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Potential for solar thermal energy in the heap bioleaching of chalcopyrite in Chilean copper mining

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ABSTRACT

Bioleaching of chalcopyrite is only possible in the presence of thermophilic micro-organisms. While suitable conditions can be generated within a heap naturally through the exothermic reaction, the effectiveness of the process can be improved with an additional heat source. Chilean copper mines are primarily located in the Atacama Desert, which has the highest solar irradiation levels on the planet. Solar thermal energy can be incorporated into the heap bioleaching process to raise the temperature in the heap and increase the copper extraction rates.

A heap bioleaching system, including ponds and a solar thermal collector field, has been simulated over one year using HeapSim and TRNSYS. The maximum copper extraction achievable for the system without a solar thermal field is 67% with a 7 kg/h m^2 solution flow rate. A maximum extraction of 85% over one year could be achieved with a collector field to heap area ratio of 1:1 and a 10 kg/h m^2 solution flow rate.

An economic analysis compares the capital cost of the solar thermal system to the revenue from additional copper extraction. The net present value and internal rate of return were positive for collector areas in the range of 10,000–150,000 m^2 for a heap area of 200,000 m^2. The peak NPV occurs at 50,000 m^2 at which point an extractionof 76% is achieved over one year of leaching.

1. Introduction

Chile as a country is very much connected to copper mining, producing over 30% of the world supply in 2013, making it the leading producing country in the world, and consequently copper mining is a major part of the economy. While demand and production continues to grow, the grade of copper ore and the number of new discoveries continues to decline (Bukacheva et al., 2014).

Heap bioleaching is a passive technique of extracting copper from low grade ore. After crushing, ore is stacked on impermeable sheeting, and lixiviated with an acidic solution and aerated from the base. As the solution flows through the heap, it reacts with the surface of the ore in the presence of oxygen, and the solution becomes enriched with copper. This solution is collected in a pond and is pumped to the solvent extraction plant. Heap bioleaching occurs in the presence of temperature sensitive bacteria in order to support the process for sulphidic phases in the ore (Watling, 2006).

Heap leaching was traditionally only used for acid leaching of oxide based ores; bio-leaching occurred naturally on the sulphide phases present in the ores and was eventually actively pursued for secondary copper sulphides (chalcocite, covellite) from the 1990s, the main departure being the introduction of active aeration (Pradhan et al., 2008). Some adaptations are being investigated to improve its suitability also for common primary sulphide ores such as chalcopyrite.

The heap bioleaching of chalcopyrite, $CuFeS_2$ can be described by multistage reactions in Eq. (1) (Pradhan et al., 2008).

$$\begin{aligned} &CuFeS_2 + 4H^+ + O_2 \rightarrow Cu^{+2} + Fe^{+2} + 2S + 2H_2O \\ &4Fe^{+2} + 4H^+ + O_2 \xrightarrow{\text{Iron oxidising microbes}} 4Fe^{+3} + 2H_2O \\ &2S + 3O_2 + 2H_2O \xrightarrow{\text{Sulfur oxidising microbes}} 2SO_4^- + 4H^+ \\ &CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{+2} + 5Fe^{+2} + 2S \end{aligned} \tag{1}$$

The reaction process is exothermic. As evident in these equations, micro-organisms are required to catalyse the reaction. The survival and activity of these micro-organisms depend on the temperature of the ore and lixiviant (Pradhan et al., 2008; Brandl, 2001; Franzmann et al., 2005).

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The micro-organisms that exist in the heap occur naturally in acidic mine water and grow from these initial populations, although in some bio-leaching operations a start-up inoculum is grown in dedicated tanks to boost the natural population. The bacteria are categorised based on what substrate they oxidise, either ferrous ions or sulphur and by the temperature ranges in which they live (cryophile, mesophile, moderately thermophile and extremophile). The moderate thermophiles relevant for these reactions are active in the temperature range of 45–60 °C (Dew et al., 2011).

The local temperature within the heap is influenced by the reactions occurring, the operating conditions of the heap and the local climate. A heat model for the heap was developed by Dixon (2000) and predicts the temperature profile throughout the heap. This considers heat transport by the flow of solution and (humid) air through the heap, heat released by reaction and heat effects on the heap surface (transpiration and solar effects). Experimental work conducted by Bouffard and Dixon (2001) shows that the solution is present in the heap as flow through discrete channels and as stagnant liquid held in pores in the ore. The heat generated by the reactions was evaluated by Petersen and Dixon (2002), who determined that the heat of reaction for some of the relevant sulphide oxidation reactions is approximately 100 kJ/mol electron (i.e. 400 kJ/mol of oxygen consumed). These factors are incorporated into the heap modelling. An important outcome of Dixon's heat model is that there exists an optimal ratio between irrigation and aeration rates at which heat is distributed within the heap optimally – high irrigation rates tend to 'wash' heat released to the bottom of the heap, leaving upper regions to operate sub-optimally.

