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Effects of intermittent liquid addition on heap hydrodynamics

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ABSTRACT

Heap leaching is a well-known mineral processing technique, whereby crushed low grade ore is used for valuable metal extraction. The technique is typically used to extract precious and base metals, however, the metal extraction efficiency is relatively low. Even though reaction kinetics are extensively studied in heap leaching, the detailed hydrodynamic studies are still required to understand the underlying flow aspects. Heap hydrodynamics plays an important role in the transport of both leaching reagents and dissolved metal species and thus uniform liquid distribution through the ore mass is required. However, liquid channelling within the heaps has been identified as one of the main contributing factors for non-uniform liquid distribution. Since liquid channelling is supposed to be an inherent property in heap leaching systems, this work was primarily designed to explore the suitable techniques to improve liquid distribution and minimise liquid channelling in heaps. Intermittent liquid addition is employed and its effect on liquid channelling is studied, which has not been reported in the literature despite the application of it in industrial heaps. Both narrowly sized ore (16–20 cm) and realistic ore mixtures (2.36–25 cm) were studied in a pseudo 2-D Perspex column and the effect of rest period in intermittent leaching on liquid channelling was studied using out-flow liquid distribution measurements. The experimental results showed improved out-flow liquid distribution profiles and less channelling flow features in intermittent liquid addition conditions. The liquid out-flow profiles in both the packed bed systems were improved by resulting more flow paths through the particles and reduced features of liquid channelling. The narrowly sized fraction formed a near-Gaussian liquid distribution, which is the expected continuous probability based theoretical flow profile with drip emitter based liquid addition in heaps.

1. Introduction

With the declining ore grades and increasing energy costs for ore milling operations, heap leaching has been an economical hydrometallurgical technique to treat low grade metallic ores. Heap leaching systems are used to extract precious metals, such as, gold and silver and base metals, such as, copper (Ghorbani et al., 2016; Petersen, 2016). However, it typically results in lower metal recovery efficiencies compared to other conventional metal extraction methods (e.g. froth flotation followed by smelting, pyrometallurgical techniques) (John, 2011; Ilankoon, 2012). Since the application of conventional techniques has become less effective economically due to declining ore grades, increased ore complexity, and higher costs for energy and labour, industrial heap leaching is considered as an economically viable alternative in minerals processing industry. Thus, the metal extraction efficiencies in heap leaching need to be improved.

A heap leaching system is simply a massive stockpile of ore constructed mainly by conveyor belt stacking and dump trucks (Petersen, 2016). The irrigation of the heap commences from the top surface and the solution percolates down the stockpile with the dissolved metal species. Heaps use crushed ore below 25 mm with a heap height of 6–10 m with an estimated area in the order of 0.5 km^2 (Ghorbani et al., 2016; Petersen, 2016). Percolation of the liquid within the heap is governed by the Bond number (i.e. ratio between gravity to capillary forces, $Bo = \rho g L^2/\gamma$, where L is the length scale of the particles, γ is the surface tension, ρ is the density of the liquid and g is acceleration due to gravity) and the liquid flow portrays a transition regime between capillary dominated to gravity dominated (Ilankoon and Neethling, 2012).

Liquid distribution is discerned to be the key factor in heap leaching as the dissolved metal species are transported via the active liquid flow paths (Bartlett, 1997; Bouffard and Dixon, 2001; Ilankoon and Neethling, 2016). The flow paths are expected to be widely and uniformly distributed to enable high metal extraction efficiencies in heap leaching. Many studies have been carried out in order to understand the underlying flow mechanisms in heaps using laboratory columns (e.g. Ilankoon and Neethling, 2013, 2016; Fagan et al., 2014) and pilot and industrial scale heaps (e.g. Murr, 1979; Cathles and Murr, 1980; Murr

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et al., 1982). Additionally, heap flow simulation/modelling studies were performed by several investigators (e.g. Dixon, 1992; Petersen and Dixon, 2007; McBride et al., 2014, 2016, 2017). By solving the Richards's equation, Dixon (2003) presented a narrow Gaussian liquid out-flow profile for an isotropic packed bed irrigated from a central point source. Leahy et al. (2006) also assumed a uniform liquid distribution within the heap for the computational modelling of heap hydrodynamics. However, Ilankoon and Neethling (2016) presented strong channelling flow features or preferential flow paths in 2-D packed beds irrigated continuously by a central drip emitter with realistic size distributions. Two main liquid flow types were distinguished, namely, a rapidly formed inter-particle flow and a much slower intra-particle flow. The formed main inter-particle flow paths in heap systems thrive to retain the liquid flow history owing to the hysteresis effect with occasional variations (Ilankoon and Neethling, 2012; Fagan et al., 2014). McBride et al. (2017) modelled the heap liquid flow based on the experimental results obtained by Ilankoon and Neethling (2016). The modelling of continuous liquid addition conditions accounted the liquid flow channelling features and corroborated the inapplicability of the random walk hypothesis (i.e. probability based liquid distribution) to determine the liquid distribution within an unsaturated gravity dominated packed bed, which was initially proposed by several researchers (e.g. Scott, 1935; Tour and Lerman, 1939; Porter, 1968).

Improving liquid distribution and minimising liquid channelling has thus been significant in heap hydrodynamics research studies. In trickle bed reactors (TBRs), which are analogous systems to heap leaching, an up-flow liquid addition is practiced to obtain a uniform liquid distribution by avoiding preferential flow (Iliuta et al., 1997). However, this is not applicable in heaps due to completely different liquid addition strategies and heaps are also not enclosed packed beds compared to TBRs. Afewu (2009) proposed a denser drip emitter spacing to promote uniform wetting in heap leaching systems, but liquid channelling has not been discussed. Particle heterogeneities, variable bulk densities and particle segregation during heap construction are identified as the main contributing factors for liquid channelling (Yusuf, 1984; Bartlett, 1992; Wu et al., 2007). Although realistic particle size distributions promote the lateral liquid spread, it would not result in an improved liquid distribution in terms of active flow paths (Ilankoon and Neethling, 2016; McBride et al., 2017).

