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Parametric Sensitivity Study of Adsorption in a Periodic Countercurrent Cascade of Stirred Tanks

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Abstract

Material balance equations are developed to describe adsorption on activated carbon in either batch or continuous countercurrent systems. The carbon is divided into two regions with distinctly different kinetic characteristics. A Freundlich isotherm is used to describe the equilibrium adsorption of gold cyanide on activated carbon. Kinetic and equilibrium parameters estimated from batch tests are shown to predict the behavior of a small-scale continuous plant accurately. A parametric sensitivity analysis of this model is conducted in order to explain the factors which influence the efficiency of a carbon-in-pulp (CIP) plant used for the recovery of gold from cyanided pulps. The periodicity of the transfer of carbon countercurrent to the flow of pulp is shown to have almost no effect on the behavior of a CIP plant. Mixing should be more efficient in the stages where low concentrations in solution occur.

INTRODUCTION

The separation of solutes from a fluid by adsorption onto activated carbon has received wide attention in the literature. Most of the published work in this field is concerned with the removal of organics from municipal and industrial wastewaters (*1-3*). In contrast, very few fundamental studies have been published on the adsorption of metals or metal complexes on activated carbon (*4, 5*). Since the 1960s, activated carbon has also been used commercially for the extraction of gold and silver from cyanided pulps.

Quartzitic gold ores are usually milled to 10% + 150 μm and 30% − 75

μm in order to fully liberate fine particles of gold or gold-bearing pyrite. Refractory pyrite is normally recovered by froth flotation and then roasted to a calcine. This calcine and the ore are cyanided at a pH between 9 and 11 in aerated tanks to dissolve the gold and silver as cyanide complexes. Lime is used to control the pH. In the next section of a gold extraction plant the cyanided pulp, which contains about 50 mass% solids, is contacted with granular activated carbon in a countercurrent cascade of stirred tanks. The carbon is retained in each tank by fine interstage screens which allow only the leached ore particles and the pregnant solution through. Air lifts or slurry pumps are used to move carbon and some pulp countercurrent to the gravitational flow of leached slurry. This is called the carbon-in-pulp (CIP) process (*6–10*). Loaded carbon from the first adsorption tank is stripped by a hot caustic cyanide solution, acid-washed, thermally regenerated, and then recycled to the adsorption circuit. The granular activated carbon which is mechanically suspended in the pulp should be sufficiently abrasion-resistant.

By 1973 the CIP process had been introduced at the Homestake Mine in South Dakota for the treatment of 2050 tons/day of cyanided slimes (*6*). Following this pioneering development of CIP technology in the United States, further development work in South Africa (*7–9*) and Australia (*10*) contributed significantly to the improvement of the process. Today, the CIP process enjoys widespread acceptance in all gold-producing countries as an effective method for the extraction of gold.

The efficiency of the adsorption section of a CIP plant determines not only the fraction of soluble gold lost in the residues but also the inventory of gold loaded on carbon in the plant and the size of the elution, reactivation, and electrowinning sections. It is therefore essential to have a model available for predicting and assessing the efficiency of a CIP adsorption circuit. Such a model should be able to use adsorption data from one reactor configuration in order to predict the adsorption performance of another configuration.

In spite of its practical importance, the analysis of adsorption phenomena in multistage countercurrent units has not received adequate attention. Nicol et al. (*11*) recently applied a simple rate equation to the modeling of CIP plants. They assumed linear concentration gradients in both the solution and carbon phases, and solved their equations for the case of a linear isotherm. Williams and Glasser (*12*) used the Langmuir-type rate expression, suggested by Menne (*7*), in the modeling of CIP and carbon-in-column contacting systems. In neither of these studies is a clear distinction made between film diffusion and intraparticle diffusion. These papers consider only very dilute solutions and low loadings on the carbon when film diffusion controls.

In this paper a parametric sensitivity analysis of a periodic countercurrent adsorption cascade is presented. It is valuable to know what effect variation of a parameter has on results. In some models, variation of one parameter can be compensated by alterations in others. Existing modeling techniques will be applied here to small-scale CIP data in order to show how such a plant could be designed and operated. The sensitivity analysis will be used to quantify the influences of factors upon the efficiency of a CIP plant.

COUNTERCURRENT ADSORPTION MODEL

The principles of a dual-rate kinetic model for the adsorption of gold cyanide on activated carbon in batch systems have been explained by van Deventer (*13*). In a recent paper by Jansen van Rensburg and van Deventer (*14*) it was shown that this model predicted the behavior of a packed bed accurately from data collected in batch tests on real gold leach solutions. This model is an extension of the branched pore kinetic model proposed by Peel et al. (*15*). Weber and Liang (*16*) formulated a similar model in which a macrospherical particle of carbon was comprised of uniformly distributed microspheres.

In this paper the carbon pore structure is partitioned artificially into a fraction (α) consisting of macropores and a fraction ($1 - \alpha$) consisting of micropores. Arguments to support this partitioning have been published (*13, 14*). As it is not possible to determine the value of α *a priori,* it should be evaluated from experimental rate data. It is further assumed that:

Only macropores open onto the superficial surface of the carbon.
The carbon particles can be treated as equivalent spheres.
Accumulation of adsorbate in the liquid phase in the pores is negligible.
Adsorbate adsorbed on the superficial surface of the carbon is in equilibrium with the liquid film surrounding the carbon particle.
Mass transport consists of the following sequential mechanisms: film diffusion, surface diffusion in the macropores, and diffusion of adsorbate from the macropores into the micropores.

