Transactions of the Nonferrous Metals Society of China, Vol. 9, No. 1, pp. 137-144, 1999

DESIGN OF AN EXPERT CONTROL SYSTEM FOR LEACHING PROCESS

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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 problem in the process control is to determine the optimal pHs of the overflows of the continuous leaches and track them. This paper deals with the design of an expert control system for the leaching process, which solves the key problem. A methodology is proposed for determining and tracking the optimal pHs with an expert control strategy based on a combination of steady-state mathematical models and rule models of the process.

Key words leaching process, expert control systems, mathematical models, rule models

1 INTRODUCTION

The main processes in zinc hydrometallurgy are leaching, purification and electrolysis[1, 2]. 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. However, it is difficult to obtain the required performance by using the conventional control methods based solely on mathematical models because of the complexity of the chemical reactions[3].

Recent advances in expert systems provide a way of controlling the leaching process. Since the 1980s, expert systems have been widely studied and applied to the control of chemical processes[4~7]. Such systems can be used to control complex process with time-variance, nonlinearity and uncertainty factors[8]. In the leaching process, complex relationships among the factors influencing the chemical reactions involved can be expressed by a combination of mathematical models and rule models. Both types of models are based on the experience of experts and operators and on accumulated empirical knowledge of the process. 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. The conventional control methods only involves tracking the fixed pHs by adding dilute sulfuric acid to the process. The pHs are selected in advance. The amount of the dilute sulfuric acid is determined based solely on the mathematical models obtained from the main chemical reaction equations. The mathematical models do not consider other chemical reactions, variances of the reaction conditions and imperfection of the reactions. This paper deals with the design of an expert control system for the leaching process (ECSL). The proposed design method overcame the disadvantages of the conventional methods. ECSL solves the key problem by using an expert control strategy based on a combination of mathematical models and rule models. In this paper, the architecture of ECSL is described. A methodology is proposed for determining and tracking optimal pHs by using an expert control strategy based on a combination of mathematical models and rule models.

2 PROCESS DESCRIPTION AND SYSTEM ARCHITECTURE

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

2.1 *Process Description*

The leaching process is shown in Fig. 1[2]. The spent electrolyte contains sulfuric acid. The process consists of one series of neutral leaches and two identical series of acid leaches. The zinc-bearing material is delivered to four water-powered classifiers and mixed with an oxidized iron solution and spent electrolyte. The overflow is pumped to the neutral leach, and the underflow is to the acid leaches. The spent electrolyte is also added to the neutral and acid leaches. The main reaction in the tanks is

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

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 acid leaches. The overflows from the acid leaches are pumped to 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, for the components 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.

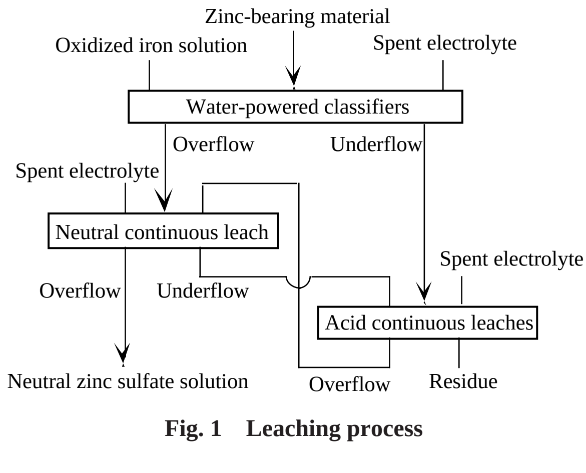

Fig. 1 Leaching process

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

Zn	Cu	Cd	Co
140000~170000	160~450	400~1000	8~25

Ni	As	Sb	Ge	Fe
8~15	0.4~1	0.2~0.5	0.14~0.5	20~35

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 ECSL*

ECSL uses the architecture shown in Fig. 2 to satisfy the above requirements. The main components are an expert controller (ECL), three 761 series signal-loop controllers, and an automatic measurement system (AMS). The ECL is connected with the 761 controllers by a special wiring concentrator and voltage converter and with AMS by a manufacturing automation protocol. Loop 1 is for the neutral leach, and loops 2 and 3 are for the acid leaches.

ECL 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 added to the neutral and acid leaches, 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 performs on-line measurement of the pHs, temperatures, and concentrations, etc.

