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A model-based expert control system for the leaching process in zinc hydrometallurgy

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Abstract

One important step in zinc hydrometallurgy is the leaching process, which involves the dissolving of zinc-bearing material in dilute sulfuric acid to form a zinc sulfate solution. The key point in the control of the process is to determine the optimal pHs of the overflows of the continuous leach process and track them. This paper describes a model-based expert control system for the leaching process, which is being used in nonferrous metals smeltery. Specifically, steady-state mathematical models and rule models are first constructed based on the chemical reactions involved, the empirical knowledge of engineers and operators, and empirical data of the process. Then, a methodology is proposed for determining and tracking the optimal pHs with an expert control strategy based on a combination of mathematical models and rule models of the process. The results of actual runs show that the proposed control strategy is an effective way to control the leaching process. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Zinc hydrometallurgy; Leaching process; Expert control; Steady-state mathematical models; Rule models

1. Introduction

The main processes in zinc hydrometallurgy are leaching, purification and electrolysis (Mathewson, 1959; Zhuzhou Smeltery, 1973). Leaching involves dissolving zinc-bearing material in dilute sulfuric acid to form a zinc sulfate solution. Purification removes the impurities in this solution to make a satisfactory electrolyte. Finally, electrolysis is used to recover metallic zinc from the electrolyte as a high-purity product. The primary purpose of leaching is to dissolve as much of the soluble zinc in zinc-bearing material as possible. To achieve this, effective process control is imperative. Conventional control methods are based solely on mathematical models of the process. However, it is difficult to obtain the required performance by using these methods because of the complexity of the chemical reactions (Gui and Wu, 1995).

Recent advances in expert systems provide an effective way of controlling the leaching process. Since the 1980s, expert systems have been widely studied and applied to process control (Hayes-Roth et al., 1983; Jackson, 1986; Åström et al., 1986; Liebowitz and DeSalvo, 1989; Efstathiou, 1989; Gupta and Sinha, 1996). An expert system is a computer program that emulates the behavior of human experts within a specific well-defined domain of knowledge to solve a problem in the domain (Liebowitz, 1995). Such a system can be used to control a complex process possessing time-variance, nonlinearity and uncertainty factors if it is designed to perform control operations for the process (Cai et al., 1996). On the contrary, in the leaching process, complex relationships among the factors that cannot be expressed by mathematical models can be expressed by rule models. These rule models are based on the experience of experts and operators, and accumulated empirical knowledge of the process. Thus, the behavior of the process can be described by a combination of mathematical models and rule models. This makes it possible to control the process by expert control techniques.

The key problem in the control of the leaching process is to determine the optimal pHs of the overflows of the continuous leaches and to track them. Conventional control methods only track fixed pHs and make adjustments by adding dilute sulfuric acid to the process. The pHs are selected in advance. The amount of acid is determined solely on the basis of mathematical models obtained from the main chemical reaction equations. The mathematical models do not consider other chemical reactions, variations in the reaction conditions, or incompleteness of the reactions.

This paper describes a model-based expert control system for the leaching process (MECSL), which has been implemented in a nonferrous metals smeltery. MECSL solves the

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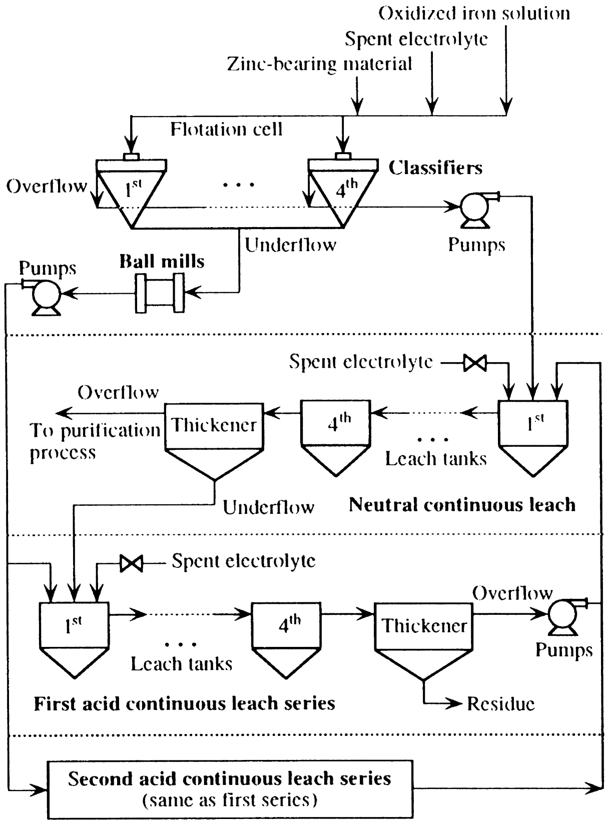


Fig. 1. Leaching process.

key problem in process control by using an expert control strategy based on a combination of steady-state mathematical models and rule models. Both types of models are based on the chemical reactions involved, the empirical knowledge of engineers and operators, and empirical data on the process. They fully considered the chemical nature and complexity of the process to maintain the optimal conditions for the chemical reactions. The results of some actual runs are presented at the end of this paper.

2. Process description and system architecture

The leaching process for which MECSL was designed uses neutral and acid continuous leach technology.

2.1. Process description and requirements

The leaching process is shown in Fig. 1 (Zhuzhou Smeltery, 1973). The process consists of one series of neutral leaches and two identical series of acid leaches. The zinc-bearing material is delivered to a flotation cell and mixed with an oxidized iron solution and spent electrolyte. This solution is delivered to four classifiers. The overflow is pumped to the 1st neutral leach tank, and the underflow is milled by four ball mills and pumped to the 1st tank of each acid leach series. The spent electrolyte, which contains sulfuric acid, is also added to the neutral and acid leaches. The main reaction in the tanks is

$$ZnO + H_2SO_4 = ZnSO_4 + H_2O. \qquad (1)$$

The solution is then sent to thickeners to settle. The overflow from the neutral leach is sent to the purification process in the form of a neutral zinc sulfate solution, and the underflow is added to the 1st tank of each acid leach series. The overflows from the acid leaches are pumped to the 1st tank of the neutral leach, and the residues are sent to the residue treatment process.