The approach described here applies to a cascade of continuous stirred tanks as depicted in Fig. 1. This reactor configuration is similar to that used in carbon-in-pulp plants. Pulp flows continuously through the system of M tanks, i.e., from Tank i to Tank $i + 1$, while a fraction β of the carbon and pulp in a tank is periodically transferred countercurrent to

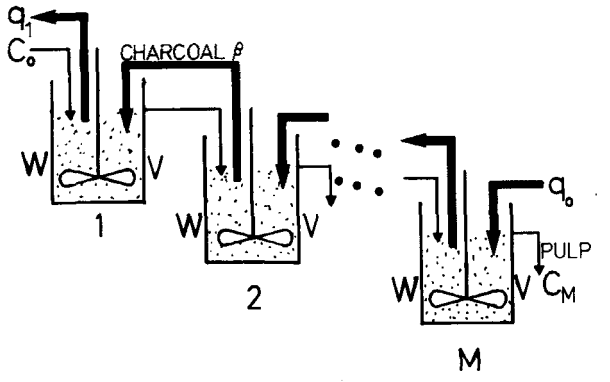

FIG. 1. Periodic countercurrent cascade of continuous flow stirred tank adsorbers

the flow of pulp, i.e., from Tank i to Tank $i - 1$. Adsorption occurs in the tanks between $t = 0$ and $t = T$, where T is the adsorption cycle time. It is assumed that the time required for transfer of carbon is very short compared to T, and that no adsorption occurs during this transfer. If the carbon is pumped continuously in the countercurrent direction, the process may be approximated by using a short cycle time T and a low fractional transfer β. A fraction β of the pulp in a tank is backmixed during transfer.

If less than a full stage is transferred at the end of a cycle, i.e., if $\beta < 1$, the carbon in a stage reveals an age and loading distribution. This means that, because some carbon particles in a tank have had a longer period of residence than other particles, some particles reveal higher loadings than other particles in the same tank.

The probability density function of this distribution in Tank i is $\phi_i(q,t)$. Here the carbon loading distribution function $\phi_i(q,t)$ is kept constant during an adsorption cycle and is only recalculated after transfer of carbon.

It is assumed here that the pulp and carbon are both perfectly mixed in each stage. Therefore, during transfer, an equal fraction β of each of the loading fractions j in a discrete distribution is moved to the previous stage. The same mixing efficiency is maintained in all the tanks. The chemical and physical properties of the carbon, the volume of pulp, and mass of carbon are identical in all the stages. No carbon by-passes a stage completely and gets transferred to Stage $i - 2$ from Stage i. It is assumed that the ore particles in the pulp are completely inert so that they serve neither as a source nor as a sink for the adsorbate.

The liquid-phase material balance for an adsorbate in Stage i is written as

$$\varepsilon V \frac{dC_i}{dt} = \varepsilon Q(C_{i-1} - C_i) - \frac{6k_f W}{d_p \rho_c} \int_0^{(\bar{q}_{ave})_{i,max}} (C_i - C_{s,i})\phi_i(\bar{q}_{ave}) d(\bar{q}_{ave}),$$

$$\text{with } i = 1, 2, \ldots, M \qquad (1)$$

By discretizing the probability density function $\phi_i(\bar{q}_{ave})$ into L_i equal loading intervals such that

$$W\Delta\phi_{i,j}(\bar{q}_{ave}) = w_{i,j} \qquad (2)$$

and

$$\sum_{j=1}^{L_i} \Delta\phi_{i,j}(\bar{q}_{ave}) = 1, \qquad \text{with } i = 1, 2, \ldots, M \qquad (3)$$

Equation (1) may be written in discrete form as follows:

$$\varepsilon V \frac{dC_i}{dt} = \varepsilon Q(C_{i-1} - C_i) - \frac{6k_f}{d_p \rho_c} \sum_{j=1}^{L_i} (C_i - C_{s,i,j}) w_{i,j}. \qquad \text{with } i = 1, 2, \ldots, M \qquad (4)$$

According to the assumptions stated earlier, mass transfer in the macropores should be described as follows:

$$\alpha \frac{\partial q_{m,i,j}}{\partial t} = \frac{\alpha D_s}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial q_{m,i,j}}{\partial r} \right) - k_b(q_{m,i,j} - (q_{b,i,j}),$$

$$\text{with } i = 1, 2, \ldots, M \quad \text{and } j = 1, 2, \ldots, L_i \qquad (5)$$

Van Deventer (*13*) explained that this type of partial differential equation may be approximated by a quadratic driving force expression to yield

$$\alpha \frac{d\bar{q}_{m,i,j}}{dt} = \frac{60\alpha \bar{D}_s}{d_p^2} \left[\frac{q_{s,i,j}^2 - \bar{q}_{m,i,j}^2}{2\bar{q}_{m,i,j}} \right] - k_b(\bar{q}_{m,i,j} - \bar{q}_{b,i,j}),$$

$$\text{with } i = 1, 2, \ldots, M \text{ and } j = 1, 2, \ldots, L_i \qquad (6)$$

