Dissolved air flotation (DAF) to improve the reuse of water in mining operations

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ABSTRACT

The northern Chile is a zone with large needs of water sources, at present, enforces are dedicated to the use of seawater in the mining operation, which is expensive since the mining operations are located at significant height and large distance from the coastline. Therefore, an economical alternative could be to reduce the water consumption by means of reuse, which requires the removal of impurities (particles or chemicals) of the water before reuse. This may be accomplished by Dissolved Air Flotation (DAF), which is a clarification process used for removing particles in water treatment. The use of DAF for water treatment and reuse (or recycling) is rapidly increasing in the mining sector.

A DAF reactor for particle removal was modelled by using computational fluid dynamics (CFD). In order to validate the model, a pilot DAF reactor is under construction, in which experiments will be carried out and the results compared with the CFD simulations. The validated model could be then used in optimization and operation of similar reactors working at other scales, conditions, or configurations; e.g., a multi-step DAF, for saving energy. Basically, the process consists of a coagulation-flocculation pre-processing followed by a cleaning process using DAF. Water containing air dissolved is introduced at high-pressure and air micro-bubbles are formed when the overpressure is released. Micro-bubbles collide with the particles forming bubble-particle bounds, which travel to the surface of the cell forming a particle-laden foam that is removed from the system. The CFD model uses an Eulerian description of the phases: the continuous water phase and the two discrete phases, namely the bubbles without particles and the bubbles bounded to particles. The system is solved for the velocity-fields, the pressure, and the air volume fraction; from these parameters the particle removal efficiency is then obtained.

Keywords: Dissolved Air Flotation (DAF); Computational Fluid Dynamics (CFD); Water Treatment
INTRODUCTION

Dissolved air flotation (DAF) is used in water and wastewater treatment and basically consists of a coagulation-flocculation pre-treatment followed by a cleaning process, in which water containing air dissolved is introduced at high-pressure and air microbubbles are formed when the overpressure is released, the bubbles then collide with the particles forming bubble-particle bounds, which travel to the surface of the cell forming a particle-laden foam that is removed from the system. The process is applied to the removal of particulate material; e.g., low-density flocs (Bondelin, et al., 2010). DAF is an alternative to sedimentation in the removal of suspended solid particles, metallic ions, microorganism and macromolecules (Kurama, et al., 2010).

The northern Chile is a zone with large needs of water sources, at present, enforces are dedicated to the use of seawater in the mining operation, which is expensive since the mining operations are located at significant height and large distance from the coastline. In the desalination of seawater, DAF is used in some situations when high level of algae are found in the seawater; e.g., during the “red tides” events (red algae bloom) (Petry, et al., 2007; Peleka and Matis, 2008). The minerals industry is being driven to save freshwater and minimize mine water discharge (Liu, et al., 2013). Therefore, an economical alternative could be to reduce the water consumption by means of reuse, which requires the removal of impurities (particles or chemicals) of the water before reuse. The use of DAF for water treatment and reuse (or recycling) is rapidly increasing in the mining sector, aqueous solutions produced during hydrometallurgical operations require suitable treatment in order to increase low concentrations of dissolved constituents and to make economically feasible their subsequent recovery, hence constituting a situation similar to the wastewater treatment (Zouboulis & Matis, 1997).

As shown in Table 1, DAF is applied in several processes in the mining industry for water cleaning and posterior reuse. Zouboulis and Matis (1997) studied in laboratory-scale experiments the removal of soluble ionic species from diluted aqueous solutions using a combination of sorption and flotation. In the first step the ionic species are sorbed by fine or ultrafine particle-size sorbents, which are removed by DAF. From the foam containing the ionic species, the ionic species may be recovered. Therefore, if natural sorbents are used the load to the environmental were negligible. In a similar process, adsorbing colloid flotation, metal ions are removed by adsorption on a precipitate, which acts as a carrier. This process is used in Chile for effective separation of Molybdenum from Cu–Mo concentrate filtrates. In the process, suspended solids (SS) are firstly separated by a “rougher” stage and Mo ions adsorbed on iron hydroxide precipitate are removed in a “cleaner” stage, which occurs at pH about 5 (Rubio et al. 2002). Other application of DAF is ore flotation assisted with microbubbles for the recovery of fine mineral particles (<13 µm) where microbubble addition shows improvements in particle recovery (2%) and in flotation kinetics (Rodrigues & Rubio, 2007).