The concentrations of zinc and impurities in the neutral zinc sulfate solution from the neutral leach should satisfy the standards shown in Table 1. In addition, an important consideration in process control is to dissolve as much of the soluble zinc in the zinc-bearing material as possible. This requires optimal conditions for the chemical reactions. Generally, these conditions are influenced by many factors, such as the pH and temperature of the solution, the duration of the reaction, and the composition and particle size of the zinc-bearing material, etc. However, for steady-state operation, the main factor is the pHs of the overflows of the neutral and acid leaches. So, the key to process control is to determine the optimal pHs and to track them. Empirical knowledge and data on the process show that the pHs of the overflows have to be 4.8–5.2 for the neutral leach and 2.5–3.0 for the acid leaches to guarantee the optimal conditions.

2.2. Architecture of MECSL

MECSL uses the architecture shown in Fig. 2 to satisfy the above requirements. The main components are an expert controller (EC), three 761 series single-loop controllers, and an automatic measurement system (AMS). The EC is contained in an expert control computer system that is connected to the 761 controllers by using a special wiring concentrator and voltage converter, and to AMS by using a manufacturing automation protocol. Three control loops, that are composed of the 761 controllers, the inverters, the pumps and the flow meters, are constructed for the neutral and acid leaches.

The pHs of overflows of the neutral and acid leaches are controlled by adding the spent electrolyte to the neutral and acid continuous leaches. The flow rates of the spent

Table 1
Standard allowable ranges of concentrations of metallic elements in neutral zinc sulfate solution (mg/l)

Zn	Cu	Cd	Co	Ni	As	Sb	Ge	Fe
140 000 –170 000	< 450	< 1000	< 25	< 15	< 1	< 0.5	< 0.5	< 35

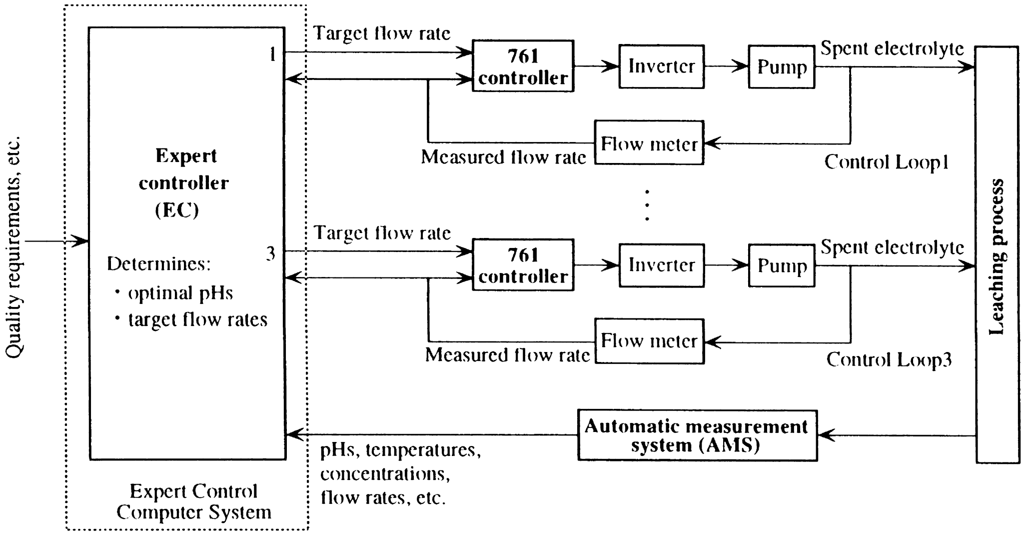


Fig. 2. Architecture of MECSL.

electrolyte, which are the control inputs of the process, are regulated by controlling the speed of the pumps through the inverters.

EC uses a reasoning strategy that combines forward chaining and model-based reasoning to determine the optimal pHs, and computes the target flow rates of the spent electrolyte that correspond to the optimal pHs, so as to achieve the optimal reaction conditions. The reasoning strategy is based on a combination of mathematical models and rule models of the process. The three 761 controllers track the target flow rates through PI control algorithms to ensure that the actual pHs match the optimal values.

AMS consists of pH meters, temperature meters, automatic concentration analyzers, and flow meters, etc. It performs on-line measurement of the pHs, temperatures, concentrations and flow rates etc.

3. Steady-state mathematical models and rule models

Leaching can be considered to be a steady-state chemical process because it is generally run within a specific operating range. Hence, the behavior of the process can be described with a combination of steady-state mathematical models and rule models. The mathematical models are based on both the chemical reactions involved and empirical data on the process, and are modified in accordance with the empirical knowledge of engineers and operators and empirical data on the process. Production rule models of the If–Then form are used to represent the empirical knowledge on the process.

3.1. Steady-state mathematical models

The steady-state mathematical models are based on the following assumptions:

1. The zinc-bearing material and the solution in the neutral and acid leach tanks are agitated and completely mixed.
2. The temperature of the solution is uniform.
3. The chemical reactions occur mainly in the leach tanks.

The mass balance principle (e.g. Inugita and Nakanishi, 1987) yields the following dynamic balance equation for the sulfuric acid in the neutral leach:

$$\varepsilon_N V_N \frac{dx_{Nh}}{dt} = F_{Co}(x_{Nh} - x_{Ch}) + F_{Ne}(x_{Nh} - x_{Nhe}) + \sum_{i=1}^{2} F_{iAo}(x_{Nh} - x_{iAh}) - \int_0^{V_N} r_{Nh} dV_N, \qquad (2)$$

where x_{Nh}, x_{Ch} and x_{iAh} are the concentrations of sulfuric acid in the solutions after the neutral leach, the classifiers and the ith acid leach series, respectively; x_{Nhe} is the concentration of sulfuric acid in the spent electrolyte added to the neutral leach; F_{Co} and F_{iAo} are the flow rates of the overflows from the classifiers and the ith acid leach series, respectively; F_{Ne} is the flow rate of the spent electrolyte added to the neutral leach; V_N is the total volume of the neutral leach tanks; ε_N is the ratio of liquid to solid in the solution in the neutral leach; and r_{Nh} is the reaction rate of sulfuric acid.

