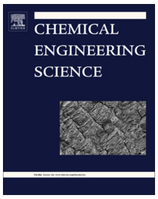
Chemical Engineering Science 172 (2017) 545–558

Contents lists available at ScienceDirect

Chemical Engineering Science

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



Modelling microbial transport in simulated low-grade heap bioleaching systems: The hydrodynamic dispersion model

Elaine Govender-Opitz [a,*], Athanasios Kotsiopoulos [a], Christopher G. Bryan [b], Susan T.L. Harrison [a]

[a] *Centre for Bioprocess Engineering Research (CeBER), Department of Chemical Engineering, University of Cape Town, Rondebosch 7701, South Africa*
[b] *Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn, TR10 9FE, UK*[1]

HIGHLIGHTS

- Microbial concentration gradient and substrate availability drives transport.
- Bulk advection-dispersion forces facilitates chemical and microbial transport.
- Integration of population balance model improved estimation of mineral leach rates.
- Ore-associated maximum specific growth rate significantly greater than that in PLS.
- Successfully predicted changes in microbial concentration in phases within ore bed.

ARTICLE INFO

Article history:
Received 26 March 2017
Received in revised form 11 June 2017
Accepted 6 July 2017
Available online 8 July 2017

Keywords:
Heap bioleaching
Unsaturated packed beds
Microbial colonisation
Microbial transport rates
Microbial growth rates
Microbial modelling

ABSTRACT

The hydrodynamic model was developed to describe microbial growth kinetics within heap bioleaching systems. Microbial partitioning between the bulk flowing pregnant leach solution (PLS) and ore-associated phases that exist within the low-grade chalcopyrite ore bed, as a function of microbial transport between these identified phases, was investigated. Microbial transport between the bulk flowing PLS and ore-associated phases was postulated to be driven by the microbial concentration gradient between the phases, with advection and dispersion forces facilitating microbial colonisation of, and transport through, the ore bed. The population balance model (PBM) was incorporated into the hydrodynamic model to estimate mineral dissolution rates as a function of available surface area appropriately. Temporal and spatial variations in microbial concentration in the PLS and ore-associated phases are presented together with model predictions for overall ferrous and ferric iron concentrations, which account for iron concentrations in the bulk flowing PLS and that in the vicinity of the mineral surface. The model predictions for PLS and ore-associated microbial concentrations are validated with experimental data, demonstrating the improvement of this model over the previously presented ‘biomass model’. Based on Michaelis-Menten type kinetics, model-predicted *true* maximum specific growth rates for *Acidithiobacillus ferrooxidans* in the PLS and ore-associated phases were found to be 0.0004 and 0.019 h^{-1}, respectively. Estimated microbial attachment and detachment rates suggest that microbial growth is more prolific in the ore-associated phases with subsequent transport to the bulk flowing PLS. Sensitivity analysis of the hydrodynamic transport model to changes in the advection mass transfer coefficient, dispersion coefficient and inoculum size are discussed. For the current reactor configuration, increasing the irrigation rate from 2 to 2.5 $L\,m^{-2}\,h^{-1}$, i.e. increasing the advection mass transfer rate, resulted in a significant decrease in microbial retention within the ore bed.

1. Introduction

Heap bioleaching is considered a feasible technology for the extraction of base metals from low-grade mineral sulphide ores. Research is currently focussed on understanding the sub-processes governing the dissolution of low-grade copper-bearing ores in heaps. Chalcopyrite is thought to be the most abundant and refractory copper-bearing mineral resource (Wang, 2005;

---

* Corresponding author.
E-mail addresses: Elaine.Govender@uct.ac.za (E. Govender-Opitz), Athanasios.Kotsiopoulos@uct.ac.za (A. Kotsiopoulos), C.G.Bryan@exeter.ac.uk (C.G. Bryan), Sue.Harrison@uct.ac.za (S.T.L. Harrison).

[1] Present address.

