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Improved inter-particle flow models for predicting heap leaching hydrodynamics

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ABSTRACT

Heap leaching is one of the most important hydrometallurgical techniques for the extraction of valuable metals from low grade ores due to the relatively low capital costs and limited comminution requirements. However, it is typically affected by low recoveries, compared to conventional mineral extraction techniques such as froth flotation followed by smelting. These low recoveries indicate that there is still significant scope for the improvement of the process performance. This overall process performance is governed by chemical kinetics, mass transport and hydrodynamic effects, with hydrodynamics being particularly not completely understood at the heap scale. The authors have previously presented a model for the hydrodynamics which accounts for both liquid holdup hysteresis and the influence of particle porosity on the fluid flow. In this previous work the model form was only validated for narrowly sized particles. This shortcoming is addressed in this paper, with the validation of the models being extended to cover a range of more complex size distributions representative of those encountered in industrial heap leaching. In this work load cell based gravimetric measurements of liquid holdup values were complimented with electrical capacitance tomography (ECT) measurements, which gave not only the average holdup, but also the liquid distribution within the columns. This study demonstrates that these new hydrodynamic models remain applicable for more realistic particle size distributions, with the need to distinguish between the behaviour of the liquid held within the particle porosity compared to that flowing around the particles being critical to accurate prediction of the hydrodynamics.

1. Introduction

The fluid flow behaviour in industrial heap leaching is an important aspect of the overall performance as it is the major driver in the mass transport of leaching reagents to the ore surface as well as for the transport of the dissolved metal species out of the heap. This flow is complex as it is unsaturated and occurs through a network of channels between particles typically in the range of millimetres to a few centimetres in size (Bartlett, 1992; de Andrade Lima, 2006; Petersen, 2016). These flows exhibit channelling/preferential flow brought about by a combination of inhomogeneity in the particle beds and gravity fingering. In addition, the particles themselves are porous and hold liquid within channels and fractures with dimensions much smaller than those of the liquid within the inter-particle spaces. This means that not all liquid in the heap is equal in terms of its impact on mass transport and leaching rate (Ilankoon and Neethling, 2016). Understanding heap hydrodynamics is thus important if the long leach times and low extraction rates typically observed in industrial heaps are to be addressed (Fagan-Endres et al., 2015; Ghorbani et al., 2016; Govender-Opitz et al., 2017).

As the fluid flow is unsaturated and gravity driven the arrangement and behaviour of the flow features is governed by the balance between gravity and capillary forces. This can be characterised by the Bond number, which is the ratio of gravity to capillary forces:

$$Bo = \frac{\Delta\rho g L^2}{\gamma} \tag{1}$$

where $\Delta\rho$ is the difference in density between the fluids (air and the leaching solution) and γ is the surface tension. The appropriate length scale (L) is that of the channels through which the liquid flows, with the transition between capillary and gravity dominated flow being at a length scale of the order of a millimetre (this length scale is often

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referred to as the capillary length). This means that while the flow structures in the channels within the particles will be completely capillary dominated, those within the inter-particle spaces will be in a transition region between gravity and capillary dominated flow (Ilankoon and Neethling, 2013). The flow characteristics also depend on factors such as heap construction procedures, application of the leach solution (drip emitter density and spacing), size of the heap, particle size distribution and properties (eg. top size, percentage of fines, clay percentage, agglomerated or not) and porosity of the ore particles (Murr et al., 1981; Yusuf, 1984; Ilankoon and Neethling, 2016).

Since the applied leaching solution occupies both the space between the particles (inter-particle space) and the pore spaces within the individual particles (intra-particle space), the porosity of the heap has two distinct length scales. This implies that the liquid holdup in these regions is not equal in terms its effect on flow rates and mass transport and thus need to be considered separately. In addition, it has been observed that these systems exhibit liquid holdup hysteresis, with liquid holdup depending not only the current flow, but also on the history of liquid addition (Ilankoon and Neethling, 2012, 2013). The existence of hysteresis in the liquid holdup in heap leaching systems presents both a challenge and an opportunity in terms of heap operation, but modelling of heap hydrodynamics has not often considered this aspect. Ilankoon and Neethling (2012, 2013) presented an inter-particle flow model (unsaturated, but with liquid flow only) which accounts for liquid holdup hysteresis with the model being validated using both non-porous (mono-dispersed glass beads with a range of different sizes) and slightly porous particles (narrowly sized copper ore particles, again at a range of different sizes).

The main objective of this work is to experimentally validate these models at a wider range of operating conditions and with a range of different size distributions, including ones typical of heap leaching systems. Both non-porous glass beads and ore particles will be studied in order to quantify the impact of the internal porosity of the particles.

