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MODELLING HEAT TRANSFER IN THE DRIPPER ZONE OF A HEAP LEACHING OPERATION

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ABSTRACT

A computational fluid dynamics (CFD) solver ANSYS-CFX is used to model the heat transfer in the region near the surface of a leach heap when drippers are buried. The potential for natural convection to occur above the dripper level, thus substantially increasing heat loss from the heap, is investigated. A parameter analysis is performed which shows that the factors that may be important to the initiation of natural convection are permeability, the depth at which the drippers are buried and the space between each dripper. The current study shows that permeability is the only parameter which has a profound effect on heat loss by natural convection.

NOMENCLATURE

b	dripper spacing, (m)
$\mathbf{B}$	body force vector, (N/m^3)
C_1	heat transfer coefficient between heap surface and top air, (W/m^3)
C_2	heat transfer coefficient between air and the material surrounding the dripper, (W/m^3)
d	heap particle size, (m)
$\mathbf{g}$	gravitational constant vector, (m/s^2)
h	static enthalpy, (J/kg/s)
H	dripper buried depth, (m)
k_{eff}	effective thermal conductivity, (W/m/K)
K	bed permeability, (m^2)
Nu	Nusselt number for air/particle inter-phase heat transfer, (-)
p	air pressure, (N/m^2)
q_{comb}	heat flux loss due to the combination of natural convection and conduction, (W/m^2)
R	resistivity due to porous media, (kg/m^3/s)
S	source or sink of energy, (W/m^3)
S_{drip}	source value at each dripper, (W/m^3)
S_{top}	source value above the heap surface, (W/m^3)
T	air temperature, (K)
T_{drip}	acid solution feed temperature, (K)
T_{top}	fixed temperature above the heap surface, (K)
T_0	buoyancy reference temperature, (K)
$\mathbf{u}$	air velocity vector, (m/s)
(x, z)	two-dimensional spatial coordinate system, (m)
α	volume fraction of heap particles (1- ε), (-)
γ	thermal expansion coefficient of air, (1/K)
ε	bed porosity, (-)
λ	air thermal conductivity, (W/m/K)
μ_a	dynamic air viscosity, (kg/m/s)
ρ_a	air density, (kg/m^3)
$\rho_{a,0}$	air density at atmospheric conditions, (kg/m^3)

INTRODUCTION

Heap leaching is appealing for processing low-grade metal bearing ores (both sulphides and oxides) due to its low capital and operation costs. However there are still aspects of the process that need to be improved, for example the recovery and leaching rate for chalcopyrite, and acid consumption in the leaching of nickel laterites.

Thermal balance within the heap is thought to be critical to many of the issues facing operators of heap leaching. Some believe that bio-leaching rates of sulphide ores might be enhanced by increasing the temperature within the heap, and work has been carried out to investigate the use of thermophiles and moderate thermophiles (Petersen and Dixon, 2002). On the other hand, work by Leahy et al (Leahy et al, 2005 & 2006) suggests that one of the mechanisms limiting the bio-leaching rate is overheating within the heap. In the case of nickel laterites, the heat of reaction is quite small, so that if one wishes to maintain the heap temperature at a level significantly higher than ambient, heat loss of heap should be minimised.

The solution used for leaching is typically fed to the heap via drippers which are laid on the surface of the heap or buried a small distance below the surface. If the solution is at ambient temperature, its application is a major factor in cooling the heap (Dixon, 2000), whereas if the heap is being heated by solution at temperature above ambient, heat loss at the top of the heap may be significant, which may be a driver for burying the drippers. Drippers may also be buried to reduce evaporation. Suppression of heat loss and evaporation by burial of drippers could be compromised if natural convection cells form in the region above the drippers, because these could substantially increase the heat and mass transfer from the dripper level to the surface of the heap.

In this paper we investigate the loss of heat from a heap in a situation where the drippers are buried beneath the surface, and, for simplicity, where no air is sparged from the bottom of the heap. To do this we simulate the region between the surface and the buried drippers, which will hereafter be referred to as the dripper zone.