3 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 can be described with a combination of steady-state mathematical models

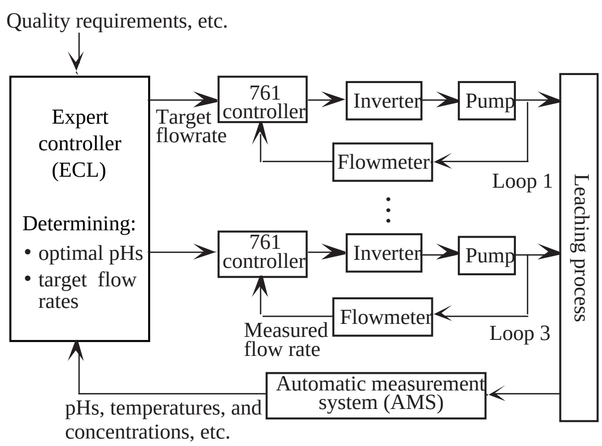

Fig 2 Architecture of ECSL

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.

3.1 *Steady-State Mathematical Models*

The steady-state mathematical models are based on the following assumptions: the zinc-bearing material and the solution in the neutral and acid leach tanks are agitated and completely mixed; the temperature of the solution is uniform; the chemical reactions occur mainly in the leach tanks.

The mass balance principle[9] yields the following dynamic balance equation for the sulfuric acid in the neutral leach:

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

where x_{Nh}, x_{Ch} and x_{iAh} are the concentrations of sulfuric acid in the solution after the neutral leach, the classifiers and the i-th 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 i-th 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 equation (2) becomes

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

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,

$$\frac{M_{ZnO}}{M_{H_2SO_4}} r_{Nh} = F_{Co} x_{Czo} f_{Nzo} \quad (4)$$

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

$$x_{Czo} = \eta_{Czo} \mu_{Czb} \frac{1}{1 + k_{Co}}, \quad (5)$$

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 expressions (3), (4) and (5) yields

$$F_{Ne} = \frac{1}{x_{Nh} - x_{Nhe}} [K_{Nh} \frac{F_{Co}}{1 + k_{Co}} f_{Nzo} - F_{Co}(x_{Nh} - x_{Ch}) - \sum_{i=1}^{2} F_{iAo}(x_{Nh} - x_{iAh})], \quad (6)$$

where

$$K_{Nh} = \frac{M_{H_2SO_4}}{M_{ZnO}} \eta_{Czo} \mu_{Czb} V_N. \quad (7)$$

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, $\hat{f}_{Nzo}$, equation (6) yields

$$F_{Ne} = \frac{1}{x_{Nh} - x_{Nhe}} [K_{Nh} \frac{F_{Co}}{1 + k_{Co}} \hat{f}_{Nzo} - F_{Co}(x_{Nh} - x_{Ch}) - \sum_{i=1}^{2} F_{iAo}(x_{Nh} - x_{iAh})]. \quad (8)$$

This 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 rate of the spent electrolyte added to the acid leach. Let F_{iAe} denote the flow rate of the spent electrolyte added to the i-th acid leach series. Then,

$$F_{iAe} = \frac{1}{x_{iAh} - x_{iAhe}} [K_{iAh} \frac{F_{iCu}}{1 + k_{Cu}} \hat{f}_{iAzo} - F_{iCu}(x_{iAh} - x_{Ch}) - F_{iNu}(x_{iAh} - x_{Nh})], \quad (9)$$

where

$$K_{iAh} = \frac{M_{H_2SO_4}}{M_{ZnO}} \eta_{Czo} \mu_{Czb} V_{iA}, \quad (10)$$

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

Expressions (8) and (9) are taken as nominal steady-state mathematical models because they only concern the chemical reaction (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 the empirical knowledge and data on the process.

Let x_{Nh}^{g} and x_{iAh}^{g} denote the target concentrations of sulfuric acid in the solutions after the neutral leach and the i-th acid leach series. From empirical knowledge, the target flow rates $F_{\mathrm{Ne}}^{\mathrm{g}}(k)$ and $F_{i\mathrm{Ae}}^{\mathrm{g}}(k)$ of the spent electrolyte added to the neutral leach and the i-th acid leach series during the k-th period are given by

$$F_{\mathrm{Ne}}^{\mathrm{g}}(k)=\alpha_{\mathrm{N}}(k)F_{\mathrm{Ne}}(k)+\sum_{l=0}^{k}\beta_{\mathrm{N}}(l)[x_{\mathrm{Nh}}^{\mathrm{g}}-x_{\mathrm{Nh}}(k)], \quad (11a)$$