2. Experimental systems and methods

2.1. Gravimetric system

A cylindrical Perspex column of 243 mm internal diameter and a height of 300 mm was suspended using a high precision load cell. Since the variation in liquid content is only a small proportion of the overall weight of the column, the system required careful calibration. The load cell calibration procedure and its validation against independent measures of liquid holdup has been previously described (Ilankoon and Neethling, 2012).

Two types of particle systems were used in this study, namely a model system using glass beads and one using crushed ore particles. The glass bead system consisted of randomly packed mono-dispersed glass spheres of 2, 10, 14 and 18 mm diameter, as mixtures of various proportions of these particles (Table 1). The ore particle system (i.e. porous system) was packed with nine sets of narrowly sized copper ore particles (see Table 1) in the range of 4–45 mm (see Ilankoon and Neethling, 2013 for more details). These narrow fractions were then blended to produce a range of size distributions with known properties, including beds that were representative of what is typically encountered in industrial heap leaching. The size distributions are summarised in Table 1.

The bi-dispersed mixtures made up of 50% by weight from each size fraction, whereas realistic ones were made based on the Gaudin Schumann (GS) particle size distribution (i.e. same size range but different mixtures give different gradients of the plot) (Eq. (2), Yusuf, 1984).

$$y = \left[\frac{x}{k}\right]^n \tag{2}$$

Table 1
Size distributions and mixtures used in gravimetric liquid holdup studies.

System	Type	Particle size/s
Model system	Mono-dispersed	2,10, 14, 18 mm
Model system	Bi-dispersed	10 + 14 mm (50% by weight) 10 + 18 mm (50% by weight) 14 + 18 mm (50% by weight)
	Poly-dispersed	10 + 14 + 18 mm (33.3% by weight)
Ore system	Narrowly sized	4–8, 8–11.2, 11.2–13.2, 13.2–16, 16–20, 20–26.5, 26.5–31.5, 31.5–37.5, 37.5–45 mm
Ore system	Bi-dispersed	8–11.2 + 16–20 mm (50% by weight) 11.2–13.2 + 20–26.5 mm (50% by weight) 13.2–16 + 26.5–31.5 mm (50% by weight) 16–20 + 31.5–37.5 mm (50% by weight)
Ore system	Mixtures	2–31.5 mm (GS plot gradients: 0.5, 1.0, 1.5) 2–45 mm (GS plot gradients: 1.0, 1.5)

where y is the cumulative undersize distribution function, x is the particle size, k is the maximum size of the particles and n is the constant that determines the gradient of the GS plot.

To avoid particle segregation, especially during the packing of the mixtures, the column was packed with a series of thoroughly mixed small batches (approximately 2 kg each) rather than pouring the whole mixture at once.

The liquid distributor was mounted as a separate unit at the top of the bed. This was done so as not to adversely affect the gravimetric liquid holdup measurements. As this was a hydrodynamic study rather than an experimental leaching study, water was used as the liquid for all the experiments in this work. The superficial liquid flow rates investigated were 0.0075, 0.015, 0.03, 0.06 and 0.12 mm/s, which correspond to 27–432 kg m^{-2} h^{-1}. The lower values are within the typical solution application rates employed in column leaching studies (de Andrade Lima, 2006), whereas typical total heap area averaged industrial liquid addition rates range between 4 and 18 kg m^{-2} h^{-1} (Petersen and Dixon, 2007). However, local drip emitter flow rates are much higher than those in industrial heap leaching. A flow rate range covering at least an order of magnitude is required to validate the model as it takes a power law form and hence the range of studied flow rates extends well beyond those encountered in heap leaching (Ilankoon and Neethling, 2012, 2013).

2.2. ECT system

In order to investigate the applicability of the inter-particle flow model under a wide range of operating conditions (i.e. high liquid superficial velocities and liquid-gas two phase unsaturated flow conditions), electrical capacitance tomography (ECT) based liquid holdup values were also determined. The ECT experiments were performed at the East China University of Science and Technology. A detailed description of the ECT facility is given by Liu et al. (2009). A circular Perspex column of 140 mm diameter and height of 1000 mm was employed. It was packed with 10 mm glass beads and the liquid distributor was installed above the packing surface in order to add liquid (water) into the bed. The capacitance measurements were determined by a twin-plane (12 electrodes for each plane) PTL300E-TP-G ECT system (Process Tomography, UK). ECT image reconstruction obtains permittivity distribution from capacitance measurements. For unsaturated two-phase (liquid and gas) flow experiments, the normalized permittivity is defined as the volume fraction of the liquid in the empty space of the bed or liquid saturation. The local liquid holdup is given by the mean of volume averaged cross-sectional values of saturation (i.e. each electrode height of 55 mm) times the packed bed average porosity. Even though gravimetric method measures the total liquid holdup of