Hydrometallurgy 169 (2017) 79–88

Contents lists available at ScienceDirect

Hydrometallurgy

journal homepage: www.elsevier.com/locate/hydromet

Development of an integrated heap leach solution flow and mineral leaching model

Stefan Robertson

Mintek, Randburg, South Africa

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form 15 December 2016
Accepted 19 December 2016
Available online 21 December 2016

Keywords:
Heap leach model
Richard's equation
Shrinking core

ABSTRACT

A 1-dimensional solution flow and mineral leaching model was developed to simulate data from leach columns and to demonstrate a dual porosity approach whereby an ore bed is divided into mobile (advective) flow and stagnant (diffusional control) regimes. Hydrodynamic properties were modelled with Richard's and van Genuchten's equations, and hydrodynamic column tests were performed to measure the parameters needed to solve these equations. The solute balance was performed using the standard advection-dispersion equation used in soil dispersion models. However, the term describing the desorption of solute (copper) from the solid into the liquid phase was replaced with a shrinking core reaction model rate term.

The model shows that the proportion of the ore bed governed by diffusion increases as the diameter and height of the bed increase. The hydrodynamic properties therefore appear to have a significant effect on the copper extraction profiles and, if so, this could provide an explanation as to why large scale heaps leach slower than columns. The mass transfer coefficients for solute transfer between the mobile and stagnant regimes were of a similar order of magnitude as reported in tracer studies in literature.

© 2016 Mintek. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

A heap leach pad under irrigation is governed by various sub-processes ranging from bulk transport of solution and reagents by advection, inter-particle diffusion in stagnant clusters, intra-particle diffusion in reaction pores and chemical reaction at the mineral surface (Dixon and Petersen, 2003).

The heterogeneity of hydrodynamic conditions in an ore bed has been reported (e.g. Bouffard and Dixon, 2001 and de Andrade Lima, 2006) and dual porosity models describing flow through soils have been developed in 2D and 3D by authors such as Simunek and van Genuchten (2008). The application of techniques for the physical and hydraulic characterisation of ores for percolation processes have been described by a number of authors including Guzman et al. (2008), Milczarek et al. (2012) and Robertson et al. (2013). Notwithstanding this, fully published dual porosity models are limited to hydrodynamics or soil dispersion, whereas most leach models found in literature treat the ore bed as a single ore phase governed by either advection or diffusion (e.g. Bartlett, 1998; Miller, 2003; Bennet et al., 2012 and Cariaga et al., 2015).

A number of models describing both advective and diffusional control are summarised in Table 1. Bartlett (1998) and Bennet et al. (2012) model the reaction rate as a shrinking core within a single liquid phase governed by advection. Bartlett (1998) models the flow of solution as a vertical front moving through the ore bed at constant velocity and constant liquid hold-up, whereas Bennet et al. (2012) and Cariaga et al. (2015) use Richard's equation to describe the change in liquid hold-up with flowrate.

Simunek and van Genuchten (2008) and Robertson et al. (2013) use soil dispersion models which describe the hydraulic properties with Richard's equation and the solute transport with the advection-dispersion equation. The ore bed is divided into advective and stagnant flow regimes (dual porosity). The transfer of metal species from solids to solution is proportional to the concentration of metal in the solids (linear desorption), but this approach is not an accurate representation of heap leaching since the reaction rate is also a function of the concentration of reagent(s) at the mineral surface. For the shrinking core reaction model where the chemical rate is limiting, the concentration of acid at the mineral surface is equal to the concentration in the bulk solution phase. The bulk solution acid concentration is, in turn, a function of the supply of acid through the ore bed by either advective transport (mobile phase) or diffusion (stagnant phase).

Bouffard and Dixon (2001) and de Andrade Lima (2006) model the ore bed as comprising both mobile and immobile phases. They quantify the mass transfer coefficient of solute between the stagnant and mobile phases, as well as the ore bed porosity and the stagnant and flowing liquid hold-up. However, the work is limited to tracer tests and do not incorporate leaching studies.

Miller (2003) proposes that a heap may be represented by stagnant "macro-particles" governed entirely by diffusion and characterised by a

E-mail address: Stefanr@Mintek.co.za.

http://dx.doi.org/10.1016/j.hydromet.2016.12.010
0304-386X/© 2016 Mintek. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Nomenclature