The material balance for the adsorbate in the micropore region may be written as a linear driving force approximation (*15*):

$$(1 - \alpha)\frac{d\bar{q}_{b,i,j}}{dt} = k_b(\bar{q}_{m,i,j} - \bar{q}_{b,i,j}),$$

$$\text{with } i = 1, 2, \ldots, M \quad \text{and } j = 1, 2, \ldots, L_i \qquad (7)$$

If no accumulation occurs at the superficial surface of the carbon, a material balance for the adsorbate can be written at the carbon-pulp interface by equating the surface fluxes:

$$k_f(C_i - C_{s,i,j}) = \frac{10\alpha\rho_c\bar{D}_s}{d_p}\left[\frac{q_{s,i,j}^2 - \bar{q}_{m,i,j}^2}{2\bar{q}_{m,i,j}}\right],$$

$$\text{with } i = 1, 2, \ldots, M \quad \text{and } j = 1, 2, \ldots, L_i \qquad (8)$$

It was found that gold and silver in either synthetic solutions or real cyanide leach solutions follow a Freundlich isotherm during adsorption on active carbon. (*13, 14*):

$$q_{s,i,j} = AC_{s,i,j}^n \qquad \text{with } i = 1, 2, \ldots, M \text{ and } j = 1, 2, \ldots, L_i \qquad (9)$$

Such an isotherm, or any other appropriate equilibrium expression, should be used together with the equations above to predict the dynamics of a countercurrent adsorption cascade.

In the model explained here, the initial condition

$$\bar{q}_{m,i,j} = 0 = \bar{q}_{b,i,j} \text{ at } t = 0 \qquad (10)$$

causes the first derivative of $\bar{q}_{m,i,j}$ to become infinite at $t = 0$. Van Deventer (*13*) explained how a simple quadratic transformation of $\bar{q}_{m,i,j}$ could be used to solve this problem.

Equations (4) and (6)–(9) comprise a system of $2L_i$ algebraic and $(2L_i + 1)$ ordinary differential equations which can be solved simultaneously by means of a fourth-order Runge-Kutta-type routine for each tank i. Van Deventer (*17*) gives more details about the numerical solution of these equations. Such a numerical solution requires a great deal of computational effort, and this has to be considered in any decision to improve accuracy by increasing the number of loading intervals L_i.

The film transfer coefficient k_f can be estimated from the early adsorption period in batch runs under controlled mixing conditions. An isotherm expression can be determined from a set of suitable batch curves. The parameters for transport inside the carbon, i.e., $\bar{D}_s$, k_b, and α, can be estimated from a set of reliable batch data if the values of k_f, A, and

n are known. Jansen van Rensburg (*18*) explained the importance of water quality and the level of dissolved oxygen during the estimation of these parameters. Both these factors affect kinetic and especially equilibrium parameters. Results from a set of experiments with a constant level of dissolved oxygen and a specific quality of water cannot be extrapolated to predict the dynamics of another set of experiments where the feed has different characteristics.

SMALL-SCALE CIP RUNS

Continuous flow experiments were conducted in a cascade of five stirred tank reactors of individual volume 5.3 L in which a leached pulp flowed from one stage to the next by gravity. This configuration resembled that given in Fig. 1. A fine wire mesh of 350 μm in the overflow of a tank retained carbon inside the particular stage. Compressed air was periodically pulsed through the lower part of the screen to ensure that clogging of the screen did not restrict the flow of pulp, and to blow carbon particles on the screen back into the liquid. Both batch and continuous experiments were conducted in stirred tanks which were open to the atmosphere. The concentration of dissolved oxygen in the pulp was maintained at the saturation level of 8.2 mg/L in all stages. Consequently the compressed air had no effect on adsorption.

A downflow tube from one stage delivered overflow pulp to the bottom of the next stage in order to reduce short-circuiting of pulp. Pulp was fed from an agitated storage tank to the bottom of the first stage by a metering pump with variable flow rate setting. The flow rate was controlled manually to fluctuate by not more than 8%. All five stages were agitated by identical six-blade turbine impellers driven by Heidolph variable speed stirrers.

At the end of an adsorption cycle, agitation and flow to the cascade were terminated and a fraction β of the pulp and carbon in a stage was transferred to the previous stage after a fraction β of its carbon and pulp had been removed. Therefore, this transfer process had to start with Stage 1, where the carbon removed represented the final product. Virgin carbon was then fed into Stage 5. Batch kinetic data were measured by sealing off one of the stages in the cascade of five tanks.

The Le Carbone G210 AS coconut shell carbon used had an apparent density of 890 kg/m^3 and revealed particle sizes between 1.7 and 2.0 mm. The temperature of the pulp varied between 18 and 22°C during a run. Gold ore from a Witwatersrand gold mine was leached in an alkaline potassium cyanide solution for 5 days. The resultant pulp had a specific

gravity of 1.40, a mass fraction of solids of 0.49, a volumetric fraction of liquid ε of 0.715, and a pH of 8.9. The pulp contained solids which were 100% − 150 μm, 26% + 106 μm, and 39% − 75 μm. This considerable difference in particle size between the ore particles and the carbon caused interstage screening to be very effective. The solids fed to the CIP pilot plant as well as the solids in the tailings which left the cascade yielded a gold assay of 0.002 ppm. This indicates that the ore particles were inert during the adsorption process. In some practical CIP plants, further leaching still occurs in the adsorption section. Fine carbonaceous material and alumina, however, may serve as a sink for gold in CIP plants which treat reclaimed dump material. The ore used here was comprised mainly of quartz.