Intermittent liquid addition is postulated as one of the techniques to improve metal extraction efficiencies in heap leaching (Sheikhzadeh et al., 2005). In intermittent leaching, the continuous liquid addition is disturbed by a resting period followed by the new liquid addition. This irrigation technique has resulted in an increased leaching efficiencies according to many studies pertaining to minerals processing and soil remediation (e.g. Al-Sibai et al., 1997; Cote et al., 2000; Saririchi et al., 2012; Ghorbani et al., 2016). During the continuous liquid addition, the capillary effects draw the liquid away from the liquid flow paths and allow the diffusion to take place. Once the solution addition ceases, an inverse capillary effect is created and it drains the liquid held in inter- and intra-particle pore spaces to be washed away with the diffused metal species upon a subsequent liquid addition (Pradhan et al., 2008). This attributes to the reported increased leaching efficiency (Cote et al., 2000). Pradhan et al. (2008) thus proposed intermittent leaching is ideal for coarse particle leaching and much efficient leaching is expected from opting for a longer dry period (Cote et al., 2000). Furthermore, the cost for intermittent leaching operations can be much lower compared to the continuous liquid addition operations in industrial heap leaching (Kappes, 2002).

Intermittent liquid addition in industrial heaps is thus practiced as a rule of thumb without the comprehension of the fundamentals related to the liquid flow path evolution. The liquid flow paths development after a rest period within the heap has not been studied since these flow features are invisible in the macro-scale due to the dense and the opaque nature of the ore bed. Limited systematic studies in intermittent liquid addition, may have abated the complete elucidation of uniform liquid distribution and minimisation of liquid channelling in heap leaching. This study addressed that aspect and the effects of intermittent liquid addition were investigated in terms of overall liquid flow path evolution within a packed bed pertaining to heap hydrodynamics.

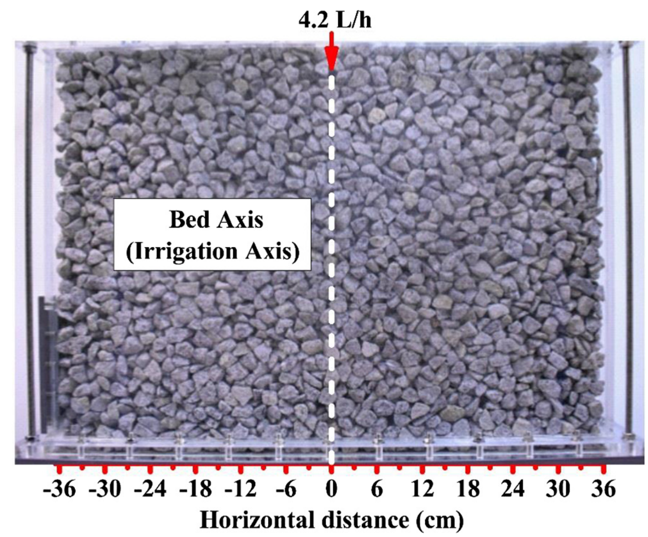

Fig. 1. The 2-D experimental packed bed system used in this work. Out-flow liquid collection ports (25 in total) are also shown at the bottom of the bed.

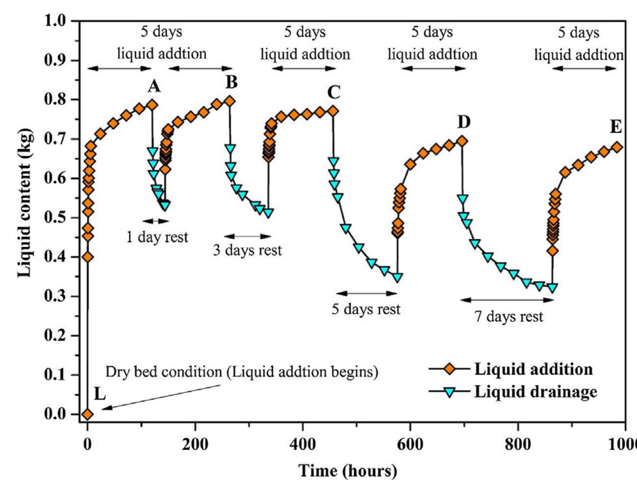

Fig. 2. Intermittent liquid addition methodology used in this work. Continuous liquid addition was followed by different rest periods, which were 1 day, 3 days, 5 days and 7 days, respectively.

2. Materials and methods

The experimental packed bed system in this work, was prepared in a Perspex pseudo 2-D column and it was similar to the setup employed by Ilankoon and Neethling (2016). The dimensions of the 2-D bed were 80 cm in length, 60 cm in height and 10 cm in thickness (Fig. 1). For the liquid content measurements, two load cells were employed and the column was suspended on them from the two ends of the column.

Quartz rich tectosilicate particles were used in this work. Estimated porosity of the particles was determined by soaking a selected aggregate sample in deionised water for 5 days and the values ranged from 0.5 to 7%. The initial ore mixture was fractionated into several size fractions, 2.36–4.75, 4.75–8, 8–10, 10–12.5, 12.5–16, 16–20 and 20–25 mm. Two types of packings were utilized in this study, which were a narrowly sized fraction (16–20 mm) and a realistic ore mixture (2.36–25 mm). Taking the geometric mean particle radius as the characteristic length, the Bond number will be about 11 and 2 for fluid flow