Process performance of bacterial leaching reactors: The contribution of mathematical modelling

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Bacterial leaching represents an unusual problem in biochemical engineering, because the substrate for bacterial growth is not supplied directly, but is a product of another reaction, the leaching of mineral particles. Leaching arises from the bacterial oxidation of ferrous ions to ferric ions, which in turn oxidize the mineral. For the bacterial dissolution of pyrite, these reactions are:

$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ \xrightarrow{bacteria} Fe^{3+} + \tfrac{1}{2}H_2O + \tfrac{1}{Y}N \quad [1]$$

$$FeS_2 + 8H_2O + 14Fe^{3+} \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad [2]$$

(Y represents a stoichiometric yield factor, and N represents the amount of bacteria.)

Equations [1] and [2] represent a cyclic auto-catalytic system since more ferric ions are added to the system with an increase in the extent of leaching.

In addition, leaching is a particulate reaction dependent on the distribution of sizes of the particles in the feed to the reactor. This sets bacterial leaching apart from other biochemical reactors, because few other bacterial processes include the reaction of particulate material. The particle size distribution is influenced by both reaction and flow into and out of the continuous reactor, and since the rate of dissolution is dependent on the particle size, these phenomena must be explicitly described.

Consider a feed stream to a tank reactor containing a slurry of sulphide minerals. The particles in the slurry have a distribution of size, $n(l)$, where $n(l)dl$ is the number of particles per unit volume of slurry in the size range l to $l+dl$.

If particle size is the only distributed property of the particles that is necessary for a complete description of the particle kinetics, then the change in the distribution with reaction and flow in a tank reactor at steady state is given by:

$$n_0(l^*) = n(l^*) - \frac{\bar{t}R}{\bar{l}}\frac{dn(l^*)}{dl^*} \quad [3]$$

where R is the linear rate of particle shrinkage and has been assumed to be independent of size, $\bar{t}$ is the mean residence time, $\bar{l}$ is the mean particle size in the feed, and l^* is $l/\bar{l}$. $n_0(l^*)$ and $n(l^*)$ represents the inlet and outlet size functions, respectively.

The term on the left-hand side of Equation [3] represents the material coming into the reactor with size l, while the first term on the right-hand side represents the material leaving the reactor with size l, and the second term on the right-hand side represents the change in particle size as a result of reaction. Thus, Equation [3] is in the familiar form of an ordinary material balance, that is, in = out + reacted.

Equation [3] has immediate explanatory value possessed by none of the previous models of bacterial leaching. The dimensionless leaching number, N_C, is the expression preceding the differential term in Equation [3], given by:

$$N_c = \frac{\bar{t}R}{\bar{l}}, \quad [4]$$

This expression indicates that in order to increase the amount of material dissolved, the leaching number must increase. This means that either the residence time, $\bar{t}$, or the leaching rate, R, must increase, or the mean particle size in the feed, $\bar{l}$, must decrease.

Two other leaching technologies that compete with bacterial leaching for the processing of sulphide minerals in the technology marketplace are pressure oxidation, and leaching after fine milling. The set of reactions in each of these technologies is similar to or even the same as that in bacterial leaching. Each of these leaching technologies balances the leaching number, N_C, at roughly the same value as that obtained in bacterial leaching by changing the values of the parameters of N_C. These operating regimes are summarized in Table I. Thus, the fine grinding and leaching process decreases $\bar{t}$ and $\bar{l}$, and increases temperature (which increases R through the activation energy) compared with bacterial leaching. Pressure leaching increases temperature and decreases $\bar{t}$ compared with bacterial leaching. (In addition, some processes have attempted to increase the intrinsic leaching rate by the addition of agents known to increase the rate of dissolution reactions, such as halide ions.) The leaching number establishes the theoretical relationship between the technologies.

TableI

Operating regimes based on the dimensionless leaching number, N_C

Technology	Temperature	Residence time	Particles size	N_c
Bacterial leaching	Low	High	Moderate	Moderate
Pressure leaching	High	Low	Moderate	Moderate
Fine grinding and leaching	Moderate	Moderate	Low	Moderate

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Therefore, not only does the number balance account for the effect of particle size on the performance of the reactor, but it also yields valuable new insight into the relationship between various competing leaching technologies.

The model is completed by the addition of material balances for the ferrous and ferric ions, the dissolved oxygen and for each bacterial species to the number balance for each mineral present in the feed.

