Assessing Your Plants Flotation Behaviour Using Gas Dispersion Parameters

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The Presentation will cover

- The **importance of bubble size** and therefore **frother** in flotation performance
- The **gas dispersion parameters**
- The **concepts of CCC, CCCX and HLB**
- How the key operating variables affect bubble size (a **model for D_{32}**)
- A “**Road Map**” for process optimization
- Some **implications** for process improvement
- **Case study**: Lac des Iles
Illustrating the importance of frother and small bubbles in flotation (video)

View inside a Denver laboratory flotation machine: water-air system: no air/air added/air with frother

Courtesy of McGill and Metso CBT Flotation Module 2002 (originally BPT 1996)
Frother functions are multiple:

1. Stabilizing **small bubbles** (0.5 – 2 mm) in pulp phase by preventing coalescence

2. Bubble size and shape affect bubble surface area flux, gas hold-up and interfacial surface area of gas and hence particle collection efficiency and flotation kinetics

3. Froth formation and stability thus influencing water drainage/recovery, hence gangue rejection and concentrate grade
Adding frother affects the size, shape and distribution of bubbles

Sauter Mean Bubble Diameter

\[ D_{32} = \frac{\sum_{1}^{n} d^3}{\sum_{1}^{n} d^2} \]

(Not the average bubble size)

Coalescing \rightarrow Non-coalescing
Gas Dispersion Terminology

Sauter mean bubble size (mm)
• characteristic of the bubble size distribution (gas volume/surface area)

\[ D_{32} = \frac{\sum_1^n d^3}{\sum_1^n d^2} \]

Superficial gas velocity (cm/s)
• gas flow/unit of cell x-sect area

\[ J_g = \frac{Q_{gas}}{A_{Xsect}} \]

Bubble surface area flux (1/s)
• area of bubble surface/sec/unit of cell x-sect area

\[ S_b = 60 \cdot \frac{J_g}{D_{32}} \]

Flotation rate constant (1/s)
• \( R_{froth} \) is recovery across the froth
• \( P \) is the “floatability” factor for particles

\[ k_{overall} = R_{froth} \cdot k_{pulp} \]
\[ k_{pulp} = P S_b \]
What is the relationship between flotation (rate, k) and bubble size?

The $k-S_b$ relationship (Gorain):

$$k_{pulp} = P S_b = P \cdot 60 \frac{J_g}{D_{32}}$$

Hence:

$$k \propto \frac{1}{d^{2}}$$

But does $P$ also vary with bubble size?

Hernandez–Aguilera et al\textsuperscript{1} have found

$$k \propto \frac{1}{d^{3}}$$

Others\textsuperscript{2} suggest a stronger dependence

$$k \propto \frac{1}{d^{3}}$$

\begin{itemize}
  \item \textsuperscript{1} Hernandez-Aguilar, J.R.; Basi, J.; Finch, J.A. Improving column flotation operation in a copper/molybdenum separation circuit. CIM J. 2010,
  \item \textsuperscript{2} Yoon, R.H. Microbubble flotation. Miner. Eng. 1993, 6, 619–630.
\end{itemize}
What is the relationship between flotation (rate, k) and bubble size?

Use a 1\textsuperscript{st} order recovery model having n cells in series

\[
\text{Recovery} = R_\infty \left[ 1 - \left( 1 - \frac{k_i t_i}{1 + k_i t_i} \right)^n \right]
\]

Assumptions

- 1\textsuperscript{st} order flotation kinetics, fully mixed cells
- \( k \) base line = 0.1 s\textsuperscript{-1}
- 8 Flotation cells in series (n=8)
- Flotation time \( t = 30 \) min
- \( R_\infty = 90\% \),
- Froth recovery = 100\% (\( R_{\text{froth}} = 1 \))
An example: Why bubble size is important in flotation recovery

Impact on recovery of reducing bubble size ($D_{32}$) from 1.7 to 1.2 mm by changing frother type/concentration

<table>
<thead>
<tr>
<th>K ($s^{-1}$)</th>
<th>Baseline</th>
<th>1/d</th>
<th>1/d²</th>
<th>1/d³</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$_{32}$ mm</td>
<td>1.7</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Rec’y %</td>
<td>83.0</td>
<td>87.0</td>
<td>89.0</td>
<td>89.7</td>
</tr>
</tbody>
</table>