Dissolved air flotation may also be applied for cleaning of aqueous effluents generated in mining activities; e.g. Acid mine drainage (AMD). Cadorin et al. (2007) experimentally studied the removal of sulfate and Fe and Mn ions from AMD in coal and metal sulfides mines. They are precipitated at pH 12 using lime and aluminum salts; the sulfate precipitates as ettringite and the metals as hydroxides. They showed that DAF may effectively remove the solids formed.

Al-Zoubi and Al-Thyabat (2012) show the combined use of DAF and nanofiltration (NF) in cleaning of wastewaters from a mine in Jordan, where about 10 000 m$^3$ of wastewater are discarded daily containing about 1 000 ton solids, of which 200 tons are of P$_2$O$_5$. They use column flotation and DAF, however, the recovery of column flotation was low, only 20%. A better recovery was obtained
when using DAF (83%). In a posterior paper (Al-Zoubi & Al-Thyabat, 2012), the solid free wastewater was purified using DAF and NF. SS is almost complete removed from the wastewater, while the removal of chloride and sulfate is about 50%. The effluent treated by DAF was then filtrated by NF. The removal of chloride was slightly increased, while that sulfate was totally removed.

Table 1 Examples of DAF applications in the mining industries and the wastewater treatment

<table>
<thead>
<tr>
<th>Compound Recover (Removed)</th>
<th>System Type</th>
<th>Recovery Efficiency</th>
<th>Water Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae</td>
<td>Continuous</td>
<td>27-53%</td>
<td>Lake freshwater</td>
<td>Chu, et al. (2011)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Continuous</td>
<td>70-80%</td>
<td>Municipal wastewater</td>
<td>Pouet &amp; Grasmick (1995)</td>
</tr>
<tr>
<td>Ammonium ions</td>
<td>Batch and Continuous</td>
<td>88-99.21%</td>
<td>Surface water</td>
<td>Kurama, et al. (2010)</td>
</tr>
<tr>
<td>Cadmium cations</td>
<td>Batch</td>
<td>&gt;95%</td>
<td>-</td>
<td>Zouboulis, et al. (1997)</td>
</tr>
<tr>
<td>Chromium</td>
<td>-</td>
<td>98 %</td>
<td>Plating wastewater</td>
<td>Esmaeili, et al. (2014)</td>
</tr>
<tr>
<td>Copper, Zinc and Chromium (VI)</td>
<td>Batch</td>
<td>&gt;95%</td>
<td>-</td>
<td>Zamboulis, et al., 2004</td>
</tr>
<tr>
<td>Heavy metals Fe(III) and Mn(II)</td>
<td>Batch</td>
<td>94 %</td>
<td>Acid mine drainage</td>
<td>Menezes, et al., (2011)</td>
</tr>
<tr>
<td>Iron containing minerals (Fe-Mn)</td>
<td>Batch</td>
<td>76 %</td>
<td>Albite, Fe-Min and slimes</td>
<td>Karagüzel, (2010)</td>
</tr>
<tr>
<td>Isopropyl xanthate ions</td>
<td>Batch</td>
<td>&gt;90%</td>
<td>Synthetic solutions</td>
<td>Oliveira, &amp; Rubio (2009)</td>
</tr>
<tr>
<td>Mercury</td>
<td>Laboratory unit</td>
<td>&gt;98%</td>
<td>Process water</td>
<td>Tassel, et al. (1997)</td>
</tr>
<tr>
<td>Oil</td>
<td>Batch</td>
<td>88-98%</td>
<td>Synthetic solution</td>
<td>Oliveira, et al. (1999)</td>
</tr>
<tr>
<td>Oils, dyes and metal ions</td>
<td>Batch and Continuous</td>
<td>&gt;75%</td>
<td>Synthetic and industrial water</td>
<td>Feris, et al. (2004)</td>
</tr>
<tr>
<td>Oil-water emulsion</td>
<td>Batch</td>
<td>71 %</td>
<td>Synthetic emulsions</td>
<td>Bensadok, et al. (2007)</td>
</tr>
<tr>
<td>Oil-water emulsion</td>
<td>Bench Scale</td>
<td>&gt;99,3%</td>
<td>Synthetic wastewater</td>
<td>Al-Shamrani, et al. (2002)</td>
</tr>
<tr>
<td>Phosphate</td>
<td>Bench Scale</td>
<td>86.4% with 20.6% P2O5</td>
<td>Wastewater</td>
<td>Al-Thyabat &amp; Al-Zoubi, (2012)</td>
</tr>
<tr>
<td>Radioactive substance 226Ra(II)</td>
<td>-</td>
<td>&gt;91.4%</td>
<td>Wastewater</td>
<td>Stoica, et al. (1995)</td>
</tr>
<tr>
<td>Scenedesmus quadricauda (algae)</td>
<td>Batch</td>
<td>80-90%</td>
<td>Surface water</td>
<td>Phoochinda &amp; White (2003)</td>
</tr>
</tbody>
</table>
The most of the development in DAF has been carried out by experimental work, but several authors have also used modelling; e.g., Behin and Bahrami (2012) used computational fluid dynamics (CFD) for modelling of the flow pattern in the flotation tank. Its results were compared with experiments through of the residence time distribution curves, finding a good agreement. Bondelind, et al. (2010) using single- and two-phase models of DAF in 2D and 3D simulations finding that a 2D model cannot resolve successfully the flow in the contact zone, but major flow characteristics may be adequately described.

