HEAP LEACHING AERATION: SCIENCE OR ART?

CONTENTS

- MOTIVATION
- FUNDAMENTALS REVIEW
- CASE STUDY
- STATE OF THE ART
- FINAL REMARKS
WHY AERATION IS NEEDED?

Because the ultimate oxidative agent in the leaching of metallic sulphides is always the OXYGEN:

\[
2\text{Fe}^{3+} + \text{CuS} = \text{Cu}^{2+} + 2\text{Fe}^{2+} + S^0
\]

\[
\frac{1}{2} \text{O}_2 + 2\text{Fe}^{2+} + 2\text{H}^+ \xrightarrow{\text{BACTERIA}} 2\text{Fe}^{3+} + \text{H}_2\text{O}
\]

\[
\frac{1}{2} \text{O}_2 + \text{CuS} + 2\text{H}^+ = \text{Cu}^{2+} + S^0 + \text{H}_2\text{O}
\]

And, also because the cheapest oxygen source is the ambient air.
HARD CLIMBING FOR THE AIR...

WHAT IS THE LIQUID SATURATION AT THIS LEVEL?

IRRIGATION

WETTED SURFACE

LOW MOISTURE ZONE

VADOSE ZONE

SATURATED ZONE

AERATION

LIQUID DRAINAGE
Laminar flow of fluid through porous media is described using Darcy’s law:

\[
\frac{\Delta P}{\Delta L} = \frac{\mu}{k} q
\]

If the resistance \((\mu/k)\) remain constant, the pressure gradient \((\Delta P/\Delta L)\) is proportional to the velocity \(q\) of the fluid. But as the flow becomes turbulent, the pressure drop increases faster than the velocity. In such a case the Forchheimer’s equation applies:

\[
\frac{\Delta P}{\Delta L} = \frac{\mu}{k} q + \beta \rho q^2
\]
If the Darcy´s law applies to any fluid, then

\[ K_L = k \frac{\rho_L g}{\mu_L} \implies k = K_L \frac{\mu_L}{\rho_L g}; \quad K_A = k \frac{\rho_A g}{\mu_A} \implies K_A = \left( K_L \frac{\mu_L}{\rho_L g} \right) \frac{\rho_A g}{\mu_A} \]

Klinkenberg (1941) found large discrepancies between permeability measured to air and that measured with water. He suggested that interaction between the gas molecules and the capillary walls produces a gas slippage which reduces the viscous drag and increases the gas permeability. Then,

\[ K_A = \left( K_L \frac{\mu_L}{\rho_L g} \right) \left( 1 + \frac{b}{P_m} \right) \frac{\rho_A g}{\mu_A} \]
HYDRAULIC AND PNEUMATIC CHARACTERISTIC CURVES

The van Genuchten equation (1980) is often used to model the effect of liquid content on conductivity. In that case:

\[
K_L(\theta) = K_L \left( \frac{\theta - \theta_R}{\theta_S - \theta_R} \right)^{1/2} \left[ 1 - \left( \frac{\theta - \theta_R}{\theta_S - \theta_R} \right)^{1/m} \right]^m \left[ 1 - \left( \frac{1 - \theta - \theta_R}{\theta_S - \theta_R - \theta_{RGAS}} \right)^{1/m} \right]^m \right]^2 \]

Similarly, 

\[
K_A(\theta) = K_A \left( \frac{1 - \theta - \theta_R}{\theta_S - \theta_R - \theta_{RGAS}} \right)^{1/2} \left[ 1 - \left( \frac{1 - \theta - \theta_R}{\theta_S - \theta_R - \theta_{RGAS}} \right)^{1/m} \right]^m \left[ 1 - \left( \frac{\theta - \theta_R}{\theta_S - \theta_R} \right)^{1/m} \right]^m \right]^2 \]
The Richards equation (continuity and momentum coupled equations) under appropriate B.C. drives to the relations $\theta = \theta(t)$ and $q = q(t)$. For the liquid phase:

Unidimensional form of the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( \frac{dh}{dz} + 1 \right) \right]$$

B.C.:

$$\begin{align*}
\theta(z, 0) &= \theta(0) \\
-K \frac{\partial}{\partial z} (h + z) &= q(0, t) \\
\frac{\partial \theta(L, 0)}{\partial z} &= 0; \quad t \geq 0
\end{align*}$$