The model is compared with pilot plant data for three different ores. These results are shown in Figure 1. They show that the model is in excellent agreement with the data.

Sensitivity (or risk) analysis, and the conditions for washout

A sensitivity analysis evaluates the effect of a change in a parameter on the performance of the reactor. For example, sensitivity analysis evaluates the risk to the process that the practitioner may face if the bacterial growth rate changes, or if the sulphide mineralogy changes.

There are three dimensionless parameters associated with the three reactions occurring in the reactor. These dimensionless parameters are the following:

$$N_{Fe} = \mu_{\max}\bar{t}, \quad N_{mt} = \frac{k_L aV}{G_0 H} \quad \text{and } N_c = \frac{R\bar{t}}{\bar{l}}$$

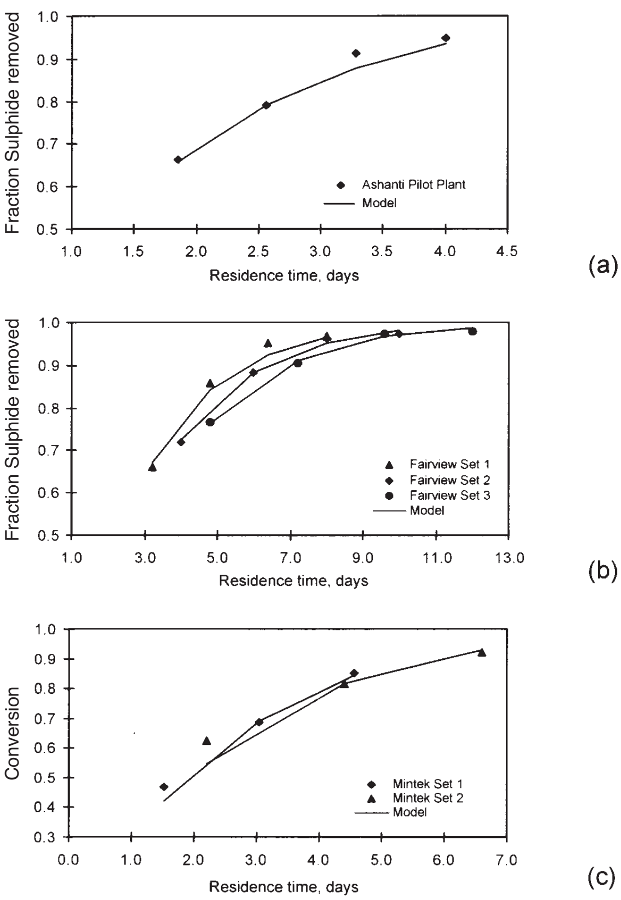

Figure 1—The correspondence of the model and the pilot plant data for three different operations. (a) Ashanti pilot plant data (Nicholson *et al.*), (b) Fairview pilot plant data (Miller1990; Dew1995) and (c) Mintek pilot plant data (Pinches *et al.*1987)

where N_{Fe} is the dimensionless parameter associated with bacterial growth, N_{mt} is the dimensionless parameter associated with oxygen mass transfer, and N_c is the dimensionless leaching number discussed previously. G_0 is the total gas flow rate into the reactor in mol/min, and H is the Henry's law constant for oxygen.

The sensitivity of a bacterial leaching reactor is explored using the model. The results are shown in Figures 2, 3, and 4. It is shown that there are three washout conditions, in which the leaching conversion drops to zero. The washout conditions are dependent on the growth rate of the bacteria, on the rate of dissolution of the mineral, and on the rate of mass transfer of oxygen to the reactor. The critical washout condition is that arising from the rate of mineral dissolution.

If all other parameters remain constant, the performance of an operating reactor cannot be enhanced by either enhancing the mass transfer or the bacterial growth. The improvement in the reactor performance can only be achieved by increasing the leaching number.

The strategy adopted in the bioprocessing of chalcopyrite is to increase the leaching rate. The kinetics of dissolution of this mineral are too slow at 40°C, the temperature commer-