c	concentration of solute (kg/m^3)
C_b	concentration of acid in bulk (g/L)
c_{mo} and c_{im}	concentrations of solute in the mobile and immobile regions (kg/m^3)
d	particle diameter (mm)
D, D_{mo}	dispersion coefficient of mobile phase (m^2/s)
dM_{acid}	incremental mass of acid reacted per unit volume (kg/m^3)
dM_{Cu}	incremental mass of copper species reacted per unit volume (kg/m^3)
dF	incremental overall conversion of species in ore bed
dF_i	incremental conversion of species in size fraction i
F	mass fraction of species dissolved (conversion)
f_{mo}	fraction of sorption sites in contact with the mobile phase (kg/kg)
h	hydraulic pressure head (cm)
K	hydraulic conductivity (cm/s)
$k_{Chrysocolla}$	mineral rate constant (mm/(g/L)/h)
k_{Cu}	copper rate constant (mm/(g/L)/h)
k_{Gangue}	gangue rate constant (mm/(g/L)/h)
$k_{Malachite}$	mineral rate constant (mm/(g/L)/h)
$k_{Pseudo\text{-}malachite}$	mineral rate constant (mm/(g/L)/h
k_{Rate}	rate constant (mm/(g/L)/h)
K_{sat}	saturated hydraulic conductivity (cm/s)
k_1	empirical constant (1/cm)
m, n	empirical constants
M_{Cuim}	mass of copper species in contact with the immobile phase per unit volume (kg/m^3)
M_{Cu0}	initial mass of copper species in the ore bed per unit volume (kg/m^3)
M_{Cumo}	mass of copper species in contact with the mobile phase per unit volume (kg/m^3)
N	number of size fractions
Pe	Peclet number
q	linear velocity in downwards direction (cm/s)
q_{mo}	volumetric fluid flux density in mobile phase (m/s)
Re	Reynolds number
S	relative degree of saturation
s	sorbed concentration of species (kg/kg)
s_{mo} and s_{im}	sorbed concentrations in contact with the mobile and immobile regions (kg/kg)
u	linear velocity (m/s)
W_i	mass fraction of copper in each size fraction (g/g)
z	length of ore bed in downwards direction (cm)
r_s	mass transfer rate term for solutes between the mobile and immobile regions (kg/m^3/s)
θ	moisture content (m^3/m^3)
θ_{im}	moisture content in immobile phase (m^3/m^3)
θ_{mo}	moisture content in mobile phase (m^3/m^3)
θ_r	residual moisture content (m^3/m^3)
θ_s	saturation moisture content (m^3/m^3)
μ	dynamic viscosity (kg/m/s)
ρ	bulk density (kg/m^3)
ψ	suction pressure (cm)
ω, ω_{ACID}, ω_{Cu}, ω_{mim}	mass transfer coefficient for solutes between the mobile and immobile phases (1/s)

total effective diffusional path length. Dixon and Petersen (2003) divide the heap into discrete advection flow channels separated by stagnant macro-particles within which diffusion is limiting. Mineral dissolution takes place within the stagnant pores and the intrinsic reaction rate is governed by the generalised equation:

$$\frac{dF}{dt} = k(T)\,f(C)(1-F)^{\phi} \tag{1}$$

The particle size distribution is represented by a single topological exponent ϕ, where F is the mineral conversion, k(T) is a temperature-dependent rate constant and f(C) is a function of the solution composition.

Whereas scale-up from columns to larger diameter columns or heaps may be represented by an increase in the diffusional path length in the above models, a more appropriate representation will be a dual porosity model with an increase in the proportion of the ore bed governed by diffusion. In order to demonstrate this effect, a dual porosity model similar to the soil dispersion model was developed. However, the intrinsic reaction rate was described by a shrinking core reaction model solved over a number of size fractions, rather than the linear desorption expression used previously.

Experimental testing was performed to measure the hydraulic conductivity and pore pressure relationships needed to solve Richard's equation and to validate the flow properties in the ore bed. The model was applied to the leaching of a copper oxide ore, where the intrinsic reaction rate is easier to model and the hydrodynamic effects on the overall copper leach kinetics can be better illustrated. Whereas copper oxide orebodies are becoming depleted in traditional heap leach regions such as Chile, new African projects often entail the processing of copper oxide ores with high clay content. Therefore, an understanding of the physical and hydraulic properties which govern the flow of solution through the ore bed is important. The model will be extended to include the leaching of mineral sulphides at a later stage.

2. Theory

The continuity equation for conservation of solution in a control volume can be expressed by Richard's equation for dual porosity, where q (cm/s) is the linear velocity, θ_{mo} (m^3/m^3) is the mobile moisture content, θ_{im} (m^3/m^3) is the immobile moisture content, K (cm/s) is the hydraulic conductivity, h_{mo} (cm) is the hydraulic pressure head and z (cm) is the height of the ore bed (Simunek and van Genuchten, 2008).

$$\frac{\partial\theta_{mo}}{\partial t} = -\frac{\partial q}{\partial z} = -\frac{\partial}{\partial z}\left[-K\left(\frac{\partial h_{mo}}{\partial z}\right)\right] - \frac{\partial\theta_{im}}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h_{mo}}{\partial z}\right)\right] - \frac{\partial\theta_{im}}{\partial t} \tag{2}$$

The immobile moisture in the ore bed is essentially filled up during agglomeration, and any further moisture increase during irrigation can therefore be assumed to be mobile moisture, hence $\frac{\partial\theta_{im}}{\partial t} = 0$. Then, substituting $h = z + \psi$, where ψ (cm) is the pore suction pressure, and changing the convention of flow so that z increases in the downwards direction, Eq. (2) can be reduced to:

$$\frac{\partial\theta}{\partial t} = \left(\frac{\partial\theta}{\partial z}\right)^2\left(-\frac{\partial K}{\partial\theta}\frac{\partial\psi}{\partial\theta} - K\frac{\partial^2\psi}{\partial\theta^2}\right) - K\left(\frac{\partial\psi}{\partial\theta}\left(\frac{\partial^2\theta}{\partial z^2}\right)\right) - \frac{\partial K}{\partial\theta}\frac{\partial\theta}{\partial z} \tag{3}$$

The hydraulic conductivity and the pore pressure relationships can be described by van Genuchten's Eqs. (4), (5) and (6), where S is the relative degree of saturation, θ_r (m^3/m^3) is the residual moisture content, θ_s (m^3/m^3) is the moisture content at saturation, K_{sat} (cm/s) is the saturated hydraulic conductivity, and m, n and k_1 are constants. Taking the derivative with respect to S yields Eqs. (7), (8) and (9), which may be substituted into Eq. (3). The change in moisture content with respect to ore bed height ($\frac{\partial\theta}{\partial z}$) may be solved with the Crank-Nicolson

Download English Version:

https://daneshyari.com/en/article/4769313

Download Persian Version:

https://daneshyari.com/article/4769313

Daneshyari.com