$k \propto \frac{1}{d^3}$

$k \propto \frac{1}{d^2}$

$k \propto \frac{1}{d}$

**Graph:**

- **$k = 0.1$**
- **$k = 0.14$**
- **$k = 0.2$**
- **$k = 0.28$**

% Recovery

- $k = 0.1$: 83.0
- $k = 0.14$: 87.0
- $k = 0.2$: 89.0
- $k = 0.28$: 89.7

**Equations:**

- $k \propto \frac{1}{d^3}$
- $k \propto \frac{1}{d^2}$
- $k \propto \frac{1}{d}$
The CCC and CCCX (%) concepts and modeling $D_{32}$

CCC95 values closely approximate Laskowskī’s CCC (critical coalescence concentration) values but easier to establish mathematically.

Modeling $D_{32}$

$D_{32} = d_l + a \cdot \exp \left[ -b \cdot \frac{ppm}{CCC95} \right]$  

$CCCX(\%) = 100 \cdot (1 - \exp \left[ -b \cdot \frac{ppm}{CCC95} \right])$
Linking $D_{32}$ to frother type (CCC95) and Concentration (ppm) – normalized by (PPM/CCC95)

- 5 frother types
- 2 gas rates ($J_g$)

Frother can be characterized by its CCC95 (@ $J_g=0.5$ cm/s)

\[ D_{32} = 0.874 + 2.26 \cdot \exp \left[ -3.09 \cdot \frac{ppm}{CCC95} \right] \]
The link between CCC95 and HLB

**HLB**

Hydrophile – Lipophile Balance

A measure of the solubility of a surfactant in water.

Calculated empirically from the molecular structure (Davies method)

\[
\text{HLB} = 7 + \sum (\text{hydrophilic group numbers}) + \sum (\text{lipophilic group numbers})
\]

<table>
<thead>
<tr>
<th>Functional group</th>
<th>Group contribution number</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrophilic</strong></td>
<td></td>
</tr>
<tr>
<td>–OH</td>
<td>1.9</td>
</tr>
<tr>
<td>–O−</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Lipophilic (or hydrophobic)</strong></td>
<td></td>
</tr>
<tr>
<td>–CH</td>
<td>–0.475</td>
</tr>
<tr>
<td>CH₂</td>
<td></td>
</tr>
<tr>
<td>–CH₃</td>
<td>=CH</td>
</tr>
</tbody>
</table>

The limiting bubble size $d_l$ is controlled by molecular structure (HLB).

Frothers with higher HLB (solubility) = smaller limiting bubble size

Data from Zhang et al, 2012, Minerals, Vol 2, pp 208-227
CCC95 values can be predicted from molecular structure of the frother.

Zhang et al (2012, Minerals, Vol 2) have developed specific equations for predicting CCC95 from HLB
D_{32} Model Development: Operating variables investigated

✓ Frother type and concentration
• Gas rate $J_g$ (volumetric air flow/cell area)
• Power input ($\propto$ impeller speed$^3$)
• Gas Density (altitude)
• Viscosity (water temperature)

Testing in 2-phase water-gas system

Metso 0.8 m$^3$ RCS™ cell
**D**\textsubscript{32} relationships developed for J\textsubscript{g}, viscosity and gas density (altitude)

**Gas Rate, J\textsubscript{g}**

\[ D_{32} = D_0 + a \cdot (100 \cdot J_g)^{0.5} \]

**Viscosity factor** \( f_v \)

\[ f_v = \left( \frac{\mu}{\mu_{20}} \right)^{0.776} \]

\( \mu_{20} \) is viscosity at 20 °C

**Power Input**

- No significant impact on \( D_{32} \) for impeller speed 4 to 10 m/s

**Density factor** \( f_d \)

\[ f_d = \left( \frac{\rho_o}{\rho_g} \right)^{0.132} \]

\( \rho_o \) is density of air at sea level (STP)
Interaction effects: normalized relative to HLB and CCC95 at $J_g = 0.5$ cm/s

