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Modeling the hydrodynamics of heap leaching in sub-zero temperatures

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ABSTRACT

Heap leaching involves the application of a leach solution onto stacked low grade ores. Solution percolates through the ore, dissolving metals from various minerals, and is recovered at the base. This process is conceptually a simple one, but quickly becomes complex when considering the sub-processes, such as dissolution chemical reactions, oxidation, precipitation, ore with different leaching characteristics, and multi-lift heaps with dynamically changing irrigation schemes.

In addition, changing meteorological conditions, such as heavy rain, evaporation and extreme ambient temperatures have a significant effect on the hydrodynamics. Various factors, such as large variations in ore hydraulic properties, saturated–unsaturated flow, preferential flow pathways, perched water tables, infiltration into dry ore or possible freezing of solution within the heap, can lead to reduced leaching efficiency.

This contribution describes the methods employed within a computational fluid dynamics heap leach model to account for freezing climate conditions. Validation of one-dimensional thermal phase change is performed and a theoretical column of coarse and fine ore is partially frozen to illustrate how the preferred flow path can be counter-intuitive. Finally, a three-dimensional heterogeneous gold oxide 'test' heap is simulated assuming non-thermal reactions and sub-zero ambient temperatures. The results demonstrate how recovery can be affected by cold weather changing the hydrodynamics of the heap.

1. Introduction

Heap leaching is a process to extract precious metals, such as copper, gold, zinc and uranium, from ore. This is often the preferred method for extracting metal from low grade ore deposits as it provides a low capital cost relative to other methods. Heap leaching typically involves applying a leaching solvent, such as cyanide or acids, over a crushed stockpile of ore; Bartlett (1998) gives an overview of these technologies. A leaching solution containing a reactant is irrigated on to the top exposed surface of the ore. The solution percolates through the heap allowing the reactant to diffuse into the ore particle micro-pores dissolving the metal. The dissolved metal in solution is then transported through the stockpile and drains into collecting ponds at the base of the heap. Solution collected in the ponds is sent for subsequent processing to extract the valuable metals. Heap leaching has been in existence for decades but has evolved over time to a highly controlled process with refined techniques for extracting a range of metals from complex ore deposits in increasingly diverse climates. Dhawan et al. (2012) provides an overview of heap leaching technology for a range of ore types.

The ideal heap leach location is a temperate semi-arid desert location, such as western U.S. (Kappes, 2002). However, heap leach operations are frequently located in a range of climates, from tropical to desert climates. Operations located in climates with heavy rains experience tons of water added to the leach system. These heavy rainfalls can change the hydrodynamics of the ore body with systems possibly experiencing strong liquid holdup hysteresis. Ilankoon and Neethling (2012) showed that packed bed experiments suggest that the fluid flow depends not only on the current flow conditions but also on the flow history. Often this additional water is recycled to the heap, for water management purposes, resulting in heaps that act as water storage systems with high phreatic levels. In contrast leach pads can be found in the southern borders of the Sahara desert, where the hot desert climate experiences very little rainfall. High ambient temperatures do not adversely affect leaching kinetics and can lead to increased overall recovery. The use of dripper irrigation requires that only small quantities of water are required, employing good water management practices, water consumption can be less than 0.3 tons of water per ton of ore (Kappes, 2002). As heap leach technologies have advanced, heap leaching operations have expanded into more

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Nomenclature

c	specific heat capacity (J kg^{-1} K^{-1})
C	species concentration (mol m^{-3})
B	rate modifier (dimensionless)
D	dispersion coefficient (m^2 s^{-1})
D_{eff}	effective particle diffusion coefficient (m^2 s^{-1})
h	pressure head (m)
k_{int}	intrinsic permeability (m)
K	hydraulic conductivity (ms^{-1})
g	gravity (ms^{-1})
G_{wT}	Gain factor (dimensionless)
L	latent heat of fusion (J kg^{-1})
m	mass (kg)
M	molecular weight of the mineral (kg m^{-3})
n	van Guenchten parameter related to the pore-size distribution
Q	ratio of ice to liquid (m^3 m^{-3})
r	radius
r_m	reacted particle radius
S	sink/source term (m^3 s^{-1})
t	time (s)
T	temperature (K)
T^*	melting temperature (K)
u	velocity (ms^{-1})
VF	volume fraction (m^3 m^{-3})
x	mass fraction (kg kg^{-1})
z	gravity direction (dimensionless)