For steady-state operation, r_{Nh} is the steady-state reaction rate, so Eq. (2) becomes

$$F_{Ne}(x_{Nh} - x_{Nhe}) = r_{Nh} V_N - F_{Co}(x_{Nh} - x_{Ch}) - \sum_{i=1}^{2} F_{iAo}(x_{Nh} - x_{iAh}). \qquad (3)$$

Let f_{Nzo} denote the steady-state particle reaction rate of zinc oxide with sulfuric acid and x_{Czo} denote the concentration of zinc oxide in the overflow from the classifiers. Then,

$$\frac{M_{\mathrm{ZnO}}}{M_{\mathrm{H_2SO_4}}} r_{\mathrm{Nh}} = F_{\mathrm{Co}} x_{\mathrm{Czo}} f_{\mathrm{Nzo}} \tag{4}$$

is obtained for the zinc oxide in the neutral leach by the principle of steady-state mass balance, where M_{ZnO} and $M_{\mathrm{H_2SO_4}}$ are the molecular weights of zinc oxide and sulfuric acid, respectively. X_{Czo} can be computed from

$$x_{\mathrm{Czo}} = \eta_{\mathrm{Czo}} \mu_{\mathrm{Czb}} \frac{1}{1 + k_{\mathrm{Co}}}, \tag{5}$$

where η_{Czo} is the zinc oxide content of the zinc-bearing material; μ_{Czb} is the specific gravity of the zinc-bearing material; and k_{Co} is the ratio of liquid to solid in the overflow from the classifiers.

Combining Eqs. (3), (4) and (5) yields

$$F_{\mathrm{Ne}} = \frac{1}{x_{\mathrm{Nh}} - x_{\mathrm{Nhe}}} \left[K_{\mathrm{Nh}} \frac{F_{\mathrm{Co}}}{1 + k_{\mathrm{Co}}} f_{\mathrm{Nzo}} - F_{\mathrm{Co}} \left(x_{\mathrm{Nh}} - x_{\mathrm{Ch}} \right) - \sum_{i=1}^{2} F_{i\mathrm{Ao}} \left(x_{\mathrm{Nh}} - x_{i\mathrm{Ah}} \right) \right], \tag{6}$$

where

$$K_{\mathrm{Nh}} = \frac{M_{\mathrm{H_2SO_4}}}{M_{\mathrm{ZnO}}} \eta_{\mathrm{Czo}} \mu_{\mathrm{Czb}} V_{\mathrm{N}}. \tag{7}$$

f_{Nzo} can be estimated based on the experience of experts and operators and accumulated empirical knowledge on the neutral leach process. Using this estimate, $\hat{f}_{\mathrm{Nzo}}$, in Eq. (6) yields

$$F_{\mathrm{Ne}} = \frac{1}{x_{\mathrm{Nh}} - x_{\mathrm{Nhe}}} \left[K_{\mathrm{Nh}} \frac{F_{\mathrm{Co}}}{1 + k_{\mathrm{Co}}} \hat{f}_{\mathrm{Nzo}} - F_{\mathrm{Co}} \left(x_{\mathrm{Nh}} - x_{\mathrm{Ch}} \right) - \sum_{i=1}^{2} F_{i\mathrm{Ao}} \left(x_{\mathrm{Nh}} - x_{i\mathrm{Ah}} \right) \right]. \tag{8}$$

This is the steady-state mathematical model for determining the flow rate of the spent electrolyte added to the neutral leach.

The same method is used to obtain the flow rates of the spent electrolyte added to the acid leaches. Let $F_{i\mathrm{Ae}}$ denote the flow rate of the spent electrolyte added to the ith acid leach series. Then,

$$F_{i\mathrm{Ae}} = \frac{1}{x_{i\mathrm{Ah}} - x_{i\mathrm{Ahe}}} \left[K_{i\mathrm{Ah}} \frac{F_{i\mathrm{Cu}}}{1 + k_{\mathrm{Cu}}} \hat{f}_{i\mathrm{Azo}} - F_{i\mathrm{Cu}} \left(x_{i\mathrm{Ah}} - x_{\mathrm{Ch}} \right) - F_{i\mathrm{Nu}} \left(x_{i\mathrm{Ah}} - x_{\mathrm{Nh}} \right) \right], \tag{9}$$

where

$$K_{i\mathrm{Ah}} = \frac{M_{\mathrm{H_2SO_4}}}{M_{\mathrm{ZnO}}} \eta_{\mathrm{Czo}} \mu_{\mathrm{Czb}} V_{i\mathrm{A}}, \tag{10}$$

$x_{i\mathrm{Ahe}}$ is the concentration of sulfuric acid in the spent electrolyte added to the ith acid leach series; $F_{i\mathrm{Cu}}$ and $F_{i\mathrm{Nu}}$ are the flow rates of the underflows from the classifiers and the neutral continuous leach that are added to the ith acid leach series, respectively; $V_{i\mathrm{A}}$ is the total volume of the tanks in the ith acid leach series; $\hat{f}_{i\mathrm{Azo}}$ is the estimated steady-state particle reaction rate for zinc oxide with sulfuric acid in the ith acid leach series; and k_{Cu} is the ratio of liquid to solid in the underflow from the neutral continuous leach.

Eqs. (8) and (9) are taken as nominal steady-state mathematical models because they only concern the chemical reaction occuring in Eq. (1). However, there are also other chemical reactions and factors that influence the process. For these reasons, models (8) and (9) need to be modified by empirical knowledge and data on the process.