- Polyglycol frothers (e.g. DF250, F140, F150)

$$CCC_{95} = CCC_{95} \bigg|_{J_g=0.5} \cdot (0.6736 + 0.6528 \cdot J_g)$$

- Alcohol frothers (e.g. MIBC, Pentanol)

$$CCC_{95} = CCC_{95} \bigg|_{J_g=0.5} \cdot (0.8639 + 0.2723 \cdot J_g)$$

- Adjustment factor for the limiting bubble size ($\pm$)

$$f_l = 0.099 \cdot (7.825 - HLB)$$
Overall $D_{32}$ model

• Overall equation for determining $D_{32}$ from the key flotation variables
• factors $f_v$ (viscosity), $f_d$ (density), $f_l$ (limiting $D_l$) as described earlier

$$D_{32} = f_v \cdot f_d \cdot \varphi [J_g, frother (ppm, CCC95, HLB)]$$

• Note that a model for $D_{32}$ also becomes a model for predicting the bubble surface area flux $S_b$ since

$$S_b = \frac{6J_g}{D_{32}}$$
Overall $D_{32}$ model

- The function $\varphi$ is given by

$$\varphi = 0.267 + f_l + 0.064 \cdot (100 \cdot J_g)^{0.5} + \left[ 2.316 - (f_l + 0.267) + 0.0619 \cdot (100 \cdot J_g)^{0.5} \right] \cdot \exp \left[ -3.09 \cdot \frac{ppm}{CCC95} \right]$$

- The effect of $J_g$ and frother type on the CCC 99 curve (minimum limiting bubble size)
- The effect of $J_g$ on the CCC0 curve (maximum limiting bubble size)
- The exponential-decay effect of frother concentration and type on the CCC0 curve

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![Graph showing the effect of $J_g$ on $D_{32}$ and CCC curves for different frother concentrations.](image-url)
Gas Dispersion Data Collection in Plant
Model validation with plant data
- notion of a “Process Road Map”

<table>
<thead>
<tr>
<th>Company →</th>
<th>NA Palladium</th>
<th>WMC*</th>
<th>Xstrata Ni</th>
<th>Escondida</th>
<th>Impala Platinum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Plant Site</td>
<td>Lac des Iles</td>
<td>Leinster</td>
<td>Raglan</td>
<td>Los Colorados</td>
<td>UG2</td>
</tr>
<tr>
<td>Cell Manufacturer</td>
<td>Outotec TC</td>
<td>Outotec 16U</td>
<td>Outotec 28U</td>
<td>Outotec TC</td>
<td>Bateman TC, Metso TC</td>
</tr>
<tr>
<td>Cell Size (vol), m³</td>
<td>130</td>
<td>16</td>
<td>28</td>
<td>100</td>
<td>50, 30</td>
</tr>
<tr>
<td>Circuit Duty</td>
<td>R/S</td>
<td>R/S</td>
<td>R/S</td>
<td>R</td>
<td>R, C</td>
</tr>
<tr>
<td>Site Location</td>
<td>Canada</td>
<td>Australia</td>
<td>Canada</td>
<td>Chile</td>
<td>South Africa</td>
</tr>
<tr>
<td>Metal/mineral floated</td>
<td>Palladium</td>
<td>Nickel</td>
<td>Nickel</td>
<td>Copper</td>
<td>Platinum</td>
</tr>
</tbody>
</table>

* Now BHP Billiton, R = rougher, S = scavenger, C=cleaner

Model curves are for DowFroth 250 “equivalent” frother concentration
Examples of model prediction

Increasing bubble size requires that the “optimum” frother concentration increases with increasing gas rate ($J_g$)

Higher HLB frothers yield lower limiting bubble size

As a result, these frothers provide opportunity for increasing $S_b$, hence flotation kinetics and fine particle recovery
Coarse versus fine particle flotation: hydrodynamic implications*