$\theta = \theta(t)$ and $q = q(t)$
\[
P\left[\theta_S \leq \theta; N\left(\bar{\theta}, \sigma_\theta\right)\right] \leq P_0\left[\theta_S \leq \theta; N\left(\bar{\theta}_L, \sigma_{\theta_L}\right)\right] = \delta
\]
# RELEVANT PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0-18</th>
<th>18-36</th>
<th>36-42</th>
<th>42-48</th>
<th>48-50</th>
<th>50-52</th>
<th>52-54</th>
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</thead>
<tbody>
<tr>
<td>Mass, t</td>
<td>6,387,271</td>
<td>6,387,271</td>
<td>2,129,090</td>
<td>2,129,090</td>
<td>709,697</td>
<td>709,697</td>
<td>709,697</td>
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<tr>
<td>Height, m</td>
<td>18</td>
<td>18</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Area, m²</td>
<td>197,138</td>
<td>197,138</td>
<td>197,138</td>
<td>197,138</td>
<td>197,138</td>
<td>197,138</td>
<td>197,138</td>
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<tr>
<td>Apparent density, t/m³</td>
<td>1.74</td>
<td>1.81</td>
<td>1.83</td>
<td>1.84</td>
<td>1.85</td>
<td>1.85</td>
<td>1.86</td>
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<tr>
<td>Initial porosity, °/1</td>
<td>0.34</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
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<tr>
<td>Current porosity, °/1</td>
<td>0.30</td>
<td>0.27</td>
<td>0.26</td>
<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
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</tr>
<tr>
<td>Sat. Hyd. Conductivity, m/s</td>
<td>1.45E-02</td>
<td>5.75E-03</td>
<td>4.15E-03</td>
<td>3.65E-03</td>
<td>3.38E-03</td>
<td>3.27E-03</td>
<td>3.16E-03</td>
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<tr>
<td>CuT grade%</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td>CuS grade, %</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Ore density, t/m³</td>
<td>2.60</td>
<td>2.60</td>
<td>2.60</td>
<td>2.60</td>
<td>2.60</td>
<td>2.60</td>
<td>2.60</td>
</tr>
<tr>
<td>Initial ore moisture, %</td>
<td>3.50</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Mean irrigation rate, L/h/m²</td>
<td>6.0</td>
<td>5.9</td>
<td>5.9</td>
<td>5.9</td>
<td>5.9</td>
<td>5.9</td>
<td>5.9</td>
</tr>
</tbody>
</table>

**Floor Levels:**
- **THIRD FLOOR**
- **SECOND FLOOR**
- **FIRST FLOOR**
THEORETICAL OXYGEN CONSUMPTION

Without Biomass Production:

\[
\text{Cpy: } \text{CuFeS}_2 + 2 \text{Fe}_2\left(\text{SO}_4\right)_3 + 2 \text{H}_2\text{O} + 3 \text{O}_2 = \text{CuSO}_4 + 5 \text{FeSO}_4 + 2 \text{H}_2\text{SO}_4
\]
\[
\text{Cc: } \text{Cu}_2\text{S} + 2 \text{Fe}_2\left(\text{SO}_4\right)_3 + \text{H}_2\text{O} + 1.5 \text{O}_2 = 2 \text{CuSO}_4 + 4 \text{FeSO}_4 + \text{H}_2\text{SO}_4
\]
\[
\text{Cv: } \text{CuS} + \text{Fe}_2\left(\text{SO}_4\right)_3 + \text{H}_2\text{O} + 1.5 \text{O}_2 = \text{CuSO}_4 + 2 \text{FeSO}_4 + \text{H}_2\text{SO}_4
\]
\[
\text{Py: } 2 \text{FeS}_2 + 2 \text{H}_2\text{O} + 7 \text{O}_2 = 2 \text{FeSO}_4 + 2 \text{H}_2\text{SO}_4
\]

With Biomass Production (g Biomass/g Consumed Fe\textsuperscript{2+} = 0.00836)

\[
\text{Cpy: } \text{CuFeS}_2 + \text{Fe}_2\left(\text{SO}_4\right)_3 + 0.103 \text{CO}_2 + 0.021 \text{NH}_3 + 1.041 \text{H}_2\text{O} + 3.397 \text{O}_2 = 0.021 \text{C}_9\text{H}_7\text{O}_2\text{N} + \text{CuSO}_4 + 3 \text{FeSO}_4 + \text{H}_2\text{SO}_4
\]
\[
\text{Cc: } \text{Cu}_2\text{S} + \text{Fe}_2\left(\text{SO}_4\right)_3 + 0.083 \text{CO}_2 + 0.017 \text{NH}_3 + 0.033 \text{H}_2\text{O} + 1.917 \text{O}_2 = 0.017 \text{C}_9\text{H}_7\text{O}_2\text{N} + 2 \text{CuSO}_4 + 2 \text{FeSO}_4
\]
\[
\text{Cv: } \text{CuS} + 0.041 \text{CO}_2 + 0.008 \text{NH}_3 + 0.017 \text{H}_2\text{O} + 1.959 \text{O}_2 = 0.008 \text{C}_9\text{H}_7\text{O}_2\text{N} + \text{CuSO}_4
\]
\[
\text{Py: } 2 \text{FeS}_2 + 0.041 \text{CO}_2 + 0.008 \text{NH}_3 + 1.017 \text{H}_2\text{O} + 7.459 \text{O}_2 = 0.008 \text{C}_9\text{H}_7\text{O}_2\text{N} + \text{Fe}_2\left(\text{SO}_4\right)_3 + \text{H}_2\text{SO}_4
\]
# Overall Oxygen Demand