Let $x^{\mathrm{g}}_{\mathrm{Nh}}$ and $x^{\mathrm{g}}_{i\mathrm{Ah}}$ denote the target concentrations of sulfuric acid in the solution after the neutral leach and the ith acid leach series. From empirical knowledge, the target flow rates $F^{\mathrm{g}}_{\mathrm{Ne}}(k)$ and$F^{\mathrm{g}}_{i\mathrm{Ae}}(k)$ of the spent electrolyte added to the neutral leach and the ith acid leach series during the kth period are given by

$$F^{\mathrm{g}}_{\mathrm{Ne}}(k) = \alpha_{\mathrm{N}}(k) F_{\mathrm{Ne}}(k) + \sum_{l=0}^{k} \beta_{\mathrm{N}}(l) \Delta x_{\mathrm{Nh}}(k), \tag{11a}$$

$$\Delta x_{\mathrm{Nh}}(k) = x^{\mathrm{g}}_{\mathrm{Nh}} - x_{\mathrm{Nh}}(k), \tag{11b}$$

$$F_{\mathrm{Ne}}(k) = \frac{1}{x^{\mathrm{g}}_{\mathrm{Nh}} - x_{\mathrm{Nhe}}(k)} \left[K_{\mathrm{Nh}}(k) \frac{F_{\mathrm{Co}}(K)}{1 + k_{\mathrm{Co}}(k)} \hat{f}_{\mathrm{Nzo}}(k) - F_{\mathrm{Co}}(k)(x^{\mathrm{g}}_{\mathrm{Nh}} - x_{\mathrm{Ch}}(k)) - \sum_{i=1}^{2} F_{i\mathrm{Ao}}(k)(x^{\mathrm{g}}_{\mathrm{Nh}} - x_{i\mathrm{Ah}}(k)) \right]; \tag{11c}$$

$$F^{\mathrm{g}}_{i\mathrm{Ae}}(k) = \alpha_{i\mathrm{A}}(k) F_{i\mathrm{Ae}}(k) + \sum_{l=0}^{k} \beta_{i\mathrm{A}}(l) \Delta x_{i\mathrm{Ah}}(k), \tag{12a}$$

$$\Delta x_{i\mathrm{Ah}}(k) = x^{\mathrm{g}}_{i\mathrm{Ah}} - x_{i\mathrm{Ah}}(k), \tag{12b}$$

$$F_{i\mathrm{Ae}}(k) = \frac{1}{x^{\mathrm{g}}_{i\mathrm{Ah}} - x_{i\mathrm{Ahe}}(k)} \left[K_{i\mathrm{Ah}}(k) \frac{F_{i\mathrm{Cu}}(k)}{1 + k_{\mathrm{Cu}}(k)} \hat{f}_{i\mathrm{Azo}}(k) - F_{i\mathrm{Cu}}(k)(x^{\mathrm{g}}_{i\mathrm{Ah}} - x_{\mathrm{Ch}}(k)) - F_{i\mathrm{Nu}}(k)(x^{\mathrm{g}}_{i\mathrm{Ah}} - x_{\mathrm{Nh}}(k)) \right], \tag{12c}$$

where $\alpha_{\mathrm{N}}(k)$, $\beta_{\mathrm{N}}(l)$, $\alpha_{i\mathrm{A}}(k)$ and $\beta_{i\mathrm{A}}(l)$ are empirical coefficients determined from empirical knowledge.

Assume that C_{Nopt} and $C_{i\mathrm{Aopt}}$ are the optimal pHs of the overflows from the neutral leach and the ith acid leach series. The following expressions are used to obtain $x^{\mathrm{g}}_{\mathrm{Nh}}$ and $x^{\mathrm{g}}_{i\mathrm{Ah}}$ from C_{Nopt} and $C_{i\mathrm{Aopt}}$, respectively:

$$x^{\mathrm{g}}_{\mathrm{Nh}} = \frac{M_{\mathrm{H_2SO_4}}}{2M_{\mathrm{H}}} 10^{(7 - C_{\mathrm{Nopt}})} \tag{13}$$

$$x^{g}_{iAh} = \frac{M_{H_2SO_4}}{2M_H} 10^{(7-C_{iAopt})}, \tag{14}$$

where M_H is the atomicity of hydrogen. Let C_{Ch}, C_{Nh} and C_{iAh} denote the pHs of the solutions from the classifiers and the neutral and acid leaches, respectively. Then x_{Ch}, x_{Nh} and x_{iAh} can be computed from C_{Ch}, C_{Nh} and C_{iAh}, respectively, by using expressions that have the same form as Eqs. (13) and (14).

Eqs. (11a)–(11c) and (12a)–(12c) are modified steady-state mathematical models of the leaching process that are used to determine the target flow rates of the spent electrolyte added to the neutral and acid leaches.

3.2. Rule models

The optimal pHs are mainly related to the following factors:

1. The composition and particle size of the zinc-bearing material.
2. The temperature of the solution.
3. The concentrations of zinc and impurities in the overflows from the neutral and acid leaches.

However, it is difficult to express the exact relationships among the optimal pHs and these factors by mathematical models alone. To obtain the optimal pHs and the corresponding target flow rates, empirical knowledge and data on the process are needed. They are represented by production rule models of the following form (Hayes-Roth et al., 1983; Jackson, 1986; Efstathiou, 1989; Ishiduka and Kobayashi, 1991)

$$R^{\#}: \text{ If } \textit{condition} \text{ Then } \textit{action}, \tag{15}$$

where $R^{\#}$ is the number of the rule model, *condition* is the operating state of the process or a logical combination, and *action* is the conclusion or operation.

