concentrate by entrainment and recalculate the tail
8. Repeat calculation until mass in each particle class converges to constant
Stage Recovery = \sum m_i \left( 1 - \left( 1 + \frac{FF}{N} k_i \lambda \right)^{-N} \right)

(Loveday and Hemphill, 2006)

where
m_i = mass fraction of species “i”

k_i = rate constant of species “i”

\lambda = residence time, and

FF = the froth factor which accounts for loss of particle in the froth by detachment etc.

A better fit to plant data incorporated the fractional recovery of mineral by the froth:

R_F = \left( 1 + \frac{k_F \lambda_F}{N} \right)^{-N}

Overall Recovery = \frac{R_p - R_F}{1 - R_p + R_p R_F}
Plant Models for Optimisation

- Plant survey data used to estimate the model parameters for up to 3 mineral species by regression.

- Fitting data for stages (banks) of cells rather than individual cells simplifies the regression.

- The computer simulation allowed adjustment of froth residence times and hence the mass pull of concentrates.

- Pulling rate could not be linked to control variables e.g. froth depth and air rate due to changes in froth stability.

- Assumes that rate constants remain same – pulling rates need to be kept within realistic levels.
> Investigate the response of the main indicators of performance, Recovery and Grade, to process variables (e.g. reagent concentration, air flow rate, agitator speed etc.)

> Using a Response Surface Methodology (RSM) to evaluate multiple variables and their interactions rather than the one-variable-at-a-time approach

> RSM is a collection of statistical and mathematical methods to optimise the response surface influenced by many process variables
<table>
<thead>
<tr>
<th>Supplier Name</th>
<th>Agitation</th>
<th>Flotation Cell Type</th>
<th>Tank Sizes</th>
<th>Air Requirements</th>
<th>Position of Mechanical Agitator</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFE Minerals</td>
<td>Mechanical</td>
<td>Circular Cell</td>
<td>Unknown</td>
<td>Forced Air</td>
<td>Centre</td>
</tr>
<tr>
<td>Outotec Technology</td>
<td>Mechanical</td>
<td>Circular &amp; Square type</td>
<td>5 m³ – 200 m³, New 300 m³</td>
<td>Forced Air</td>
<td>Bottom</td>
</tr>
<tr>
<td>GL&amp;V</td>
<td>Mechanical &amp; Pneumatic</td>
<td>Circular &amp; Square type</td>
<td>5 m³ – 200 m³</td>
<td>Forced Air I &amp; Wemco Self Induced</td>
<td>Centre &amp; Bottom</td>
</tr>
<tr>
<td>Metso Minerals</td>
<td>Mechanical &amp; Pneumatic</td>
<td>Circular &amp; Square type</td>
<td>5 m³ – 200 m³</td>
<td>Forced Air</td>
<td>Bottom</td>
</tr>
<tr>
<td>Bateman Flotation Equipment</td>
<td>Mechanical</td>
<td>Circular &amp; Square type</td>
<td>5 m³ – 120 m³</td>
<td>Forced Air</td>
<td>Bottom</td>
</tr>
</tbody>
</table>
Grade Optimisation in Graphite Flotation

Source: Aslan et al (2008)
Recovery Optimisation in Graphite Flotation

Source: Aslan et al (2008)
Recovery Optimisation in Coal Flotation

Lab results scaled up using: 1. Airflow number  2. Froth number

Control Systems - Froth Image Analysis

- Frothmaster (Outotec)
- METCAM (SGS)
- VisioFroth (Metso)
- JKFrothcam
Flotation Circuit Control

> Techniques in 1950
  - Panning dish
  - Assays

> On line X-ray analysis 1965
  - Tube system
  - Radio-isotope system
In-stream Analyser

- Density probe
- Pb probe
- Zn probe
- To adjacent flotation cells
- Existing slurry vessel
- Pulp in

Mineral Processing
Engineering Design
Training
Specialist Services
Frothmaster - Outotec

Measurements:
> Froth speed and direction
> Bubble size distribution
> Froth stability
> Colour histogram (R,G,B)
> Statistical information
> Measures
  - Directional froth velocity
  - Froth stability
  - Bubble size distribution
  - 6 image colour readings
> Measuring froth velocity, bubble size, colour, stability and texture
JKFrothCam measures froth characteristics on-line

This provides an opportunity to manage flotation through automatic control of:
- Air additions
- Pulp level set points
- Reagent additions
Image Analysis for Flotation Control

**Measure:**
- Froth type
- Froth velocity
- Bubble size

**Set:**
- Air flow rate
- Collector

**Flotation Cell**

**Control:**
- Frother dosage for *froth type*
- Froth depth for *froth velocity* to achieve grade and recovery

**Operator**

**Computer**

**Froth Data**

**Cameras**

**Control system**

**Courtesy of JK Tech Pty Ltd**
JKFrothCam Data

- Every few seconds, JKFrothCam measures:
  - Froth type
  - Froth velocity
  - Mid_TU (an indicator of froth bubble size)

From these characteristics, metallurgical parameters can be predicted using a soft(ware) sensor
- % solids
- % mineral or element
> Texture Spectrum Analysis (Froth Type Recognition)
> Each Froth Type is related to a known condition:
>  - Ideal conditions
>  - Low frother
>  - High frother
>  - Overloaded bubbles
600 Series SuperCell Flotation Machines

- Installed Robinson Nevada
- 8m high and 7m dia.
- Power 746 kW

Source: FLSmidth, 2013
Boddington, Australia
The plant is processing 36 Mtpa of ore feed. There are three trains of rougher scavengers with a coarse cleaner, scavenger cleaner and regrind. Flash flotation units are also installed. The roughers are OK150TC cells whilst the scavengers are OK200TC cells supplied by Outotec.

Panaust, Laos
The copper flotation concentrator rougher scavenger consists of four OK 200m2 roughers and four OK 200 m³ scavenger tank cells. The design residence time is 25 minutes. The cleaners consist of three 70 m³ tank cells. A cleaner scavenger bank consists of three OK 70 m³ tank cells.

Ernest Henry, Australia
The copper flotation concentrator consists of five banks of Wemco rougher cells with 127 m³ capacity a total of nine cells. See attached flow sheet
Boddington Flowsheet

Mineral Processing

Engineering Design

Training

Specialist Services
Boddington layout
Ernest Henry Flow sheet
> Tank cells now preferred

> Coarse grinds are a limitation

> Forced air more favoured

> Flotation cell size will continue to increase

> Column cells established as final cleaners in the copper industry

> Energy reduction initiatives- coarse flotation and cell designs

> Internal launders mandatory for large tank cells

> Flotation control making progress


THANK YOU

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