The aim of the paper is the study of DAF, applied to the separation of particulate material in order to clean wastewater for posterior reuse. CFD will be used in the modelling of the process and the results of the simulations will be compared with observations in a tank a lab-scale. The strategy is to validate the model in lab scale, once that the model is adequately validated, this could be used for modelling of flotation system in industrial scale. Therefore, the experimental setup is sufficiently flexible for accommodate different design.

METHODOLOGY

As described above, the methodology is based in the development of a CFD model to take into account the movement of the water and bubbles in the reactor and the interaction of the bubbles with the impurities (particles) to be removed from the wastewater. Several approaches exist with different complexity degrees; the most complex modelling is used when we are interested in describe how the location of specific bubbles changes with time. In that case, the Navier-Stoke equations are applied for the liquid and bubbles in detail. When the detailed location of given bubbles is not important, as in our case, the model calculates the average volume fraction occupied by the gas phases instead of determining the location of each phase in detail (Buscaglia et al., 2002).

The model

We use Multiphase Eulerian model with three phases: the water phase, the clean air-bubbles phase, and the loaded air-bubbles phase. The particulate material will be considered as a scalar and this does not interact with the water, but is the source of loaded air bubbles, and the sink of the clean air-bubbles. The partial differential equations are solved for the velocity-fields, the pressure, and the volume fraction using the CFD code FLUENT 15. The three phases are treated as interpenetrating continua and are described by phasic volume fractions. The inlet boundary conditions are the inlet velocities for water and air. The outlet boundary conditions are the pressure at the outlet zones. The model considers two water in-flows; one for the water to be treated and another for the water containing the dissolved air, from which the air will be released. This inlet is also used for the air bubbles, which are assumed to be 0.05 mm in diameter. The implicit scheme is used to solve the model equations.