Table 1 indicates a number of species other than gold in the liquid phase of the feed pulp. At the low pH used, silver, copper, nickel, and iron usually form cyanide complexes which compete with gold cyanide for active sites on the carbon. Although calcium and magnesium have been found to enhance the loading of gold, the decomposition of cyanide on carbon could cause calcium carbonate to precipitate within the pores of the carbon. In this study it was assumed that the combined effect of these foreign species was merely a shift in the adsorption isotherm relative to the isotherm for pure gold cyanide.

Solution phase concentrations of gold were determined by atomic absorption spectrophotometry, while loadings of gold on the carbon were determined by x-ray fluorescence using a loose-powder technique. The gold content of the ore was determined by fire-assay.

TABLE 1
Liquid-Phase Composition of Cyanide Leached Pulp

Constituent	Concentration (ppm)
Au	8.3
Ag	0.6
Cu	24.1
Ni	8.1
Ca	363.8
Fe	3.7
Mg	2.8
Free CN^-	28.9

MODEL PREDICTIONS

Figure 2 shows batch kinetic data for five tests at a stirring speed of 240 rpm in the reactors, each containing 5.3 L of cyanide leach pulp. The concentration of gold in the liquid phase in these runs was followed until equilibrium was attained. The resultant equilibrium values and the best fit Freundlich expression are given in Fig. 3. This isotherm was used together with kinetic data obtained when 1.5 g of activated carbon was added to the pulp in order to estimate the following kinetic parameters for the adsorption of gold from this cyanide pulp:

$$\bar{D}_s = 1.15 \times 10^{-12}\ \mathrm{m^2/s}$$

$$k_h = 3.9 \times 10^{-6}\ \mathrm{s^{-1}}$$

$$\alpha = 0.59$$

$$k_f = 7.6 \times 10^{-5}\ \mathrm{m/s}$$

These parameters were then used to calculate the other curves in Fig. 2. Predicted curves are shown as solid lines. Excellent agreement was obtained between experimental and predicted values. The same parameters were also used to calculate predictions for the continuous countercurrent CIP runs.

Figures 4 and 6 show experimental and calculated values for the concentration of gold in the liquid phase and the loading of gold on the carbon during two continuous CIP runs in which different flow rates of carbon were used. Solution and carbon profiles are shown after 7 cycles

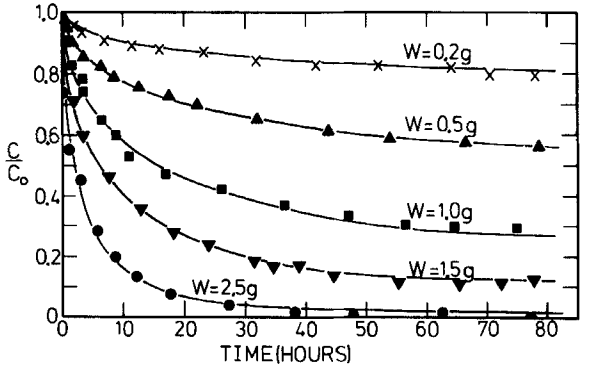

FIG. 2. Batch kinetic results for the adsorption of gold on activated carbon from cyanide leach pulp at a stirring speed of 240 rpm. V = 5.3 L.

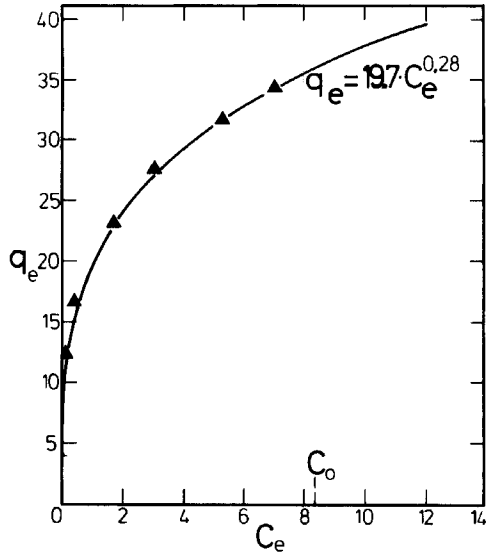

FIG. 3. Equilibrium adsorption of gold on activated carbon from cyanide leach pulp.

of operation. Again, reasonable agreement was obtained between calculated and experimental values.

Figure 5 shows the calculated loading distributions for carbon in the different stages after 7 cycles of operation under conditions similar to those used in Fig. 4. All these distributions are fairly narrow. This shows that the numerical solution is fairly insensitive to the number of discrete loading fractions under the conditions considered.

The simulations presented in this paper support the application of the model to a wide range of practical conditions. The next section presents a parametric sensitivity analysis of the model which is used to explain the factors which influence the efficiency of a CIP plant.