$$\begin{aligned}F_{\mathrm{Ne}}(k)=&\frac{1}{x_{\mathrm{Nh}}^{\mathrm{g}}-x_{\mathrm{Nhe}}(k)}\{K_{\mathrm{Nh}}(k)\frac{F_{\mathrm{Co}}(k)}{1+k_{\mathrm{Co}}(k)}\hat{f}_{\mathrm{Nzo}}(k)\\&-F_{\mathrm{Co}}(k)[x_{\mathrm{Nh}}^{\mathrm{g}}-x_{\mathrm{Ch}}(k)]\\&-\sum_{i=1}^{2}F_{i\mathrm{Ao}}(k)[x_{\mathrm{Nh}}^{\mathrm{g}}-x_{i\mathrm{Ah}}(k)]\};\end{aligned} \quad (11b)$$

$$F_{i\mathrm{Ae}}^{\mathrm{g}}(k)=\alpha_{i\mathrm{A}}(k)F_{i\mathrm{Ae}}(k)+\sum_{l=0}^{k}\beta_{i\mathrm{A}}(l)[x_{i\mathrm{Ah}}^{\mathrm{g}}-x_{i\mathrm{Ah}}(k)], \quad (12a)$$

$$\begin{aligned}F_{i\mathrm{Ae}}(k)=&\frac{1}{x_{i\mathrm{Ah}}^{\mathrm{g}}-x_{i\mathrm{Ahe}}(k)}\{K_{i\mathrm{Ah}}(k)\frac{F_{i\mathrm{Cu}}(k)}{1+k_{\mathrm{Cu}}(k)}\hat{f}_{i\mathrm{Azo}}(k)\\&-F_{i\mathrm{Cu}}(k)[x_{i\mathrm{Ah}}^{\mathrm{g}}-x_{\mathrm{Ch}}(k)]\\&-F_{i\mathrm{Nu}}(k)[x_{i\mathrm{Ah}}^{\mathrm{g}}-x_{\mathrm{Nh}}(k)]\},\end{aligned} \quad (12b)$$

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.

Expressions (11) and (12) 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: 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. However, it is difficult to express the exact relationship among the optimal pHs and these factors by mathematical models alone. To obtain the optimal pHs and the corresponding target flow rates, the empirical knowledge and data on the process are needed. They are represented by production rule models of the following form[4, 6, 7]

$$R^{\#}: \text{ If } \textit{condition} \text{ Then } \textit{action}, \quad (13)$$

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 $\hat{f}_{\mathrm{Nzo}}(k)$, $\hat{f}_{i\mathrm{Azo}}(k)$, $\alpha_{\mathrm{N}}(k)$, $\beta_{\mathrm{N}}(k)$, $\alpha_{i\mathrm{A}}(k)$ and $\beta_{i\mathrm{A}}(k)$ from the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of sulfuric acid in the solutions added to the neutral and acid leach tanks.

The empirical data was 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 a key to determining the optimal pHs and the appropriate target flow rates.

The main content of the *condition* part in form (13) is: the composition and particle size of the zinc-bearing material (which are divided into m and n levels, respectively); the temperature of the solution (high, medium, low, and not in the allowable range); the concentrations of zinc and impurities in the overflow from the neutral leach (large, medium, small, and not in the allowable range); the concentrations of sulfuric acid in the solutions added to the neutral and acid leaches (large, medium and small); the pHs of the solutions from the classifiers, and from the neutral and acid leaches (large, small, and not in the allowable range); and the flow rates of the spent electrolyte added to the neutral and acid leaches (large, small, and not in the allowable range). 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 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}, $f_{i\mathrm{Acz}}$ and $f_{i\mathrm{Aci}}$ 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; C_{Nopt} and $C_{i\mathrm{Aopt}}$ are the optimal pHs of the overflow from the neutral leach and the i-th acid leach series; and C_{N} and $C_{i\mathrm{A}}$ are the initial values of C_{Nopt} and $C_{i\mathrm{Aopt}}$, respectively.

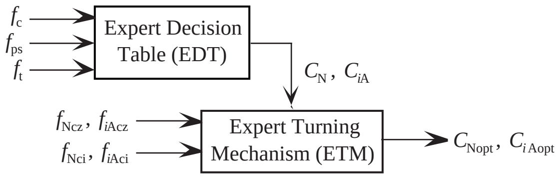

Fig. 3 Flow chart for determining optimal pHs

The optimal pHs are determined in two steps: first, C_N and C_{iA} are obtained by EDT from f_c, f_{ps} and f_t, and then C_{Nopt} is obtained by turning C_N from f_{Ncz} and f_{Nci}, and C_{iAopt} is obtained by turning C_{iA} from f_{iAcz} and f_{iAci}.