Previous models of heap and dump leaching/bioleaching, and acid mine drainage have attempted to treat the whole depth of the bed, with approximate, albeit reasonable, sub-models to treat the detailed mechanisms occurring in various zones within the heap. The models have accounted for heat and mass transfer occurring in a three phase system consisting of the ore particles in the heap, acid solution and air (Casas et al., 1998; Leahy et al., 2003; Pantelis and Ritchie, 1992; Dixon and Hendrix, 1993; Bartlett and Prisbrey, 1996; Lu and Zhang, 1997). A more comprehensive review of the current state of heap leaching models reported in literature was given by Dixon (2003) and Leahy (2006). To the authors' knowledge, none of the models mentioned above has included a study of the detailed heat transfer mechanisms in the dripper zone.

The aim of this work therefore is an attempt to fill the gap in the literature by developing a preliminary two-dimensional (2-D) CFD model for simulating the heat transfer in the dripper zone. Heat transfer in the dripper zone is a very complex process in that heat loss can be due to forced convection, natural convection or conduction or a combination of all three. There will be temperature gradients both within the heap bed and the air layer flowing over the bed. A multi-dimensional CFD model is required to investigate these issues. The CFD model will also be able to investigate the effect of bed permeability, the depth at which the drippers are buried (hereafter referred to dripper buried depth) and the distance between each dripper (hereafter referred to dripper spacing) on the heat transfer in the surface near the heap.

MODEL DESCRIPTION

Assumptions

The geometry used for simulating the dripper space is a two-dimensional porous medium of rectangular shape as shown in Figure 1 with the heap shown in bold and the extent of the computational domain shown by the dashed line.

The following key assumptions have been made in conducting the CFD simulation:

- The heap is assumed to be two-dimensional: it is likely that the distance between holes along the dripper lines is much less that the spacing between dripper lines (i.e. dripper spacing);
- Flow field symmetry has been assumed: just half of the zone between drippers is simulated;
- Permeability and porosity are assumed to be uniform through the heap bed;
- The heat loss due to water evaporation was neglected in the current study;
- Conductive heat transfer through the bed material was neglected; hence the simulation can be treated as a single phase gas flow through porous media;
- It was assumed that there is no airflow across the top of the heap at this stage.

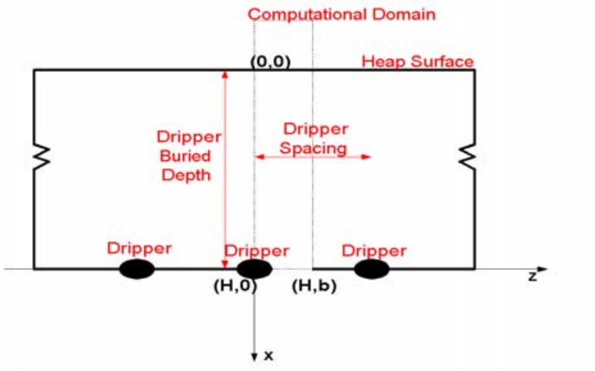

Figure 1: Schematic Heap Dripper Zone

Air flow

The steady state air flow occurring in the porous heap can be described by the equation of continuity and the steady state Navier-Stokes equations as below:

$$\nabla \bullet \mathbf{u} = 0 \tag{1}$$

$$\rho_a \nabla \bullet (\mathbf{uu}) = -\nabla p + \mu_a \nabla^2 \mathbf{u} + \mathbf{B} \tag{2}$$

where p, $\boldsymbol{u}$, $\mathbf{B}$, μ_a and ρ_a are the pressure, velocity, body forces, air viscosity and density respectively. The body force $\mathbf{B}$ accounts for the Darcy resistance to flow in the porous medium and gravity by taking the form

$$\mathbf{B} = -R\mathbf{u} + \rho_a \mathbf{g} \tag{3}$$

where $\mathbf{g}$ is the gravitational vector and R is the porous resistivity (Al-Khlaifat and Arastoopour, 1997) given by

$$R = \frac{\varepsilon \mu_a}{K} \tag{4}$$

Here ε and K are the porosity and permeability of the heap respectively. The buoyancy effect induced by the air density ρ_a variation due to differences in the air temperature is incorporated into the model using the Boussinesq approximation. In the body force term for ρ_a in equation (3), the air density is taken to be