PARAMETRIC SENSITIVITY STUDY

Except where other parameter values are specifically mentioned, the following parameters were used to calculate the kinetic curves in Figs. 7 to 13:

$$k_f = 4.0 \times 10^{-5} \text{ m/s}$$
$$k_h = 2.0 \times 10^{-6} \text{ s}^{-1}$$

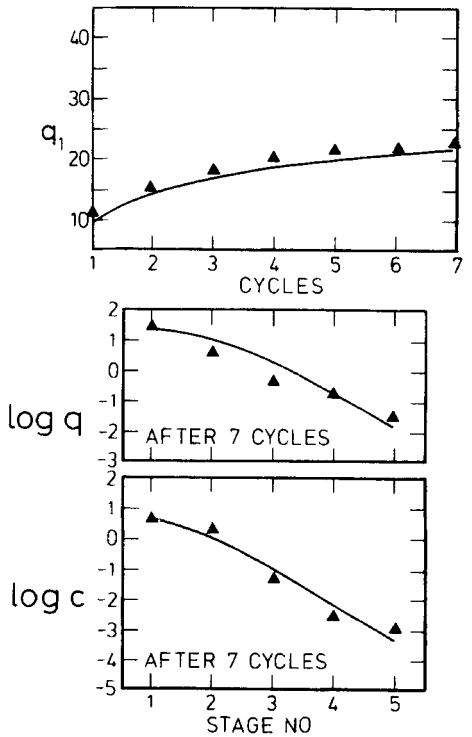

FIG. 4. Profile of loading of gold on carbon and concentration of gold in solution at Q = 4.44 L/h, W = 40 g, β = 0.4 g, and T = 16 h.

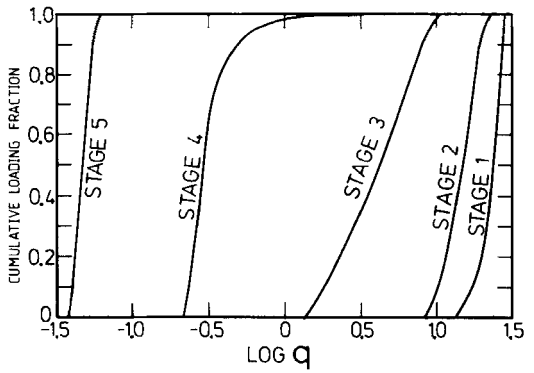

FIG. 5. Cumulative loading distributions in the different stages after 7 cycles with Q = 4.44 L/h, W = 40 g, β = 0.4, and T = 16 h.

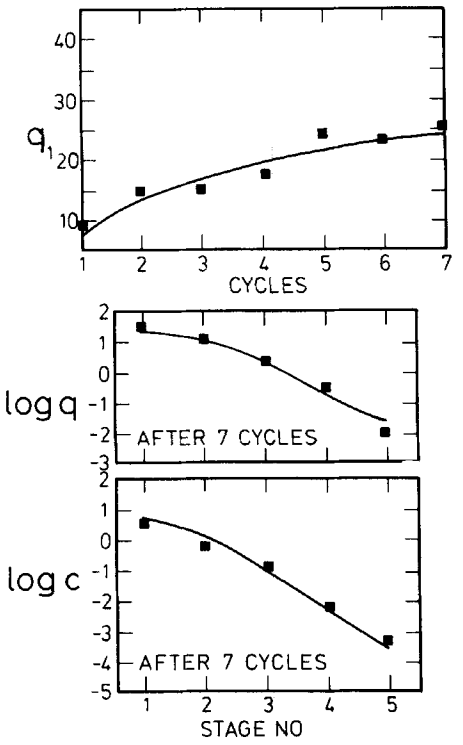

FIG. 6. Profile of loadings of gold on carbon and concentration of gold in solution at Q = 4.44 L/h, W = 50 g, β = 0.2, and T = 16 h.

$A = 50.0$
$d_p = 1.7 \times 10^{-3}$ m
$D_s = 3.0 \times 10^{-12}$ m^2/s
$\alpha = 0.40$
$n = 0.10$
$\rho_c = 900$ kg/m^3

In addition to these parameters, the following conditions were used in the continuous CIP model to calculate the curves in Figs. 7 to 13:

Concentration of gold in feed solution = 10 g/m^3
Volume of liquid in a stage = 5.3 L
Mass of carbon in a stage = 50 g
Volumetric flow rate of liquid = 5.3 L/h
Number of stages = 5

Fractional transfer of carbon = 0.5
Time of adsorption cycle = 24 h
Maximum number of loading fractions (to reduce calculation time) = 1

Mixing Conditions

Figure 7 shows that the film coefficient k_f has a greater influence on the final average loading on the carbon in Stage 1, q_1, during the earlier period of adsorption. It is well known that an increase in the rate of stirring increases the value of k_f up to a certain level, which depends on the particle size of carbon and the rheology of the slurry. Above $k_f = 4.0 \times 10^{-5}$ m/s, an increase in the value of k_f has no significant influence on the carbon and solution profiles. When a very low value of k_f is used, i.e., the carbon is not well suspended so that the thickness of the

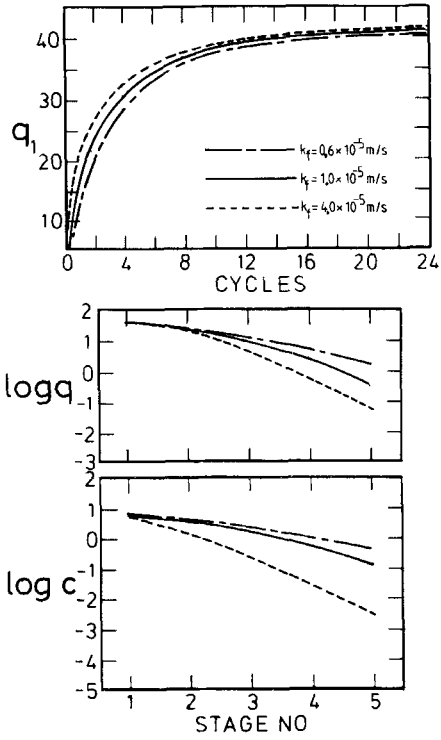

FIG. 7. Sensitivity of the countercurrent model to variations in the liquid film transfer coefficient, k_f.

liquid film is increased, a dramatic increase occurs in both the loading of adsorbate in the last stages and the concentration of adsorbate in the barren solution.