<table>
<thead>
<tr>
<th>Factor</th>
<th>Fines</th>
<th>Coarse</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble Size</td>
<td>Small</td>
<td>Larger (and very small)</td>
<td>Probability of Collision</td>
</tr>
<tr>
<td>Bubble Water Film</td>
<td>Thin</td>
<td>Thick</td>
<td>Probability of attachment</td>
</tr>
<tr>
<td>Flotation time</td>
<td>More</td>
<td>Less important</td>
<td>Fines are slow</td>
</tr>
<tr>
<td>Turbulence</td>
<td>Ok</td>
<td>Quiescent Zone</td>
<td>Probability of detachment</td>
</tr>
<tr>
<td>Collector strength</td>
<td>High dose, Selective</td>
<td>More hydrophobic</td>
<td>Reduce induction time</td>
</tr>
<tr>
<td>Frother strength</td>
<td>Weaker</td>
<td>Stronger</td>
<td>Reduce detachment</td>
</tr>
<tr>
<td>Conditioning</td>
<td>Separate</td>
<td>Separate</td>
<td>Not together</td>
</tr>
<tr>
<td>Most Important</td>
<td>Small bubbles, time and kinetics</td>
<td>Chemistry</td>
<td></td>
</tr>
</tbody>
</table>

*Slide courtesy of Frank Cappuccitti, Flottec
Using the Model to Benchmark Plant Performance

Case Study:
*Lac des Iles Pd Concentrator*  
*(Ontario, Canada)*

10% Difference in Pd recovery between plant and pilot testing  
(testing in 2003 and 2005)
Large difference in plant and pilot plant/lab bubble size

Bubble Size Distribution - % minus 1mm bubbles

Lab Tests
Plant and Pilot Tests

Pilot/lab cells
Plant cells
LDI - Comparison of 2003 and 2005 \(D_{32}\) and \(S_b\) with “road map” model

2005 test of blended frother to 6\(^{th}\) scavenge cell

- Note repeatability of 2003 and 2005 data @ 5 ppm MIBC
- Additional frother moves \(D_{32}\) to match 2003 pilot plant values

Data from Hernandez-Aguilar et al (2006)
LDI – Pd recovery improvement resulting from decrease in bubble size with increased frother

<table>
<thead>
<tr>
<th>Particle Size Fraction (microns)</th>
<th>Pd Recovery for $D_{32}$ in Specified Bubble Size Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.2 mm</td>
<td>1.2 mm to 1.6 mm</td>
</tr>
<tr>
<td>&gt; 1.6 mm</td>
<td></td>
</tr>
<tr>
<td>+45</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>7.9</td>
</tr>
<tr>
<td>-45 +10</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td>-10</td>
<td>69.1</td>
</tr>
<tr>
<td></td>
<td>24.6</td>
</tr>
<tr>
<td></td>
<td>29.9</td>
</tr>
</tbody>
</table>

Pd recovery across 6th cell with additional frother to increase %-1mm bubbles (Hernandez-Aguilar et al, 2006)
Maneuvering on the “Process Roadmap” - A benchmarking tool

- Increasing $S_b$ by $J_g$ alone will achieve only a limited increase and loose small bubbles
- Increasing $S_b$ by increasing frother concentration, CCCX, is far more effective than increasing $J_g$

<table>
<thead>
<tr>
<th></th>
<th>Frother</th>
<th>$J_g$ (cm/s)</th>
<th>$D_{32}$</th>
<th>$S_b$ (1/s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CCC75</td>
<td>0.75</td>
<td>1.71</td>
<td>26.3</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>CCC75</td>
<td>1.5</td>
<td>2.08</td>
<td>43.3</td>
<td>- eliminated small bubbles</td>
</tr>
<tr>
<td>C</td>
<td>CCC99</td>
<td>0.75</td>
<td>0.82</td>
<td>54.9</td>
<td>- increased small bubbles</td>
</tr>
</tbody>
</table>
Do you know where your plant is located on the $D_{32}$-$S_b$-$J_g$ road map?

Note: These curves are for DF250 “equivalent” concentrations based on the $D_{32}$ model equations. Curves for other frothers will be somewhat different.
Conclusions

1. A robust empirical bubble size ($D_{32}$) and bubble surface area flux ($S_b$) model is developed incorporating the key operating variables ($J_g$, frother type and concentration, viscosity and gas density).

2. The critical role of frother in a plant’s flotation performance is demonstrated.

3. The model and “process road map” provide a powerful benchmarking tool for flotation plant optimization.
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