$$\rho_a = \rho_{a,0}\left(1 - \gamma(T - T_0)\right) \tag{5}$$

where γ is the thermal expansion coefficient of air, $\rho_{a,0}$ is constant and equal to the air density at the atmospheric conditions, and T_0 is the buoyancy reference temperature. The density on the left hand side of equation (2) is set equal to the atmospheric value so that the momentum equation is given by

$$\rho_{a,0} \nabla \bullet (\mathbf{uu}) = -\nabla p + \mu_a \nabla^2 \mathbf{u} - \frac{\varepsilon \mu_a}{K}\mathbf{u} + \rho_{a,0}(1 - \gamma(T - T_0))\mathbf{g} \tag{6}$$

Energy balance

The temperature is described by the steady state heat equation given by

$$\rho_a \nabla \bullet (\mathbf{u}h) = \lambda \nabla^2 T + S \tag{7}$$

where h is the static enthalpy, λ is the thermal conductivity of air and S represents sources or sinks of energy.

Boundary Conditions

The conditions imposed at the boundaries of the computational domain (see Figure 1) are as follows:

$$\frac{\partial \mathbf{u}(x,0)}{\partial z} = 0, \frac{\partial T(x,0)}{\partial z} = 0 \tag{8}$$

$$\frac{\partial \mathbf{u}(x,b)}{\partial z} = 0, \frac{\partial T(x,b)}{\partial z} = 0 \tag{9}$$

$$\frac{\partial \mathbf{u}(H,z)}{\partial z} = 0, \frac{\partial T(H,z)}{\partial z} = 0 \tag{10}$$

$$p(0,z) = 1\text{atm for } 0 \le z \le b \tag{11}$$

A source/sink of energy was used in the region above the heap surface to mimic a fixed temperature boundary condition for the air (Lu and Zhang, 1997). The source term applied in equation (7) was evaluated using the following expression

$$S_{top} = -C_1\left(T - T_{top}\right) \quad (12)$$

where T is the local air temperature, T_{top} is the required fixed temperature (assumed to be 20°C) and C_1 is constant with a value set large enough to ensure the local air temperature achieves the desired fixed temperature. A typical value for C_1 was 1000 W m^{-3} K^{-1}.

The effect of the hot liquid at each dripper was included as a point source in equation (7) with the source value being given by

$$S_{drip} = -C_2\left(T - T_{drip}\right) \quad (13)$$

where T_{drip} is the acid solution feed temperature (assumed to be 60°C) and C_2 is a heat transfer coefficient between the air and the materials (ore particles and liquid) surrounding the dripper. The coefficient C_2 is estimated by analogy with interphase heat transfer in a multi-phase particle model and its value can be determined by (ANSYS, 2005)

$$C_2 = \frac{6\lambda\ Nu\ \alpha}{d^2} \quad (14)$$

where Nu is the Nusselt number for air/particle inter-phase heat transfer and was assumed to be 2.0 in this study based on the expected laminar flow within the heap (ANSYS, 2005); α is volume fraction of heap particles (1-ε) and d is the heap particle size assumed to be 1 cm in this study based on data reported in literature (Bouffard, 2005).

NUMERICAL METHOD

The steady state equations (1)-(7) were solved using ANSYS CFX 10. A 2-D extruded mesh consisting of prisms and hexahedrons was used for all simulations. A mesh independence study was conducted for one of the simulation configurations and the mesh spacings required for a mesh independent solution were determined. This mesh spacing was used on all subsequent simulations. The results were assumed converged when the normalized residuals for all variables were less than 1×10^{-5}.

As ANSYS-CFX uses a false time-stepping method when solving steady state problems different false timesteps were used to solve the momentum and energy equations.

RESULTS

The key parameters used in the CFD simulation are shown in Table 1.

In order to simplify the analysis, a wall boundary condition was imposed at the heap level where the drippers are buried. The total heat loss hence is not an appropriate parameter to quantify the enhancement of heat transfer due to natural convection.