The mineral composition of the ore and the consequent ratio of ferric Fe^{3+} to ferrous, Fe^{2+} ions during the reaction also affects the rate of extraction (Dold, 2014). A higher quantity of Pyrite (FeS_2) in the ore generally improves this ratio as it can act as a 'fuel' to generate additional heat within the heap (Koleini et al., 2011), which is useful especially in the initial heat-up phase of operation.

The results of experimental work confirm the necessity of thermophiles for chalcopyrite bioleaching. Two studies have tested the commercial process Geocoat™ which involves coating an inert rock with concentrated chalcopyrite and then leaching in tanks or heaps (Johansson et al., 1999; Petersen and Dixon, 2002). Both studies achieved extraction rates of above 90% in the presence of thermophiles in laboratory-scale experiments with controlled temperature.

Dew et al. (2011) report on a larger scale simulation that emulated a real heap, in which temperature profiles were allowed to be established through self-heating by the oxidation reaction. The primary conclusion from this work was that heap bioleaching requires careful control of heap conditions. A key factor is to reach temperatures at which thermophile micro-organisms can thrive as quickly as possible. All three studies showed an increase of copper extraction with increasing heap inlet temperature. This is also confirmed by other modelling work on temperature distribution in a chalcocite (Petersen and Dixon, 2007b) and sphalerite (ZnS) heap scenario (Petersen and Dixon, 2007c).

In this work it is proposed that solar thermal energy be incorporated in heap operation to raise the temperature of the lixiviant entering the heap, thereby more rapidly creating conditions for thermophile organisms to thrive and consequently improving the extraction rate from chalcopyrite.

The solar irradiation in the Atacama Desert in Chile is the highest on the planet, which allows for excellent performance of solar thermal systems in this region. Therefore it is plausible that heat for pre-heating heap feed solutions could be generated from solar energy.

Solar thermal energy refers to the conversion of the sun's irradiation into heat via a heat transfer fluid in a collector field. The solar collectors can be concentrating or non-concentrating and may or may not track the sun. These are selected based on the required temperature and load profile of the system.

For low temperature applications up to 100 °C, non-tracking, non-concentrating flat plate collectors as shown in Fig. 1 are generally the most appropriate. Fluid within the collector field is pumped through the collectors and the heat is extracted via a heat exchanger.

In the field of solar thermal energy, there is a concentrated effort to collaborate with industry to meet their process heat demand. The International Energy Agency (IEA) Task 49 "Solar Process Heat for Production and Advanced Applications" has this specific focus, with research groups specialising in technological optimisation, system optimisation and improved integration (SHC, 2014).

Some copper mines in Chile have already installed solar thermal systems to provide some of the heat demand for the electrowinning operations. An overview of these systems is provided in Table 1. A theoretical optimisation study on solar thermal systems to support the electrowinning process has been published by Cuevas et al. (2015).

The main challenges for solar thermal systems in these mining applications come from the harsh local conditions. The Atacama Desert is subject to seismic events, high winds, high dust levels, extreme temperature differences, precipitation events, and water restrictions. These factors need to be overcome for implementation (Nelson, 2014).

Literature has primarily focussed on the mechanisms of leaching on the one hand and design of solar collection systems on the other, but there appear no studies evaluating a combined system as a whole. Within this paper, the results of a complete system model of the heap and solar thermal system are presented. This is used as the basis for a technical and economic analysis.

2. Method

To perform this investigation, a system model was created consisting of the heap, two ponds and the solar thermal collector field as shown in Fig. 2. This model was used to simulate the performance of the heap with various parameters to determine the technical and economic optimum collector area.

2.1. Heap model

The heap was modelled using the HeapSim Heap Bioleach Simulation tool developed by Petersen and Dixon (2007a) and is a comprehensive mathematical model of the sub-processes that occur within a heap during bioleaching. The model simulates the reactions occurring in the heap at each different scale of the process including the grain surface, ore particles, particle clusters and the heap. HeapSim includes a heat model that simulates the temperature profile through the heap based on Dixon's original heat model (Dixon, 2000), including the output temperature that flows to the PLS pond. HeapSim calculates the copper output from the heap.

2.2. Solar model

The solar thermal system was modelled using the TRNSYS Simulation Studio to model the heat gain from the solar collector field. TRNSYS is a transient system simulation program with a modular structure. Each component of the system is represented by a module and these are connected as required (Solar Energy Lab, 2013).