http://dx.doi.org/10.1016/j.ces.2017.07.008
0009-2509/

Nomenclature

List of symbols

$\mu_{x,pls}$	specific microbial growth rate in the PLS [h^{-1}]
$\mu_{x,ore}$	specific microbial growth rate in the ore-associated phase [h^{-1}]
$\mu_{x,total}$	specific microbial growth rate in the total population [h^{-1}]
$\mu^{max}_{x,i}$	maximum microbial specific growth rate for each phase [h^{-1}]
ϕ_{MS}	fraction of pure mineral sulphide in ore [dimensionless]
τ	mean residence time [h]
θ	age of particle [h]
A^P	particle specific surface area [$m^2\ kg^{-1}$]
C^{2+}_{Fe}	ferrous iron concentration [mol $Fe^{2+}\ L^{-1}$]
C^{3+}_{Fe}	ferric iron concentration [mol $Fe^{3+}\ L^{-1}$]
$C_{x,pls}$	microbial concentration in the PLS [mol C L^{-1}]
$C_{x,ore}$	microbial concentration in the ore-associated phase [mol C L^{-1}]
$C_{x,total}$	microbial concentration in the total population [mol C L^{-1}]
D_r	dispersion coefficient in radial direction [$m^2\ h^{-1}$]
D_z	dispersion coefficient [$m^2\ h^{-1}$]
$f_0\ (l_0)$	the normal distribution representing the probability of particles in a specific size range [m^{-1}]
$I\ (\theta)$	the internal age distribution of particles [h^{-1}]
k_{att}	microbial attachment rate constant [h^{-1}]
k_{det}	microbial detachment rate constant [h^{-1}]
k_m	mineral leach rate constant [mol $m^{-2}\ h^{-1}$]
K_s	Michaelis-Menten constant for substrate utilisation [dimensionless]
l_0	initial particle size or diameter [m]
M^P	mass of a particle [kg]
n	order of mineral leach reaction [dimensionless]
N^T	total number of particles in the reactor [dimensionless]
q^{2+}_{Fe}	microbial specific ferrous iron oxidation rate [mol Fe^{2+} mol C h^{-1}]
q^{max}_{Fe2+}	maximum microbial specific ferrous iron oxidation rate [mol Fe^{2+} mol C h^{-1}]
r_{bio}	rate of microbial ferrous iron oxidation [mol $Fe^{2+}\ L^{-1}\ h^{-1}$]
r''_{min}	intrinsic mineral surface reaction rate [mol $m^{-2}\ h^{-1}$]
r^R	overall mineral leach rate [mol $m^{-3}\ h^{-1}$]
t	time [h]
v	advection mass transfer coefficient [m h^{-1}]
V^R	total working liquid volume in reactor [m^3 or L]
V_{PLS}	volume of bulk flowing solution or PLS within ore bed [L]
V_{ore}	volume of stagnant interstitial solution within ore bed [L]
$Y_{sx,pls}$	microbial yield coefficient in PLS [mol $C_{x,PLS}$ [mol $Fe^{2+}]^{-1}$]
$Y_{sx,ore}$	microbial yield coefficient in ore associated phase [mol $C_{x,ore}$ [mol $Fe^{2+}]^{-1}$]
$Y_{sx,total}$	microbial yield coefficient in all phase in ore bed [mol $C_{x,total}$ [mol $Fe^{2+}]^{-1}$]
z	depth of bed [m]

Watling, 2006). In chalcopyrite bioleaching however, lower mineral sulphide dissolution rates have been observed in commercial heaps (Chen and Wen, 2013; Panda et al., 2012; Watling, 2006) than previously obtained in tank bioleaching systems at temperatures exceeding 50 °C (Batty and Rorke, 2006) and pilot scale heaps (Dew et al., 2011), as a result of poor temperature progression within the heap which limits efficacy.

In the dissolution of chalcopyrite, both ferric iron and hydronium ions react with the mineral sulphide, as in Eqs. (1) and (2), respectively. Studies have shown that these reactions, together with the microbial oxidation of ferrous iron (Eq. (3)), determine the ferric to ferrous iron ratio which, in turn, affects the rate of chalcopyrite dissolution (Córdoba et al., 2008; Hiroyoshi et al., 2008). In addition, the microbial oxidation of reduced sulphur species regenerates the hydronium ions (Eq. (4)) responsible for maintaining low pH conditions necessary for both optimum microbial oxidation and the prevention of iron precipitation.

$$CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{2+} + 5Fe^{2+} + 2S^0 \tag{1}$$

$$CuFeS_2 + 4H^+ + O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2S^0 + 2H_2O \tag{2}$$

$$4Fe^{2+} + 4H^+ + O_2 \overset{\text{iron oxidiser}}{\rightarrow} 4Fe^{3+} + 2H_2O \tag{3}$$

$$2S^0 + 3O_2 + 2H_2O \overset{\text{sulphur oxidiser}}{\rightarrow} 2SO_4^{2-} + 4H^+ \tag{4}$$

Although dump bioleaching has been applied successfully for the treatment of low-grade, copper-bearing ores, previous studies have demonstrated the significance of variation in temperature, oxygen concentration, concentration of chemical species, microbial activity and abundance across the length and depth of test scale dumps (Bhappu et al., 1969; Murr, 1980; Murr and Brierley, 1978). Heap bioleaching has begun to replace dump bioleaching as the more feasible technology (Chen and Wen, 2013; Norgate and Jahanshahi, 2010; Watling, 2006); however, the copper inventory within the heap often requires months before metal recovery can occur. Decreasing the holdup of this copper inventory has significant potential benefit to the industry.

Typically, commercial heap operations experience long heap start-up periods during which microbial activity is low, leading to slow temperature progression within the heap and low mineral dissolution rates. Energy loss from the heap during start-up may be minimised through effective management of the solution irrigation rate and aeration of the heap (Dixon, 2000; Lizama, 2001; Muñoz et al., 1995). The exothermic sulphide mineral dissolution reactions which generate energy within the heap are controlled by the availability of chemical and microbial species, distributed within the heap by the bulk flowing liquid stream as well as the degree of liberation and accessibility of the sulphide mineral. Escobar et al. (1996) and van Loosdrecht et al. (1990) suggested that in a mineral leaching environment, bioleaching microorganisms may be concentrated in the phases associated with the mineral.

Recent studies have demonstrated that bioleaching microorganisms are distributed non-uniformly across the identified phases within the heap; namely, in the bulk flowing pregnant leach solution (PLS), in the stagnant interstitial solution, and weakly and strongly attached to the mineral surface (Chiume et al., 2012; Govender et al., 2013; Tupikina et al., 2014). These authors found that the growth of *At. ferrooxidans* in the PLS did not represent that in the stagnant interstitial solution and attached phases, with microbial abundance in the ore-associated phases (interstitial and attached) at least two to three orders of magnitude greater than that in the PLS. In the study by Govender et al. (2013),