How empirical knowledge and data on the process is obtained is an important aspect of the construction of rule models. Empirical knowledge is culled from engineers and operators. The following empirical methods were extracted from interviews with them:

1. Method of determining the optimal pHs from the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of zinc and impurities in the overflows from the neutral and acid leaches.
2. Method of determining $\alpha_N(k)$, $\beta_N(k)$, $\alpha_{iA}(k)$, $\beta_{iA}(k)$, $\hat{f}_{Nzo}(k)$ and $\hat{f}_{iAzo}(k)$ from the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of sulfuric acid in the overflows of the neutral and acid leaches and in the solutions added to the neutral and acid leach tanks.

The empirical data were culled from past operating runs, measured values and statistical data on the process. This kind of data contains statistical data on the relationships among the optimal pHs, the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of zinc and impurities in the overflows from the neutral and acid leaches, etc. It is also a key to determining the optimal pHs and the appropriate target flow rates.

The main content of the *condition* part of form (15) is:

1. The composition and particle size of the zinc-bearing material (which are divided into *m* and *n* levels, respectively).
2. The temperature of the solution (high, medium, low, and not in the allowable range).
3. The concentrations of zinc and impurities in the overflows from the neutral and acid leaches (large, medium, small, and not in the allowable range).
4. The concentrations of sulfuric acid in the solutions added to the neutral and acid leaches (large, medium and small).
5. The pHs of the solutions from the classifiers, and from the neutral and acid leaches (large, medium, small, and not in the allowable range).
6. The flow rates of the spent electrolyte added to the neutral and acid leaches (large, medium and small).

The main content of the *action* part is instructions to select the optimal pHs, and increase, reduce or maintain the target flow rates.

The optimal pHs are obtained from an expert decision table (EDT) and an expert turning mechanism (ETM) that show the relationships among the optimal pHs, the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of zinc and impurities in the overflows from the neutral and acid leaches. EDT and ETM are constructed based on empirical knowledge and data on the process. Fig. 3 shows a flow chart for determining the optimal pHs, where f_c and f_{ps} denote the levels of the composition and particle size of the zinc-bearing material; f_t denotes the level of the temperature of the solution; f_{Ncz}, f_{Nci}, f_{iAcz} and f_{iAci} denote the levels of the concentrations of zinc and impurities in the overflows from the neutral leach and the *i*th acid leach series, respectively; and C_N and C_{iA} are the initial values

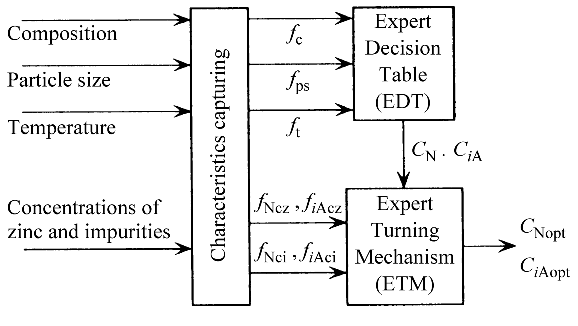


Fig. 3. Flow chart for determining optimal pHs.

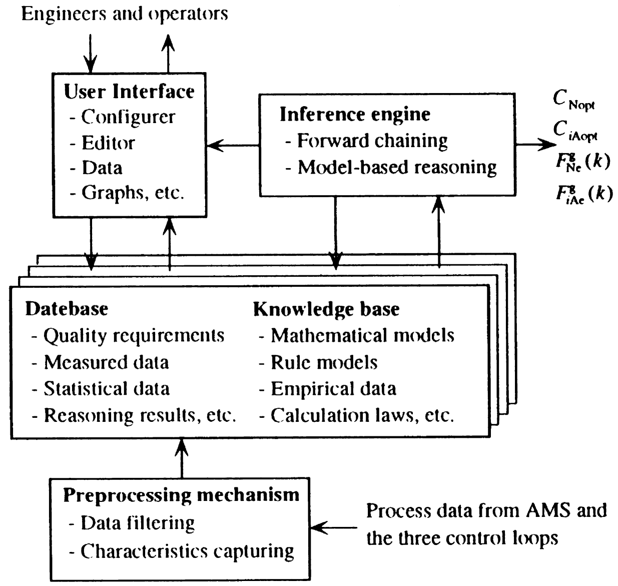


Fig. 4. Structure of EC.

of C_{Nopt} and $C_{i\mathrm{Aopt}}$, respectively. It is clear that the optimal pHs are determined in two steps:

1. C_{N} and $C_{i\mathrm{A}}$ are obtained by EDT from f_{c}, f_{ps} and f_{t}.
2. C_{Nopt} is obtained by turning C_{N} from f_{Ncz} and f_{Nci}, and $C_{i\mathrm{Aopt}}$ is obtained by turning $C_{i\mathrm{A}}$ from $f_{i\mathrm{Acz}}$ and $f_{i\mathrm{Aci}}$.

It is also assumed that a smaller f_{c} and f_{ps} correspond to a lower soluble zinc rate and a smaller particle size of the zinc-bearing material, respectively. EDT and ETM must be constructed so as to conform to basic rules 1 and 2, respectively:

1. C_{N} and $C_{i\mathrm{A}}$ increase as f_{c} or f_{t} decreases, or f_{ps} increases.
2. C_{Nopt} and $C_{i\mathrm{Aopt}}$ increase as f_{Ncz} and $f_{i\mathrm{Acz}}$ decrease or f_{Nci} and $f_{i\mathrm{Aci}}$ increase, respectively.