$\hat{f}_{Nzo}(k)$, $\hat{f}_{iAzo}(k)$, $\alpha_N(k)$, $\beta_N(k)$, $\alpha_{iA}(k)$ and $\beta_{iA}(k)$ are also determined from f_c, f_{ps}, and f_t and the concentrations of sulfuric acid in the solutions added to the neutral and acid leaches by the same method as for the optimal pHs.

Table 2 shows some typical rule models for determining the optimal pHs and the target flow rates, where C_{N11h}, C_{N3nm}, C_{Nm21}, ΔC_{Nls}, ΔC_{Nmm}, ΔC_{Nsl}, C_{iA11m}, C_{iA45l}, C_{iAmnh}, ΔC_{iAll} and ΔC_{iAss} are empirically determined values. This method is also used to construct the rule models for determining $\hat{f}_{Nzo}(k)$, $\hat{f}_{iAzo}(k)$, $\alpha_N(k)$, $\beta_N(k)$, $\alpha_{iA}(k)$ and $\beta_{iA}(k)$.

4. DETERMINATION OF OPTIMAL TARGET VALUES

The mathematical models and rule models in the previous section are combined into ECL to determine the optimal pHs and the target flow rates. This section describes a methodology for determining these values.

4.1 *Structure of ECL*

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

Table 2 Some typical rule models for determining the optimal pHs of overflows after leaching

R^{N1}: If $f_c = 1$ and $f_{ps} = 1$ and f_t high	Then $C_N = C_{N11h}$
R^{N2}: If $f_c = 3$ and $f_{ps} = n$ and f_t medium	Then $C_N = C_{N3nm}$
R^{N3}: If $f_c = m$ and $f_{ps} = 2$ and f_t low	Then $C_N = C_{Nm21}$
R^{N4}: If f_{Ncz} large and f_{Nci} small	Then $C_{Nopt} = C_N + \Delta C_{Nls}$
R^{N5}: If f_{Ncz} midlle and f_{Nci} medium	Then $C_{Nopt} = C_N + \Delta C_{Nmm}$
R^{N6}: If f_{Ncz} small and f_{Nci} large	Then $C_{Nopt} = C_N + \Delta C_{Nsl}$
R^{iA1}: If $f_c = 1$ and $f_{ps} = 1$ and f_t medium	Then $C_{iA} = C_{iA11m}$
R^{iA2}: If $f_c = 4$ and $f_{ps} = 5$ and f_t low	Then $C_{iA} = C_{iA45l}$
R^{iA3}: If $f_c = m$ and $f_{ps} = n$ and f_t high	Then $C_{iA} = C_{iAmnh}$
R^{iA4}: If f_{iAcz} large and f_{iAci} large	Then $C_{iAopt} = C_{iA} + \Delta C_{iAll}$
R^{iA5}: If f_{iAcz} small and f_{iAci} small	Then $C_{iAopt} = C_{iA} + \Delta C_{iAss}$

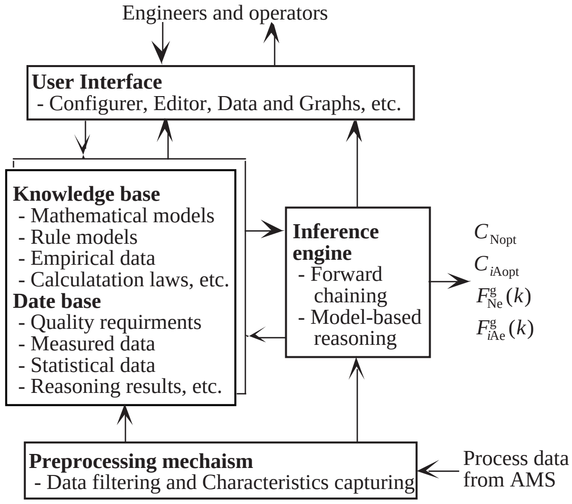

Fig. 4 Structure of ECL.

The preprocessing mechanism filters and captures the characteristics of process data from AMS. 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 steady-state mathematical models, rule models, empirical data, calculation laws, etc. The inference engine acquires data from the database and preprocessing mechanism, and then uses the knowledge in the knowledge base and a reasoning strategy that combines the forward chaining[4, 6] and model-based reasoning[7] 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.