Heap porosity	$\varepsilon = 0.3\left[\mathrm{m^3/m^3}\right]$
Heap permeability (base case)	$K = 1\times10^{-10}\left[m^2\right]$
Air density	$\rho_a = 1.185\left[\mathrm{kg/m^3}\right]$
Air viscosity	$\mu_a = 1.831\times10^{-5}\left[\mathrm{kg/m/s}\right]$
Air conductivity	$\lambda = 0.0261\left[\mathrm{W/m/K}\right]$
Particle diameter	d = 1 [cm]

Table 1: Parameters for the CFD simulations

The quantity of heat loss due to the combination of natural convection and conduction can be expressed indirectly via an effective thermal conductivity k_{eff} which is derived from $q_{comb} = k_{eff}\frac{\Delta T}{H}$ where H is the depth of the dripper, ΔT is the average temperature difference between the heap surface and the dripper depth and q_{comb} is net heat flux leaving the heap surface. A ratio of k_{eff} to λ which is the thermal conductivity for the heat loss due to pure conduction should give an indication of the "enhancement" of heat transfer provided by natural convection. This ratio will be used to investigate the effects of dripper spacing, dripper buried depth and heap permeability on the heat transfer in the dripper space throughout the results section.

The effect of the dripper spacing on the natural convective heat transfer for the base case (K=10^{-10} m^2) is shown in Figure 2. From Figure 2 it can be seen that the rate of heat transfer enhancement by natural convection does increase slightly as the dripper spacing increases from 0.3 to 1 m per dripper, and remains relatively constant as the dripper spacing increases further. Nevertheless, over the whole range of dripper spacing investigated (from 0.3m to 3m per dripper), the enhancement on heat transfer provided by natural convection is very small, less than 1%.

The effect of dripper buried depth on heat transfer enhancement for the base case (K=10^{-10} m^2) is shown in Figure 3. Over the range dripper buried depth investigated (from 0.3 m to 1.5 m), the heat transfer enhancement offered by the natural convection is negligible.

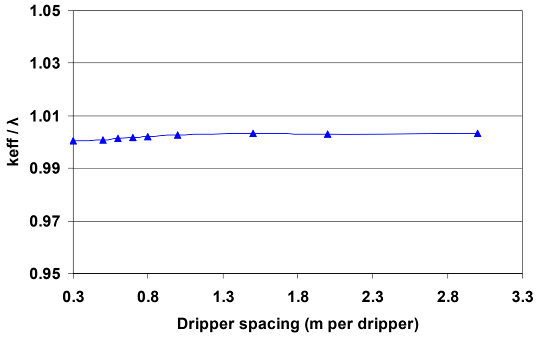

Figure 2: Effect of dripper spacing on heat transfer enhancement, H = 0.3m, K = $10^{-10}$$m^2$

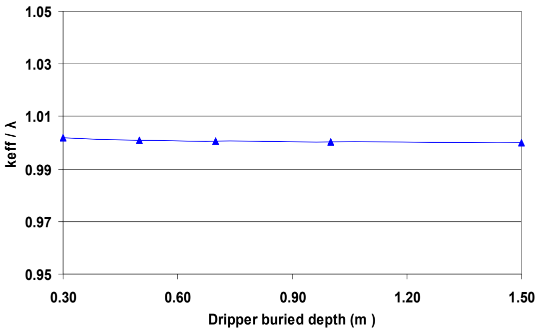

Figure 3: Effect of dripper buried depth on heat transfer enhancement, b = 0.7m/dripper, K = 10^{-10} m^2

The above observations are somewhat at odds with the expectation that the strength of natural convection should vary with the ratio of dripper buried depth to dripper spacing. One possible explanation is that the resistivity of the heap bed may substantially dampen the formation of natural convection cells within the heap.

To test this, the effect of dripper spacing and dripper buried depth have been determined for two larger values of K (1 and 2 orders of magnitude larger respectively). The flow fields for the three K values are shown in Figures 4, 5 and 6. From these figures, it can be seen that the strength of the natural convection flow intensifies dramatically at K = 10^{-8} m^2.