Based on the above basic rules and empirical knowledge and data on the process, rule models for determining the optimal pHs are constructed. For example, in the designed system, $m = 10$ and $n = 8$, and some rule models are as follows:

R^{N1}: If $f_{\mathrm{c}} = 1$ and $f_{\mathrm{ps}} = 1$ and $f_{\mathrm{t}} =$ high
Then $C_{\mathrm{N}} = C_{\mathrm{Nllh}}$,
R^{N2}: If $f_{\mathrm{c}} = 3$ and $f_{\mathrm{ps}} = n$ and $f_{\mathrm{t}} =$ medium
Then $C_{\mathrm{N}} = C_{\mathrm{N3nm}}$,
R^{N3}: If $f_{\mathrm{c}} = m$ and $f_{\mathrm{ps}} = 2$ and $f_{\mathrm{t}} =$ low
Then $C_{\mathrm{N}} = C_{\mathrm{Nm2l}}$,
R^{N4}: If $f_{\mathrm{Ncz}} =$ large
Then $C_{\mathrm{Nopt}} = C_{\mathrm{N}} + \Delta C_{\mathrm{Nzl}}$,
R^{N5}: If $f_{\mathrm{Ncz}} =$ small
Then $C_{\mathrm{Nopt}} = C_{\mathrm{N}} + \Delta C_{\mathrm{Nzs}}$,
R^{N6}: If $f_{\mathrm{Nci}} =$ large
Then $C_{\mathrm{Nopt}} = C_{\mathrm{N}} - \Delta C_{\mathrm{Nil}}$,
$R^{i\mathrm{A1}}$: If $f_{\mathrm{c}} = 1$ and $f_{\mathrm{ps}} = 1$ and $f_{\mathrm{t}} =$ medium
Then $C_{i\mathrm{A}} = C_{i\mathrm{Allm}}$,
$R^{i\mathrm{A2}}$: If $f_{\mathrm{c}} = 4$ and $f_{\mathrm{ps}} = 5$ and $f_{\mathrm{t}} =$ low
Then $C_{i\mathrm{A}} = C_{i\mathrm{A451}}$,
$R^{i\mathrm{A3}}$: If $f_{\mathrm{c}} = m$ and $f_{\mathrm{ps}} = n$ and $f_{\mathrm{t}} =$ high
Then $C_{i\mathrm{A}} = C_{i\mathrm{Amnh}}$,
$R^{i\mathrm{A4}}$: If $f_{i\mathrm{Acz}} =$ medium
Then $C_{i\mathrm{Aopt}} = C_{i\mathrm{A}} + \Delta C_{i\mathrm{Azm}}$,
$R^{i\mathrm{A5}}$: If $f_{i\mathrm{Aci}} =$ medium
Then $C_{i\mathrm{Aopt}} = C_{i\mathrm{A}} - \Delta C_{i\mathrm{Aim}}$,
$R^{i\mathrm{A6}}$: If $f_{i\mathrm{Aci}} =$ small
Then $C_{i\mathrm{Aopt}} = C_{i\mathrm{A}} - \Delta C_{i\mathrm{Ais}}$

where C_{Nllh}, C_{N3nm}, C_{Nm2l}, ΔC_{Nz1}, ΔC_{Nzs}, ΔC_{Nil}, $C_{i\mathrm{Allm}}$, $C_{i\mathrm{A451}}$, $C_{i\mathrm{Amnh}}$, $\Delta C_{i\mathrm{Azm}}$, $\Delta C_{i\mathrm{Alm}}$, and $\Delta C_{i\mathrm{Ais}}$ are empirically determined positive values.

$\alpha_{\mathrm{N}}(k)$, $\beta_{\mathrm{N}}(k)$, $\alpha_{i\mathrm{A}}(k)$, $\beta_{i\mathrm{A}}(k)$, $\hat{f}_{\mathrm{Nzo}}(k)$ and $\hat{f}_{i\mathrm{Azo}}(k)$ are determined from f_{c}, f_{ps}, f_{t} and the concentrations of sulfuric acid in the overflows of the neutral and acid leaches and in the solutions added to the neutral and acid leaches by a method and rule models similar to those for the optimal pHs.

4. Expert controller structure and control algorithms

EC is designed to determine the optimal pHs and the target flow rates based on the mathematical and rule models.

4.1. Structure of EC

The structure of EC is shown in Fig. 4. It consists of a preprocessing mechanism, database, knowledge base, inference engine and user interface.

The preprocessing mechanism filters and captures the characteristics of process data from AMS and the three control loops, i.e., it obtains all the content of the *condition* parts of form (15).

The preprocessed data are stored in the database, which also holds the quality requirements for the neutral zinc sulfate solution, measured and statistical data on the process, the reasoning results from the inference engine, etc.

The knowledge base stores the modified steady-state mathematical models, rule models, empirical data, calculation laws, etc.

The inference engine acquires data from the database, and then uses both the knowledge in the knowledge base and a reasoning strategy that combines forward chaining (Hayes-Roth et al., 1983; Jackson, 1986; Efstathiou, 1989) and model-based reasoning (Ishiduka and Kobayashi, 1991) to determine the optimal pHs and target flow rates. The target flow rates are sent to the 761 controllers.

The user interface is used to configure and edit the knowledge base, and to display and print data, graphs, reasoning results, etc.

From the view of control, EC can be considered to be an expert controller composed of two-degree-of-freedom

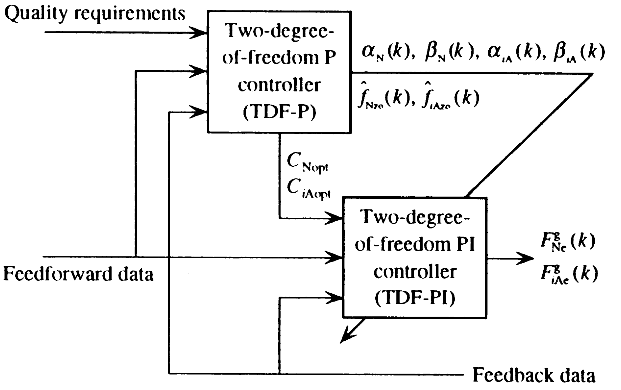


Fig. 5. Structure of EC from the control standpoint.

(TDF) P and PI controllers with variable gains. The structure of EC is shown in Fig. 5. The inputs of TDF-P are:

1. Quality requirements for the neutral zinc sulfate solution obtained from the neutral leach.
2. Feedforward data such as the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of sulfuric acid in the solutions added to the neutral and acid leaches.
3. Feedback data such as the concentrations of zinc, sulfuric acid and impurities in the overflows of the neutral and acid leaches.