4.2 *An Algorithm for Determining Optimal pHs and Target Flow rates*

The expert control strategy for the leaching process has four steps: first, determine C_{Nopt} and C_{iAopt}; second, select $\hat{f}_{Nzo}(k)$, $\hat{f}_{iAzo}(k)$, $\alpha_N(k)$, $\beta_N(k)$, $\alpha_{iA}(k)$ and $\beta_{iA}(k)$; third, determine $F^g_{Ne}(k)$ and $F^g_{iAe}(k)$; and finally, track $F^g_{Ne}(k)$ and $F^g_{iAe}(k)$. ECL performs the first to third steps, 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.

The following expressions are used in the process of determining the target flow rates:

$$x^g_{Nh} = \frac{M_{H_2SO_4}}{2M_H} 10^{(7-C_{Nopt})} \tag{14}$$

$$x_{i\mathrm{Ah}}^{\mathrm{g}} = \frac{M_{\mathrm{H_2SO_4}}}{2M_{\mathrm{H}}} 10^{(7-C_{i\mathrm{Aopt}})}, \quad (15)$$

where M_{H} is the atomicity of hydrogen. Let C_{Ch}, C_{Nh} and $C_{i\mathrm{Ah}}$ denote the pHs of the solutions from the classifiers and the neutral and acid leaches, respectively. Then, x_{Ch}, x_{Nh} and $x_{i\mathrm{Ah}}$ can be computed from C_{Ch}, C_{Nh} and $C_{i\mathrm{Ah}}$, respectively, by using expressions that have the same form as (14) and (15).

In conclusion, the following algorithm has been developed to determine the optimal pHs and target flow rates.

(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 $R^{\mathrm{N1}}\sim R^{\mathrm{N3}}$ and $R^{i\mathrm{A1}}\sim R^{i\mathrm{A3}}$, 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 $R^{\mathrm{N4}}\sim R^{\mathrm{N6}}$, and $R^{i\mathrm{A4}}$ and $R^{i\mathrm{A5}}$, respectively.

(5) Select $\hat{f}_{\mathrm{Nzo}}(k)$, $\hat{f}_{i\mathrm{Azo}}(k)$, $\alpha_{\mathrm{N}}(k)$, $\beta_{\mathrm{N}}(k)$, $\alpha_{i\mathrm{A}}(k)$ and $\beta_{i\mathrm{A}}(k)$ based on f_{c}, f_{ps} and f_{t} as well as the concentrations of sulfuric acid in the solutions added to the neutral and acid leaches.

(6) Obtain C_{Ch}, C_{Nh} and $C_{i\mathrm{Ah}}$, and also $k_{\mathrm{Co}}(k)$ and $k_{\mathrm{Cu}}(k)$, from AMS.

(7) Compute $x_{\mathrm{Nh}}^{\mathrm{g}}$ and $x_{i\mathrm{Ah}}^{\mathrm{g}}$ from C_{Nopt} and $C_{i\mathrm{Aopt}}$ by expressions (14) and (15), respectively, and also $x_{\mathrm{Ch}}(k)$, $x_{\mathrm{Nh}}(k)$ and $x_{i\mathrm{Ah}}(k)$ from C_{Ch}, C_{Nh} and $C_{i\mathrm{Ah}}$, respectively, by expressions that have the same form as expressions (14) and (15).

(8) Determine the target flow rates $F_{\mathrm{Ne}}^{\mathrm{g}}(k)$ and $F_{i\mathrm{Ae}}^{\mathrm{g}}(k)$ from mathematical models (11) and (12). If the values are outside the allowable range, they are set to an allowable value.

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

The methodologies presented in this paper were used in the design of ECSL.

ECSL was implemented based on an IPC 610 computer system, three 761 controllers and an automatic measurement system. It runs under the MS-DOS 6.22 operating system. The functions of ECL is implemented in an application software modular written in Borland C++ and 8086-series assembly language. The implementation of the functions of the three 761 controllers was achieved through their configuration.

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

6 CONCLUSIONS

ECSL has been running in a nonferrous metals smeltery. The actual runs of ECSL show that the proposed expert control strategy based on a combination of steady-state mathematical models and rule models is effective for the control of the leaching process. Both types of models can be constructed based on the chemical reactions involved as well as on empirical knowledge and data on the process. It has also been shown that ECSL provides not only the desired product, but also significant economic benefits.

The future work is how new empirical knowledge and data on the leaching process is obtained and used to improve the robustness of ECSL for the variations of the operation environment and conditions.

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