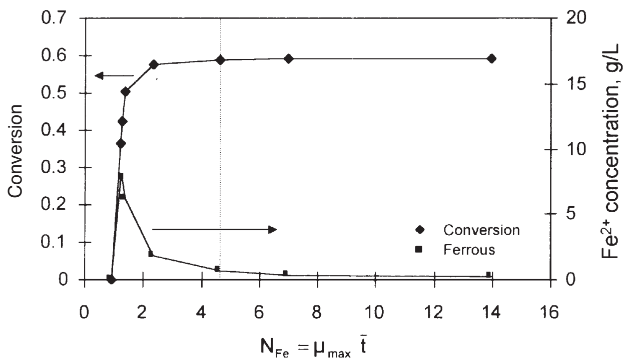

Figure 2—The sensitivity of the reactor to the dimensionless bacterial growth rate, showing that the conversion rises rapidly to a constant value as N_{Fe} increases from its limiting value of one. The dashed line indicates the position of the operating point about which the sensitivity is conducted. Also shown are the corresponding values of the concentration of ferrous ions, showing that the proximity of the washout condition can be monitored by monitoring this concentration

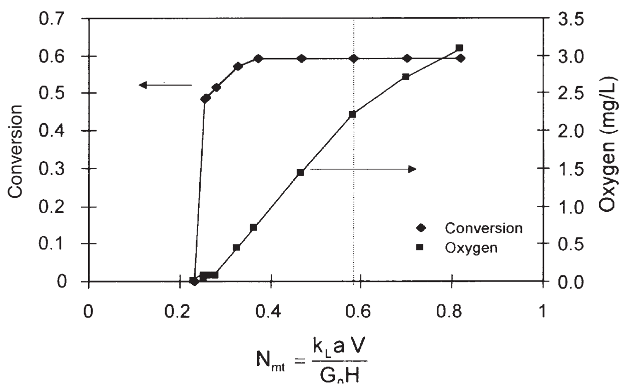

Figure 3—The sensitivity of the conversion and the oxygen concentration to the mass transfer number, N_{mt}. The results show that the conversion rises rapidly to a constant value as N_{mt} increases from the washout condition. The dashed line indicates the position of the operating point about which the sensitivity is conducted

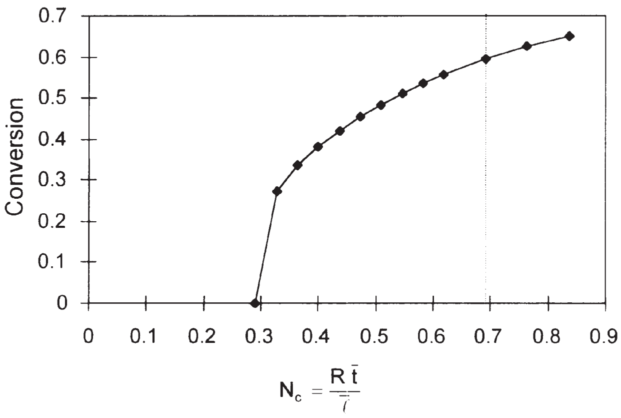

Figure 4—The sensitivity of the conversion to changes in the leaching number, N_C. The results show the washout condition related to the leaching rate. The dashed line indicates the position of the operating point about which the sensitivity is conducted

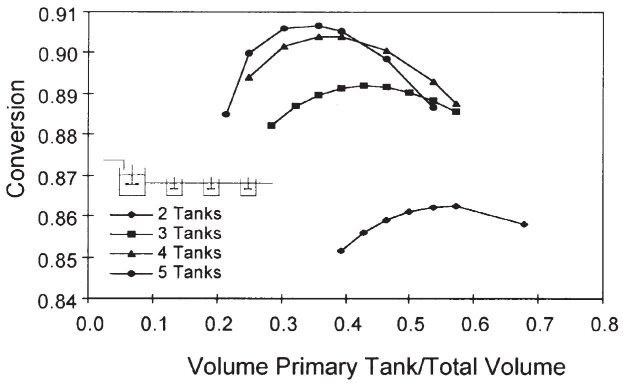

Figure 5—The effect of the ratio of the size of the first tank to the size of the total plant on the performance of the plant

cially used in bacterial leaching of pyrite and arsenopyrite concentrates. However, at temperatures in excess of 70°C, the rate of leaching increases sufficiently that the leaching number is above the washout condition. This means that acceptable reactor performance is attained. These temperatures require thermophilic organisms, which explains the increase in commercial interest in iron- and sulphur-oxidizing archae. Since another method of increasing the leaching number is to decrease the particle size, chalcopyrite concentrates leached in the presence of thermophiles may be ground to a mean size of between 10 and 20 μm.

In addition, the optimization of a plant in which reactors are configured in series was studied. This analysis shows that the primary reactor should be between 1.5 and 2 times the size of each of the secondary reactors in a series combination. The optimum size for the primary reactor in terms of the total plant size is shown in Figure 5. ◆