Although the loading in the first stage is determined by kinetic and equilibrium factors during an approach to steady state, only mass balance considerations determine the loading in the first stage at steady-state conditions. This means that mixing in the first stages could be less efficient while highly efficient mixing should occur in the last stages. Efficient mixing relates to the relative velocity between the carbon and the liquid phase.

This emphasizes the importance of predicting the value of k_f accurately during the design or scale-up of a CIP plant. In a complex system such as a CIP plant where both film diffusion and intraparticle resistance could control, it is not possible to lay down *a priori* levels of concentration above which one or the other mechanism would control.

Particle Size of Carbon

As shown in Eqs. (4) and (6), an increase in the diameter of the carbon particles decreases effectively the values of both k_f and $\bar{D}_s$, which could be expected to influence more the earlier period of adsorption. This is revealed during the attainment of equilibrium in Fig. 8, which shows behavior similar to that observed in Fig. 7. The final steady-state value of q_1 in Fig. 8 is, as expected, not affected by particle size. However, both the loading of adsorbate in the last stages of the plant and the concentration of adsorbate in the barren solution increase significantly when the particle size of carbon is increased. Improved screening efficiency could allow the use of smaller particles of carbon in a CIP plant, which could steepen profiles in the circuit.

Equilibrium Factors

Figures 9 and 10 show that variations in both equilibrium parameters A and n influence the final average carbon loading in Stage 1, q_1, more during the early period of adsorption and leave the pseudosteady-state value of q_1 unchanged. The reason for this is that the latter value is determined merely by material balancing considerations. The effect of an increase in the equilibrium loading capacity of the carbon on the operation of a countercurrent cascade appears to be similar to the effect which faster kinetics would have. Variations in A have a more pro-

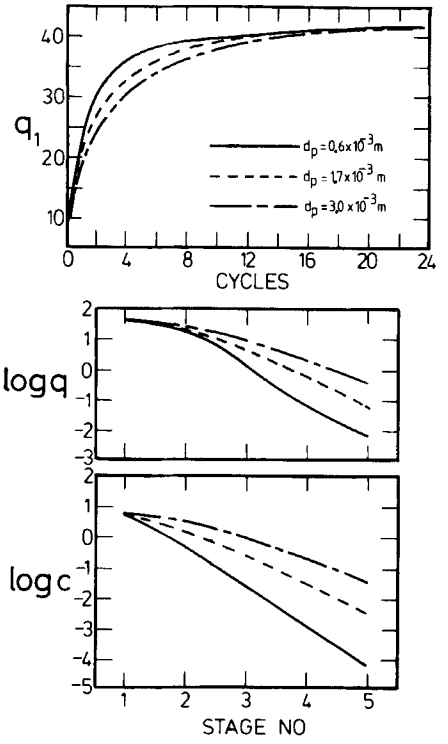

FIG. 8. Sensitivity of the countercurrent model to variations in the particle size of the carbon, d_p.

nounced effect on plant dynamics than have variations in n, which describes the shape of the isotherm. An increase in either A or n decreases the concentration of adsorbate in solution and the loading on the carbon in all the stages of the plant, except in the first stage.

Thermal regeneration is known to change not only the pore size distribution of the carbon but also the loading capacity (*19*). In general, the capacity of carbon to load gold cyanide increases with a decrease in pH, improved transfer of oxygen to the carbon, a lower concentration of free cyanide, lower temperatures, and lower concentration of competitive adsorbates such as water-miscible organics and base metal cyanides (*17–19*).

The effect of a change in the chemical composition of a pulp fed to a CIP plant could be quantified by fitting the model to data obtained from carefully planned laboratory batch kinetic tests. The parameters esti-

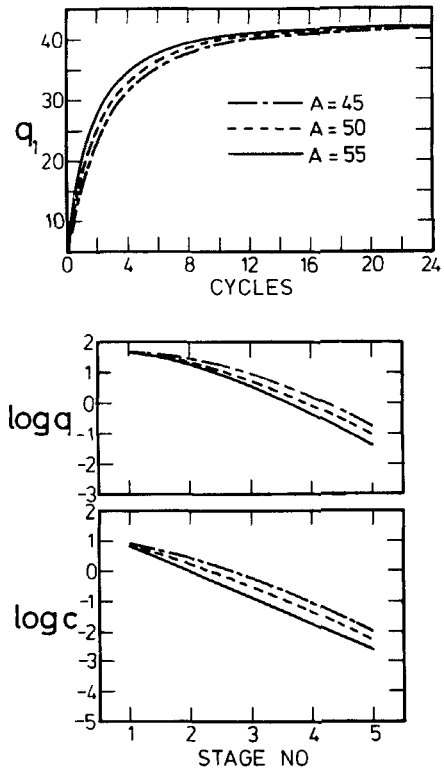

FIG. 9. Sensitivity of the countercurrent model to variations in the equilibrium parameter A.

mated from these tests may then be used to predict the change in the behavior of the full-scale plant.