## Mineralogical Component

<table>
<thead>
<tr>
<th>Mineralogical Component</th>
<th>Initial Weight Fraction, %</th>
<th>Reacted Weight Fraction, %</th>
<th>Mass, t</th>
<th>kMol of Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu₂S (Chalcosite)</td>
<td>44</td>
<td>40</td>
<td>7,195</td>
<td>45,204</td>
</tr>
<tr>
<td>CuS (Covellite)</td>
<td>44</td>
<td>30</td>
<td>5,396</td>
<td>56,437</td>
</tr>
<tr>
<td>CuFeS₂ (Chalcopyrite)</td>
<td>10</td>
<td>20</td>
<td>818</td>
<td>4,455</td>
</tr>
<tr>
<td>FeS₂ (Pyrite)</td>
<td>2</td>
<td>30</td>
<td>38,324</td>
<td>319,443</td>
</tr>
</tbody>
</table>

## Mechanism

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>O₂ Demand, kMol</th>
<th>Total O₂ Mass, kg</th>
<th>Total O₂ Volume, m³</th>
<th>Air Volume, m³</th>
<th>Air Flow Rate, m³/h</th>
<th>Overall Air Flow Rate, m³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferric Leaching</td>
<td>2,595,078</td>
<td>83,042,494</td>
<td>68,890,003</td>
<td>344,450,014</td>
<td>47,840</td>
<td>96,500</td>
</tr>
<tr>
<td>Fe(III) Regeneration</td>
<td>2,639,529</td>
<td>84,464,932</td>
<td>70,070,023</td>
<td>350,350,113</td>
<td>48,660</td>
<td></td>
</tr>
</tbody>
</table>
LIQUID EFFLUENT VECTORS
HYDRAULIC CONDUCTIVITY EVOLUTION

- **3 L/h/m²**
- **6 L/h/m²**
- **10 L/h/m²**
LIQUID SATURATION PROFILES

3 L/h/m²

6 L/h/m²

10 L/h/m²
MOISTURE PROFILES

3 L/h/m²

6 L/h/m²

10 L/h/m²
HYDRAULIC/PNEUMATIC CONDUCTIVITY V/S SATURATION (0-18 m)
HYDRAULIC/PNEUMATIC CONDUCTIVITY V/S SATURATION (52-54 m)
MAXIMUM AIR FLOWRATE

3 L/h/m²

6 L/h/m²

10 L/h/m²
AERATION EFFECT ON COPPER PRODUCTION

**LESS AIR → HIGHER TEMPERATURE (Within a range)**

**LESS AIR → LESS PRODUCTION**
- Half aeration: -2.79%
- Quarter aeration: -4.24%
CURRENT CHALLENGES

ENVIRONMENTAL AIR

BLOWER

PERFORATED PIPES

Isotropic Ideal aeration

Pressure, Flowrate

Head losses along the lines

Strip Length
CURRENT CHALLENGES

ENVIRONMENTAL AIR

BLOWER

PERFORATED PIPES

Pressure, Flowrate

Strip Height

Height gradient

Liquid saturation effect

ENVIRONMENTAL AIR

Side leakage

BLOWER

PERFORATED PIPES

Pressure, Flowrate
Rio Tinto, Spain (since 1500): Natural convection

Codelco Low Grade Sulphide Leach (1976): Natural convection, finger damp geometry

Girilambone, Australia (1998): Forced aeration, blower and perforated pipes

BHP Billiton (2004): Air distribution system composed by tubings provided with holes to liberate the air from those tubings and a protective element surrounding outside the holed tubings.

Netafim (2013): Aeration system composed by aeration pipes connected to a spaced emitter net and the aeration pipes extend through the bed toward the basal layer.
THE STATE OF THE ART...

Main Features:

- Use of gas emitters replace holes
- Tridimensional arrangement when possible

Advantages:

- Air-emission points may increase from 0.5/m² to 10/m²
- Balanced pneumatic nets are possible to implement
- Tridimensional arrangement increases overall aeration
- Strong technical support process-oriented.
THE STATE OF THE ART...
MODEL-BASED LEACH AUTOMATIC CONTROL SYSTEM

Main Application + DB Server
CONTROL MODEL-BASED
Gateway
Plant Network

Irrigation Flow + Rate
Main Matrix Pressure + Flow
Repository Level

Sub Matrix Control Pressure + Flow
Flushing Control

BHP Billiton CLUSTER PROJECT, Minera Escondida, 2011 - 2012.
MODEL-BASED LEACH AUTOMATIC CONTROL SYSTEM
MODEL-BASED LEACH AUTOMATIC CONTROL SYSTEM

8-month plant run (2012): +2 higher copper recovery points

We do not irrigate just to promote uniform application, but to MAXIMISE COPPER RECOVERY

BHP Billiton CLUSTER PROJECT, Minera Escondida, 2011 - 2012.
MODEL-BASED
LEACH AUTOMATIC CONTROL SYSTEM
A natural step is to include the aeration as part of the automatic control for bioleach applications.
FINAL REMARKS

- Forced aeration practice in sulphide heap leaching has not progressed too much since its first application at Girilambone in 1998.

- Excess in aeration not only does not guarantee enough oxygen availability for the sulphides but also remove latent heat from the strips making kinetics slower.

- Uneven aeration may affect 2% to 4% copper production.

- Introduction of the newest technology ideally supported by robust monitoring and automatic control system should produce significant improvement in the aeration practice.