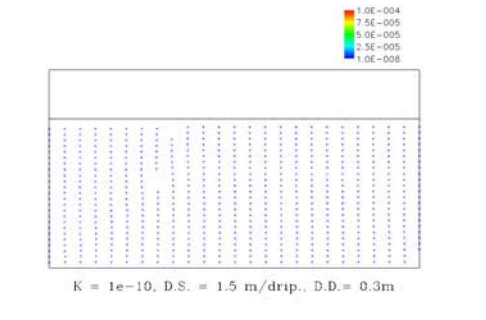

Figure 4: Flow field (m/s) for K = 10^{-10} m^2

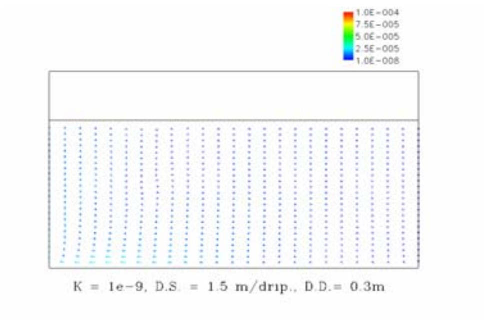

Figure 5: Flow field (m/s) for K = 10^{-9} m^2

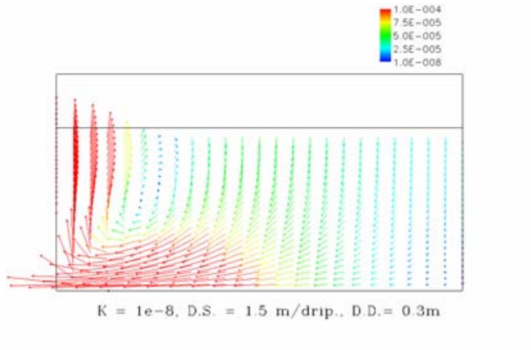

Figure 6: Flow field (m/s) for K = 1e-8 m^2

The effects of various values of K on k_{eff} /λ over a range of dripper spacing and dripper buried depth are shown in Figures 7 and 8 respectively.

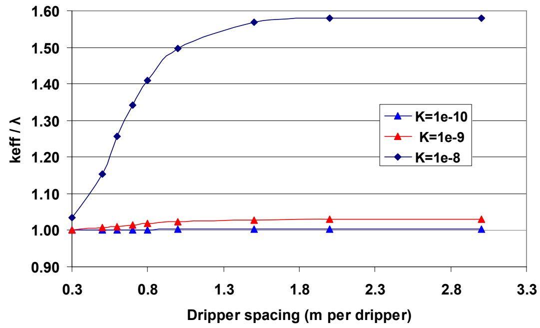

Figure 7: Effect of dripper spacing on heat transfer enhancement for various K, H = 0.3m

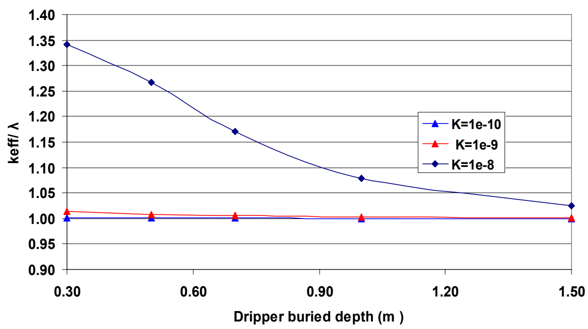

Figure 8: Effect of dripper buried depth on heat transfer enhancement for various K, b = 0.7 m / dripper

From Figures 7 and 8, it can be seen that at K = 10^{-9} m^2, the effect of the dripper spacing on the heat transfer enhancement becomes noticeable. The effect of the dripper buried depth however is less obvious. As K increases further to 10^{-8} m^2, the effect of both dripper spacing and dripper buried depth change dramatically. The pronounced effect of permeability on the natural convection flow is consistent with findings reported in the literature (Leahy et al, 2003, Lu and Zhang, 1997). From Figure 7, it can be seen that at K = 10^{-8} m^2, as dripper spacing increases from 0.3 to 1.5 m per dripper, the heat transfer enhancement by natural convection increases from about 3% to 60%. As with K = 10^{-10} m^2, the heat transfer is not enhanced any further with increase of dripper spacing beyond 1.5 m. The dependence on the strength of natural convection with dripper spacing and depth is understandable: it is well known from the natural convection literature that there are preferred aspect ratios for natural convection cells.