In the Viscous Model, we consider turbulence: realizable $k$-$\varepsilon$ model per phase, with near-wall scalable wall functions and options such as differential viscosity model, swirl dominated flow, and curvature correction are used. The system is formed by water with volume fractions $\alpha_w$, clean air-bubbles with volume fraction $\alpha_o$, and loaded air-bubbles with volume fraction $\alpha_L$. In addition to the bubbles exist small particles (impurities) whose concentration at the inlet is $C_0 = 1\text{ kg/m}^3$, and decreases along its trajectory through the seawater, as impurities are colliding with clean air bubbles. We defined the scalar $\varphi = C/C_0$, which is the relative concentration at each point of the fluid.
Impurities particles are small and in low concentration, therefore, the hydrodynamic of the system is not altered. The loaded air-bubbles consist of attaching a clean air-bubble with a particle.

**Mass Conservation Equation**

\[
\frac{\partial (\alpha_w \rho_w)}{\partial t} + \nabla \cdot (\alpha_w \rho_w \mathbf{v}_w) = 0 \tag{1}
\]

\[
\frac{\partial (\alpha_a \rho_a)}{\partial t} + \nabla \cdot (\alpha_a \rho_a \mathbf{v}_a) = -K \left( \alpha_w \alpha_a \phi \right) \frac{(\rho_a/m_p)}{m_b} \tag{2}
\]

\[
\frac{\partial (\alpha_l \rho_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{v}_l) = +K \left( \alpha_w \alpha_l \phi \right) \frac{(\rho_a/m_p)}{m_b} \tag{3}
\]

**Scalar Equation**

\[
\frac{\partial (\alpha_w \rho_w \phi)}{\partial t} + \nabla \cdot (\alpha_w \rho_w \phi \mathbf{v}_w) = -K \left( \alpha_w \alpha_a \phi \right) \frac{\rho_w}{V_b} \tag{4}
\]

In that equation, the \( K \) constant is

\[
K = PA_{col}v_{rel} \tag{5}
\]

\( P \) is the probability of adherence if the particle collides with the bubble, \( A_{col} \) cross-section area for impact, \( v_{rel} \) relative velocity between bubble and particle. The mechanisms that cause the collisions are: flotation movement of the bubbles, gravitational movement of the particles, and turbulence. Each of these mechanisms has its own value of \( P \) and \( v_{rel} \).

**The equipment**

The DAF cell was designed to allow changes in its dimensions; e.g., the width of the contact zone and the type of perforated plate at the separation zone bottom may be varied. The height of the contact zone may also be varied. Figure 1 shows a schematic picture of the DAF cell. The depth of the cell is 0.05 m; other dimensions are shown in the figure.
The wastewater enters the flotation cell at the top and descends along the inlet zone. At the bottom the wastewater enters the contact zone through a slot and is mixed with the air micro-bubbles. In the contact zone, the mixture is brought upward. The mixture flows horizontally over the shaft wall and enters the separation zone. Cleared water is removed at the bottom via a perforated plate. The tank arrangement is capable of operating at surface loadings up to 5.7 m/h.

RESULTS AND DISCUSSION

Simulations were performed considering a flow of seawater of 1.2 L/min, with a concentration of impurities of \( C_0 = 1 \) kg/m\(^3\). The performance of the reactor is determined by measuring the impurity concentration at the reactor outlet, which is expressed by the scalar \( \varphi \). In a quasi-stationary regime the gas in the compressor has a composition of nitrogen higher than that found in the air, since the oxygen is more soluble in water than the nitrogen. For this reason, at the initial stage, the oxygen dissolves in water to a higher ratio than its composition ratio. Therefore, the dissolution of nitrogen in seawater is used as the coefficient of gas dissolution in seawater, 16.6 mg/(kg atm), for a temperature of 20°C. Impurities are particles 0.02 mm in diameter with a density of 2000 kg/m\(^3\).

In these simulations, the pressure used in the saturator is 400 KPa and bubble injection rate is \( 1 \times 10^{-7} \) kg/s, which corresponds to an injection ratio bubbles/impurities of 1.04. The energy consumed in the injection is 8.25 KWh/m\(^3\) water.