Intraparticle Diffusion

Camby (*19*) observed than an increase in the temperature of steam regeneration of spent carbon increased not only the loading capacity but also the fraction of pores available as macropores. Furthermore, he observed enhanced transfer of adsorbed gold in the micropores at higher temperatures of regeneration. Fleming and Nicol (*20*) proposed that the blinding of the external surface of the carbon by slimes in the pulp, fine hematite in the calcine, or insoluble organics in the water will create an additional barrier to mass transfer. This could effectively reduce the

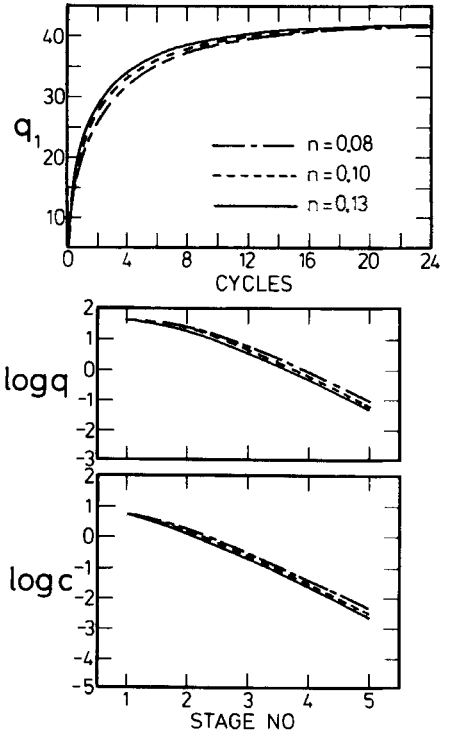

FIG. 10. Sensitivity of the countercurrent model to variations in the equilibrium parameter n.

values of $\bar{D}_s$ and α, which would then decrease the rate of diffusion of adsorbate into the carbon.

The sensitivity of the operation of a countercurrent adsorption cascade to variations in the intraparticle kinetic parameters $\bar{D}_s$, k_b, and α is illustrated in Figs. 11, 12, and 13. An increase in any of these parameters normally leads to a decrease in both the loading of adsorbate on the carbon and the concentration of adsorbate solution in all stages of the cascade, except in Stage 1. Plant dynamics appear to be more sensitive to changes in k_b than to changes in $\bar{D}_s$, especially where the kinetics in the two zones are significantly different. While the modified surface diffusion coefficient $\bar{D}_s$ influences the loadings in Stage 1 only during the first number of cycles, k_b and α exert their influence even after 24 cycles of operation for the conditions chosen.

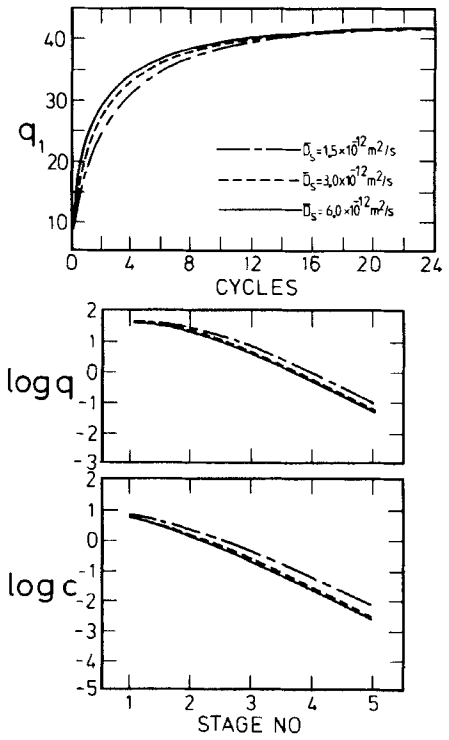

FIG. 11. Sensitivity of the countercurrent model to variations in the modified surface diffusion coefficient for transport in the macropores, $\bar{D}_s$.

Periodic Transfer of Carbon

Although carbon is sometimes transferred continuously (9), a fraction of the carbon inventory in each stage is usually removed at fixed intervals and air-lifted or pumped to the preceding stage. In some cases all the carbon in a stage is transferred during a cycle. A fraction of the pulp is then backmixed during the transfer of carbon.

Simulations were performed using different cycle durations, number of cycles, and fractions of inventory transferred. A total adsorption period of 576 h and a ratio of $T/\beta = 40$ were used.

Tables 2 and 3 show very little difference between the runs conducted with different values of β. As the value of β increases, the loadings on the carbon decrease slightly, while the concentration of adsorbate in solution increases slightly in all stages.