The effect of dripper buried depth for K = 10^{-8} m^2 is shown in Figure 8. From Figure 8, it can be seen that as dripper buried depth increases from 0.3 m to 1 m, the heat transfer enhancement by natural convection decreases substantially from about 35% to 8%. After that, the decrease of the heat transfer enhancement becomes moderate with further increase of dripper buried depth. The trend shown in Figure 8 is consistent with the trend shown in Figure 7, i.e, for a given heat source, the strength of natural convection increase with the decrease of the dripper space aspect ratio.

Permeability is an intrinsic function of the porous media and is expected to depend on parameters such as rock particle size and porosity. By assuming a laminar flow in the pore space (so that the Hagen-Poiseuille equation can be applied), an equation for calculating permeability for an assemblage of uniform spheres as a function of porosity, rock particle size and tortuosity can be derived theoretically from Darcy's law (Lake, 1989):

$$K = \frac{\varepsilon^3 d^2}{72\tau(1-\varepsilon)^2} \quad (15)$$

Equation (15) is known as the Carman-Kezeny equation where τ, the tortuosity is defined as the squared ratio of the mean flow path length to the particle size. Tortuosity is an indicator of the geometry of particles and pore channels. The value of τ is always greater than 1 and can be greater than 10, with a general average value of 3.3 (Salem and Chilingarian, 2000). For an assemblage of regularly packed spheres the value is 2.08 (Lake, 1989).

Reliable measurements of ore heap permeabilities are rarely available at operating mines. The permeability for the base case (K = 10^{-10} m^2) was estimated from values widely reported in the literature (Casas et al., 1998; Leahy et al., 2003, Pantelis and Ritchie, 1992; Lu and Zhang, 1997, Bartlett, 1998). Bartlett (1998) reported that even though equation (15) is valid for "uniform" size porous media but can still be used to estimate the intrinsic permeability if the parameter d in equation (15) is an "effective particle" diameter, which is chosen to be the largest particle diameter of the 10% cumulative passing, $d_{10,}$ and with an "effective particle" diameter of about 1.5 mm, τ = 2 and a porosity of 0.07 to 0.25, the permeability estimated from equation (15) ranges from 10^{-11} to 10^{-9} m^2. It is of interest to investigate what "effective particle" diameters and porosities will yield permeability of the order of 10^{-8} m^2. Table 2 shows various permeabilities calculated from equation (15) for "effective particle" diameter ranges from 1 mm to 20 mm and porosity from 0.3 to 0.5.

Most heap construction practices usually end up with many fine particles. It is therefore that the "effective particle" diameter of most of these heaps may not exceed 5 mm. The calculations presented in Table 2 show that for size distributions with "effective particle diameter" larger than 5 mm, it is possible that enhanced heat (and mass transfer) through natural convection could occur above buried drippers. If it is desired to suppress this effect, a lower permeability layer could be added above the drippers.

ε	"Effective particle" diameter	τ	K
	(m)		(m^2)
0.3	0.001	2	3.83E-10
0.3	0.002	2	1.53E-09
0.3	0.005	2	9.57E-09
0.3	0.010	2	3.83E-08
0.3	0.020	2	1.53E-07
0.4	0.001	2	1.24E-09
0.4	0.002	2	4.94E-09
0.4	0.005	2	3.09E-08
0.4	0.010	2	1.24E-07
0.4	0.020	2	4.94E-07
0.5	0.001	2	3.47E-09
0.5	0.002	2	1.39E-08
0.5	0.005	2	8.68E-08
0.5	0.010	2	3.47E-07
0.5	0.020	2	1.39E-06

Table 2. Permeability estimated from Carmen-Kozeny equation.

CONCLUSION

A CFD model has been developed to investigate the heat transfer in the dripper zone of heap leaching. It was found that for the permeability of heap bed reported in literature, the natural convection flow is very weak and the heat transfer in the dripper zone is dominated by conduction over the range of dripper spacing and dripper buried depth investigated.

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