Greek symbols

α	van Guenchten parameter related to the inverse of the air-entry pressure
β	parameter (K)
γ	surface tension (N m^{-1})
θ	moisture volume fraction (m^3 m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
μ	liquid viscosity (kg m^{-1} s^{-1})
ρ	liquid density (kg m^{-3})
Ω	impedance factor (dimensionless)

Subscripts

a	air
f	fluid
i	ice
j	index
p	matrix
res	residual
ref	reference value
s	solid
sat	saturated

extreme climates, with leach pads now located in increasingly colder climates. Arctic or near-arctic gold heap leach pads can experience perma-frost with some operations unable to operate during the coldest season. Smith (1997) gives an overview of the problems and operational methods encountered in cold weather. In climates with temperatures falling below zero a significant decrease in recovery can often be seen during these periods. The recovery is normally offset by an increase in recovery during warmer periods and is probably due to solution flowing more slowly as a result of changes to viscosity, surface tension and freezing of solution inside the heap. In addition reaction rates of certain minerals can be thermal dependent thus slowing the recovery.

Adverse flow behavior within the heap is often responsible for low leaching efficiency. Irrigation systems, application rates, migration of fines, heterogeneous materials and compaction can all contribute to complex unsaturated conditions. Seasonal variations, such as rainfall, high and low temperatures, can also have an impact on the flow behavior. Significant rain events can lead to saturated regions within the heap, dilution of the reagent and preferential pathways which wash the leaching solution through, bypassing any reactions with the ore body. Kunkel (2008) states that the recovery of the metal from the ore is influenced more by the solution flow characteristics than the material; in turn, unsaturated flow characteristics in heaps are influenced more by the material than the fluids. Limited and variable solute transport within the heap can significantly affect the leach reaction rates. Unsaturated zone hydrology models and numerical techniques are increasingly being employed to predict and improve the efficiency of the heap by simulating the leaching process to gain an understanding of the flow within the stockpile. A number of authors have employed fluid flow models to investigate the hydrodynamic behavior of the heap, such as Munoz et al. (1997), Bouffard and Dixon (2001), Pantelis et al. (2002), Cariaga et al. (2005), Lima (2006), Peterson and Dixon (2007), Bouffard and West-Sells (2009) and Guzman (2013). Dixon and Petersen (2003) present a method for column heap leaching using a model based on raffinate diffusing out to reaction sites from discrete channels through the ore and employed comparisons to column test results to generate confidence in the model for predicting behavior in heaps.

Computational Fluid Dynamics (CFD) technologies have enabled more complex multiphase transport in the modeling of the heap leach process (Bennett et al., 2006, 2012; Leahy et al., 2006; Wu et al., 2010; Mostaghimi et al., 2014), but much of this work has been performed employing one-dimensional columns or two dimensional slices. As the hydrodynamics of column tests do not represent the flow behavior on a full scale heap, scale-up of column test recovery to full scale heap recovery is often practiced, but the scale-up factor is dependent upon the hydraulic and physical parameters of the ore so can be very subjective (Scheffel, 2014). A scale up methodology was proposed by Mellado et al. (2011) to predict the effect of heap height and other operation-design variables. Alternatively, full scale simulations can be performed which directly account for ore and hydrodynamic variations within the heap, and McBride et al. (2012a, 2012b) have applied CFD technology to full scale industrial oxide heaps. However, any predictive model requires careful characterization of the ore (McBride et al., 2014a). Advances in material characterization tools and testing techniques allow detailed characterization of ores for simulation based analysis, based on physics, chemistry and material properties. This method directly accounts for material properties changing dynamically within the heap allowing full scale or test heap simulations to be performed to predict the effect of process parameters on recovery (Garcia et al., 2010).

An additional complexity, when modeling large scale heap operations, is capturing the effect of climate and changing meteorological conditions on the heap leach process. Furthermore, the process is never at a steady state, there is usually a combination of ore types with different leaching characteristics, and different irrigation schemes with intermediate solution possibly being recycled to the heap. Climate conditions will have some influence on the hydraulic properties of the ore. At higher temperatures, the surface tension and viscosity of the liquid is reduced. Thus, capillary pressure decreases allowing for the formulation of more

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