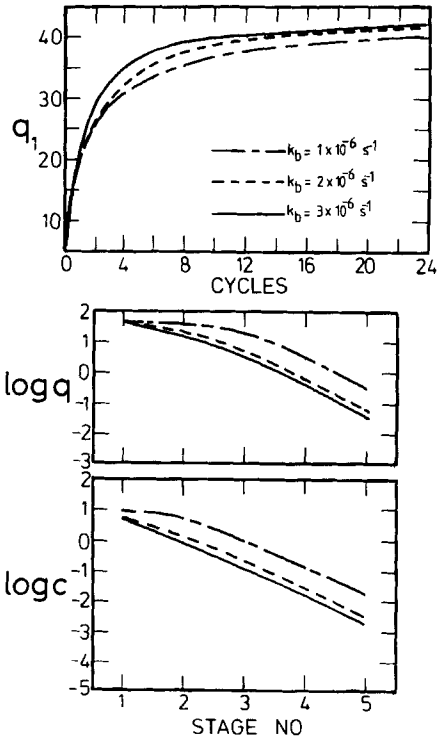

FIG. 12. Sensitivity of the countercurrent model to variations in the rate coefficient for transport in the micropores, k_b.

CONCLUSIONS

A dual rate kinetic model was used for the prediction of adsorption in a continuous countercurrent cascade used for the adsorption of gold onto activated carbon from a cyanided pulp. Kinetic and equilibrium parameters estimated from batch tests were shown to predict the behavior of a small-scale continuous CIP plant accurately. The model required no prespecified residence time distribution for the carbon phase.

Insufficient mixing, large diameters of the carbon particles, the presence of competitive adsorbates, high temperatures and pH values, insufficient regeneration of the carbon, a deficiency of dissolved oxygen, and the presence of insoluble organics and fine slime particles all act to increase the concentration of gold in the barren solution. Furthermore, these factors increase the loading of gold on the carbon in all stages, except in Stage 1, and retard the attainment of a pseudosteady state in the

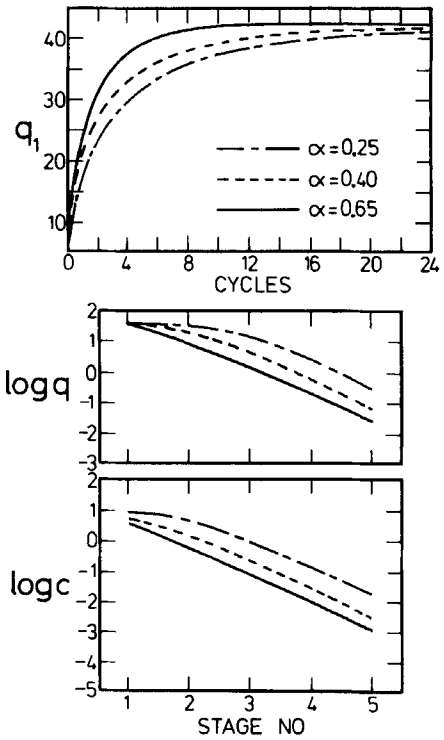

FIG. 13. Sensitivity of the countercurrent model to variations in the fraction of adsorptive capacity available as macropores, α.

TABLE 2
Effect of Fractional Transfer of Carbon on the Carbon Loading Profile (ppm) for $T/\beta = 48$

	Stage				
β	1	2	3	4	5
0.25	41,630	26,061	4227	565	72
0.50	41,531	24,972	3721	494	59
0.75	41,634	24,479	3595	481	61
1.00	41,598	23,720	3439	460	59

TABLE 3
Effect of Fractional Transfer of Carbon on the Solution Concentration Profile (g/m^3) for $T/\beta = 48$

	Stage				
β	1	2	3	4	5
0.25	6.933	1.356	0.182	0.024	0.003
0.50	7.276	1.407	0.189	0.025	0.003
0.75	7.421	1.498	0.201	0.027	0.004
1.00	7.500	1.532	0.206	0.028	0.004

plant. The sensitivity analysis further indicates that most parameters have the same effect on the shapes of the solution and carbon profiles. Variation of one parameter can be compensated by alterations in others.

The periodicity of the movement of carbon has an insignificant effect on the efficiency of a countercurrent adsorption cascade.

SYMBOLS

A	parameter in Freundlich isotherm expression
C	liquid phase concentration (g/m^3)
D_s	effective surface diffusion coefficient (m^2/s)
$\bar{D}_s$	modified surface diffusion coefficient (m^2/s)
d_p	carbon particle diameter (m)
k_b	micropore rate coefficient (s^{-1})
k_f	film transfer coefficient (m/s)
L_i	number of carbon loading intervals in Stage i
M	number of stages in cascade
n	Freundlich exponent
q	loading on the carbon (g/kg)
$\bar{q}$	average loading on the carbon (g/kg)
$(\bar{q}_{ave})_{i,max}$	maximum average loading in Stage i (g/kg)
Q	volumetric flow rate of pulp (m^3/s)
r	radial variable (m)
t	time variable (s)
T	duration of cycle (s)
V	volume of pulp in reactor (m^3)
W	mass of carbon in reactor (kg)
w_{ij}	mass of carbon in loading fraction j in Stage i

Greek Letters

α	fraction of loading capacity available as macropores
β	fraction of carbon transferred in a cycle
ε	volumetric fraction of pulp which is liquid
ρ_c	apparent carbon particle density (kg/m^3)
ϕ	loading distribution density function
$\Delta\phi_{i,j}$	discrete loading fraction

Subscripts

ave	average
b	micropores
e	equilibrium
i	number of stage in cascade
j	carbon loading fraction
m	macropores
s	liquid–carbon interface

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