Figure 2 shows the volume fraction of clean bubbles, bubbles loaded with impurities, and the impurity scalar concentration in the flotation cell. Logarithmic scales are used in Figures 2a and 2b. Figure 2c uses linear scale.

![Figure 2](image-url)

**Figure 2** Volume fractions and concentration of impurities: (a) volume fraction of clean bubbles, (b) bubbles loaded, and (c) impurity scalar concentration in the vertical plane in the middle of the flotation cell
To achieve this bubble injection rate, 7.3% of the treated water should be re-injected to the reactor. This bubble injection rate cleans up 72.8% of impurities. At the clean water outlet, the flow rate of clean bubbles is negligible, but the flow of loaded bubbles is 24.9% of the injected bubbles, because its mass is 105 times that of a clean bubble. Results for other bubble injection rates, is showed in Table 2.

Table 2  Some quantities in terms of bubble injection rates

<table>
<thead>
<tr>
<th>Bubble injection rate (kg/s)</th>
<th>Cleaning reached</th>
<th>Reinjected water</th>
<th>Energy cost (W h/m³)</th>
<th>Loaded bubbles in water outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 × 10⁻⁷</td>
<td>72.8 %</td>
<td>7.3 %</td>
<td>8.25</td>
<td>24.9 %</td>
</tr>
<tr>
<td>1.5 × 10⁻⁷</td>
<td>94.9 %</td>
<td>11.0 %</td>
<td>12.4</td>
<td>26.5 %</td>
</tr>
<tr>
<td>2.0 × 10⁻⁷</td>
<td>97.2 %</td>
<td>14.6 %</td>
<td>16.5</td>
<td>31.8 %</td>
</tr>
</tbody>
</table>

Figure 3 shows the seawater velocity in magnitude (left) and as vector (right). It may be observed that the water distribution is very uneven distributed. In general, it is thought that this water distribution is not favorable to obtain a good cleaning of the water with impurity particles. It is possible to improve this, reducing the inflow of water, but also modifying the geometry of the reactor keeping a high water flowrate.

As shown in Table 2, to improve the cleaning reached, the bubble injection and the recirculated water have to be significatively increased. Therefore, a possible alternative for improving the performance and to do the process energy efficient is to work in two stages. Higher percentages of cleaning may then be obtained working in two stages than in a single stage.

CONCLUSION

The reuse of water in mining activities is an important issue to reduce the water demand, which is critical in the northern Chile. Dissolved Air Flotation, DAF, is a convenient method to water
cleaning, and its use has been strongly increased in the last decades as was shown in Table 1. There are a lot of applications in which DAF is used for cleaning water in the mining sector.

A DAF reactor for particle removal was modelled by using computational fluid dynamics (CFD). The model was applied to a case where very small particles are removed from the water using DAF. It was found that in order to improve the cleanliness degree reached in the process, the air bubble injection and the recirculated water have to be significantly increased. Therefore, a possible alternative for improving the performance and to do the process more energy efficient is to work in two stages. Higher cleanliness percentages may be then obtained working in two stages than working in one single stage.

Once that the CFD model were validated using our experimental DAF cell at pilot scale will be used to simulate a DAF in two stages. The pilot reactor is under construction since part of the equipment was not opportunely delivered.

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NOMENCLATURE

$A_{col}$ Cross-section area for impact.

$G_0$ Concentration of impurities at the inlet.

$K$ Frequency of collisions between bubbles and particles.

$P$ Probability of union between bubbles and particles.

$t$ Time.

$m$ Mass.

$V$ Volume.

$\nu_{rel}$ Relative velocity.

$v$ Velocity vector

$a$ Volume fraction

$\phi$ Relative concentration of impurities.

$\rho$ Density.

Sub index

$a$ Clean bubbles.

$b$ Bubbles.

$L$ Load bubbles

$p$ Particles.

$w$ Seawater.
REFERENCES