The inputs of TDF-PI are:

1. The optimal pHs, which are the reference inputs of the controller.
2. Feedforward data, which are mainly the concentrations of sulfuric acid in the solutions and the flow rates of the solutions that is added to the neutral and acid leaches.
3. Feedback data such as the pHs of the overflows of the neutral and acid leaches.

In fact, TDF-P and TDF-PI are nonlinear controllers. The outputs of TDF-P are the optimal pHs C_{Nopt} and $C_{i\mathrm{Aopt}}$, the gains $\alpha_N(k)$, $\beta_N(k)$, $\alpha_{i\mathrm{A}}(k)$ and $\beta_{i\mathrm{A}}(k)$ of TDF-PI, and the steady-state particle reaction rates $\hat{f}_{\mathrm{Nzo}}(k)$ and $\hat{f}_{i\mathrm{Azo}}(k)$. They are obtained by firing rule models such as R^{N1}–R^{N6} and $R^{i\mathrm{Al}}$–$R^{i\mathrm{A6}}$, and may be different in every sampling period. Based on the optimal pHs and the gains, TDF-PI uses the steady-state mathematical models (11) and (12) to obtain the target flow rates of the spent electrolyte added to the neutral and acid leaches.

TDF-P is based on rule models and TDF-PI is based on steady-state mathematical models and rule models.

4.2. Algorithms for determining optimal pHs and target flow rates

The expert control strategy for the leaching process has four steps:

1. Determine the optimal pHs C_{Nopt} and $C_{i\mathrm{Aopt}}$.
2. Select the controller gains $\alpha_N(k)$, $\beta_N(k)$, $\alpha_{i\mathrm{A}}(k)$ and $\beta_{i\mathrm{A}}(k)$, and the steady-state particle reaction rates $\hat{f}_{\mathrm{Nzo}}(k)$ and $\hat{f}_{i\mathrm{Azo}}(k)$.
3. Determine the target flow rates $F^{\mathrm{g}}_{\mathrm{Ne}}(k)$ and $F^{\mathrm{g}}_{i\mathrm{Ae}}(k)$.
4. Track $F^{g}_{\mathrm{Ne}}(k)$ and $F^{\mathrm{g}}_{i\mathrm{Ae}}(k)$.

EC performs steps (1)–(3), i.e. it determines the optimal pHs and the target flow rates through a combination of the modified mathematical models and rule models of the process and by using forward chaining and model-based reasoning. Algorithms 1 and 2 below were developed to determine the optimal pHs and target flow rates.

Algorithm 1 (Determines pHs):

1. Compute f_{c}, f_{ps} and f_{t} from the composition and particle size of the zinc-bearing material, and the temperature of the solution, respectively.
2. Determine C_{N} and $C_{i\mathrm{A}}$ by rule models such as $R^{\mathrm{N1}} - R^{\mathrm{N3}}$ and $R^{i\mathrm{A1}} - R^{i\mathrm{A3}}$, respectively.
3. Compute f_{Ncz}, f_{Nci}, $f_{i\mathrm{Acz}}$ and $f_{i\mathrm{Aci}}$ from the concentrations of zinc and impurities in the overflows from the neutral and acid leaches.
4. Determine C_{Nopt} and $C_{i\mathrm{Aopt}}$ by rule models such as $R^{\mathrm{N4}} - R^{\mathrm{N6}}$, and $R^{i\mathrm{A4}} - R^{i\mathrm{A6}}$, respectively.

Algorithm 2 (Determines target flow rates):

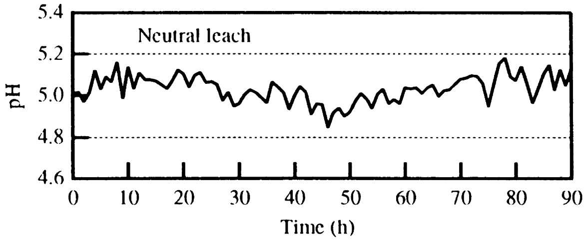
1. Select $\alpha_{\mathrm{N}}(k)$, $\beta_{\mathrm{N}}(k)$, $\alpha_{i\mathrm{A}}(k)$ and $\beta_{i\mathrm{A}}(k)$, $\hat{f}_{\mathrm{Nzo}}(k)$ and $\hat{f}_{i\mathrm{Azo}}(k)$ based on f_{c}, f_{ps} and f_{t} as well as the concentrations of sulfuric acid in the overflows of the neutral and acid leaches and in the solutions added to the neutral and acid leaches by using a method similar to that of algorithm 1.
2. Obtain C_{Ch}, C_{Nh} and $C_{i\mathrm{Ah}}$, and also $k_{\mathrm{Co}}(k)$ and $\mathrm{k}_{\mathrm{Cu}}(k)$, from AMS.
3. Compute $x^{\mathrm{g}}_{\mathrm{Nh}}$ and $x^{\mathrm{g}}_{i\mathrm{Ah}}$ from C_{Nopt} and $C_{i\mathrm{Aopt}}$ using Eqs. (13) and (14), respectively, and also $x_{\mathrm{Ch}}(k)$, $\mathrm{x}_{\mathrm{Nh}}(k)$ and $\mathrm{x}_{i\mathrm{Ah}}(k)$ from C_{Ch}, C_{Nh} and $C_{i\mathrm{Ah}}$, respectively, using expressions that have the same form as Eqs. (13) and (14).
4. Determine the target flow rates $F^{\mathrm{g}}_{\mathrm{Ne}}(k)$ and $F^{\mathrm{g}}_{i\mathrm{Ae}}(k)$ from mathematical models (11) and (12). If the values are outside the allowable range, they are set to an allowable value by firing suitable rule models.

Algorithm 1 and step 1 of algorithm 2 are carried out by TDF-P. Steps 2–4 of algorithm 2 are carried out by TDF-PI.

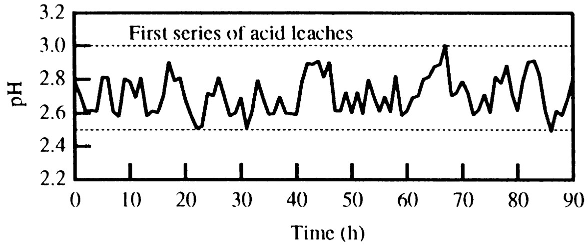
The target flow rates are tracked by the 761 controllers to ensure that the pHs of the overflows from the neutral and acid leaches match the optimal values.

5. System implementation and results of actual runs

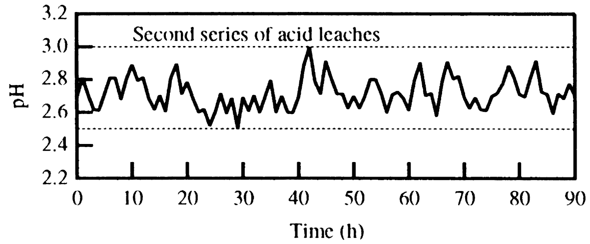
The designed MECSL has been running in a nonferrous metals smeltery. It provides not only a desired product, but also significant economic benefits.



(a) Neutral leach.



(b) First acid leach series.



(c) Second acid leach series.

Fig. 6. pHs of overflows: neutral leach; first acid leach series; second acid leach series.

5.1. Implementation of MECSL

MECSL was implemented on an IPC 610 type computer system and three 761 series single-loop controllers, and run under the MS-DOS 6.22 operating system. The functions of EC are implemented in application software written in Borland C++ and 8086-series assembly language. The implementation of the functions of the three 761 controllers was achieved through their configuration.

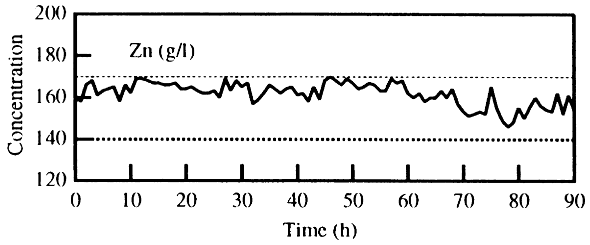
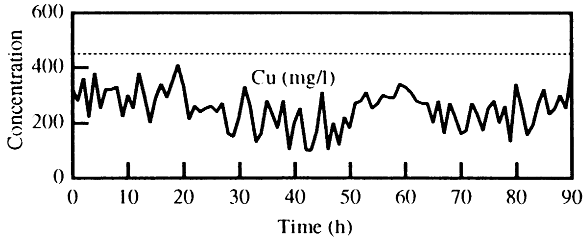
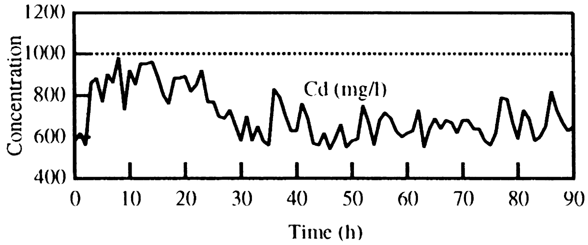


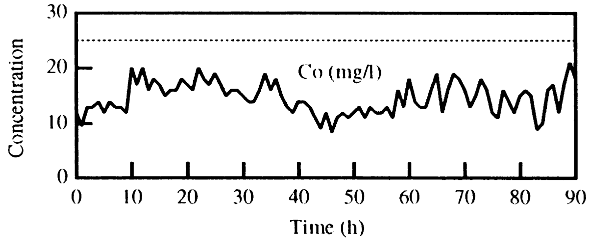
Fig. 7. Concentration of zinc.



(a) Copper



(b) Cadmium



(c) Cobalt

Fig. 8. Concentration of major impurities: copper; cadmium; cobalt.

AMS contains some special instruments that are used to measure different kinds of process data accurately. More specifically, flow rates are measured with E+H electromagnetic flow meters; pHs, with industrial pH meters; concentrations, with an X fluorescence analyzer; and weights, with electronic scales; etc.

5.2. Results of actual runs

Figs. 6–8 show some results of actual runs of MECSL. The dotted lines indicate the standard limits and the constraints given in Section 2.1. The optimal pHs of the overflows of the neutral and acid leaches were determined by EC and tracked by the 761 controllers. The optimal reaction conditions were maintained. It is clear that the pHs satisfy the given constraints, and that the concentrations of zinc and the major impurities in the neutral zinc sulfate solution meet the given standards. In addition, the concentrations of other impurities also meet the given standards.

Statistical data on the leaching process shows not only that the desired product is obtained, but also that the costs are considerably reduced. In particular, compared with the results for control based solely on the mathematical models of Eq. (1), the leach rate of zinc-bearing material is about 4.8% higher and the consumption of zinc-bearing materials is about 8.3% lower. This means that more metallic zinc can be recovered in a shorter production period.

6. Conclusions

This paper has described a model-based expert control system being used for the leaching process of a nonferrous metals smeltery. The results of actual runs of the control system show that an expert control strategy based on a combination of steady-state mathematical models and rule models is effective for the control of the leaching process. It was also shown that the control system provides not only the desired product, but also significant economic benefits. In particular, the following conclusions can be drawn:

1. Steady-state mathematical models and rule models that express the complex relationships among the factors influencing the leaching process can be constructed based on the chemical reactions involved as well as on empirical knowledge and data on the process.
2. The optimal pHs of the overflows of the continuous leach process and the target flow rates of the spent electrolyte added can be determined by combining steady-state mathematical models and rule models and by using forward chaining and model-based reasoning.
3. The optimal chemical reaction conditions can be maintained by tracking the target flow rates that correspond to the optimal pHs. In addition, the tracking can be implemented by the conventional single-loop control technique.

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