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An Expert Control and Fault Diagnosis Scheme for the Leaching Zinc Process *

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Abstract: This paper proposes an expert control and fault diagnosis scheme for the leaching zinc process, which concerns determining and tracking the optimal pHs of the leach overflows, and ensuring the safe running of the process. A real-world application of this scheme shows that it not only improves the control performance but also correctly diagnoses faults.

Key words: leaching zinc process; expert control; fault diagnosis; mathematical model; rule model
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锌浸出过程的专家控制和故障诊断方法

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摘要：针对锌浸出过程,提出一个专家控制和故障诊断方案,它涉及到决定和跟踪浸出溢流的最优 pH 值,以及确保过程的安全运行.这个方案的实际应用显示,它不仅提高了控制性能,而且也排除了故障.

关键词：锌浸出过程；专家控制；故障诊断；数学模型；规则模型

1 Introduction

Leaching is the first process in zinc hydrometallurgy, which involves dissolving zinc-bearing material in dilute sulfuric acid to form a zinc sulfate solution[1, 2]. To obtain high-purity metallic zinc and reduce costs, the composition of the zinc sulfate solution must meet the given standards, and the soluble zinc in zinc-bearing material must be dissolved as much as possible. On the other hand, because even a small fault in the leaching equipment may lead to changes in flow rates and temperatures, which can be quite hazardous, it is important to prevent the influence of faults that occur and ensure that the process runs safely. This requires a method not only of effective control, but also of fault diagnosis for the leaching process.

Conventional methods are mainly based on manual operation and mathematical models. It is difficult to obtain the desired performance with such methods because of the complexity of the chemical reactions involved. Expert systems are growing rapidly and their applications to engineering problems have provided effective means of process control and fault diagnosis[3~6]. They have recently been applied to control a hydrometallurgical zinc process, and distributed and model-based expert control techniques have been developed that achieve the control objectives of high quality and low costs[7, 8]. However, that system did not include any fault diagnosis.

This paper proposes an expert control and fault diagnosis scheme for the leaching zinc process, which is based on the model-based expert technique developed in [8]. Empirical knowledge and data on the process show that the key control problems in the control are to determine and track the optimal pHs of the leach overflows, and that the key fault diagnosis problem is to provide information about the cause and location of any fault that occurs, and the appropriate countermeasure against the fault. The scheme employs an expert controller to determine the optimal pHs and a fault diagnosis module that performs on-line and off-line fault diagnosis. This paper mainly describes the scheme and a real-world application.

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2 Basic scheme

The leaching process considered in this paper is shown in Fig. 1. It consists of one series of neutral leaches and two identical series of acid leaches[2]. Each series has four tanks and a thickener.

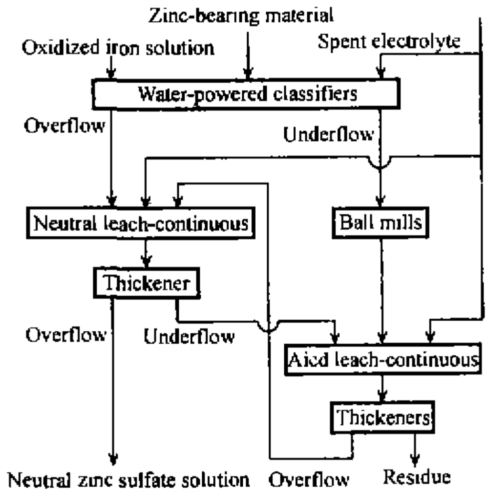

Fig. 1 Leaching process

The zinc-bearing material is mixed with an oxidized iron solution and spent electrolyte. The solution is delivered to four water-powered classifiers. The overflow is pumped to the 1st neutral leach tank, and the underflow is milled and pumped to the 1st tank of each acid leach series. The spent electrolyte is also added to the neutral and acid leaches.

The chemical reactions are carried out in the tanks. The solution is then sent to thickeners to settle. The overflow from the neutral leach is sent to the next 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.

An expert control and fault diagnosis scheme based on the hierarchical configuration shown in Fig. 2 was derived to solve the key problems in the control and fault diagnosis of the process. The scheme employs an expert controller, a fault diagnosis module, three single-loop controllers and measurement equipment.

The expert controller performs the functions of the optimization and coordination of the process control. It determines the optimal conditions for the chemical reactions and obtains the optimal values of the control parameters. The objective of the optimization and coordination is to obtain the maximum leaching rate under the compositions of the neutral zinc sulfate solution meets the given standards.

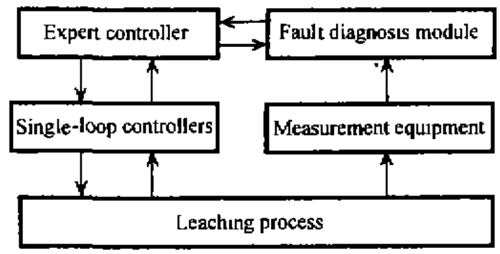

Fig. 2 Hierarchical configuration

The pHs of the overflows of the neutral and acid leaches, the main control parameters, are adjusted by adding spent electrolyte to the leaches. The expert controller employs a reasoning strategy that combines steady-state mathematical models and rule models and uses forward chaining[3] and model-based chaining[9] to determine the optimal pHs and computes the target flow rates of the spent electrolyte.

The fault diagnosis module is used to restraint the control actions, so that the pHs of the leach overflows are not too high or too low. It employs an expert reasoning strategy based on rule models with certainty factors and a Bayes representation, and combines forward and backward chaining to perform on-line and off-line fault diagnosis.

In Fig. 2, the expert controller receives the process data and control commands from the fault diagnosis module to perform the control optimization and fault recovery. The fault diagnosis module receives the data from the expert controller for the fault diagnosis.

The single-loop controllers track the target flow rates of the spent electrolyte to be added to the 1st tank of the neutral and acid leaches by means of PI control algorithms to ensure that the actual pHs match the optimal values.

The measurement equipment is applied to measure the pHs, concentrations, temperatures, flow rates, etc.

3 Design of expert controller

The expert controller consists of a characteristics-capturing mechanism, a database, a knowledge base, an inference engine, and a user interface. The knowledge base stores the rule models, steady-state mathematical models, empirical data, calculation laws, etc. The controller determines the optimal pHs through rule models and computes the target flow rates by a combination of steady-state mathematical models and rule models.

3.1 Determining the optimal pHs

It is difficult to obtain the optimal pHs by mathematical models. We can use production rule models of the If-Then form[3], which are used and assigned numbers like $R^{\#}$.

The If part contains the zinc content (f_c) on a scale of 1 to 10 and the particle size (f_{ps}) on a scale of 1 to 8 of the zinc-bearing material, the temperature of the solution (f_t = high, medium or low), and the concentrations of zinc and impurities in the leach overflows. The Then part contains instructions to select and adjust the initial and optimal pHs.

The optimal pHs are determined in two steps. The first is to select the initial pHs based on f_c, f_{ps} and f_t. The second is to adjust the initial and optimal pHs based on the concentrations of zinc and impurities. The rule models for determining the optimal pHs are constructed based on those two steps and empirical knowledge and data. Some typical rule models for the neutral leach are listed as follows:

R^{EC1}: If $f_c = 8$ and $f_{ps} = 4$ and f_t = medium,
Then $C_N = C_{N84m}$;

R^{EC2}: If $f_c = 10$ and $f_{ps} = 1$ and f_t = high,
Then $C_N = C_{N101h}$;

R^{EC3}: If $f_c = 1$ and $f_{ps} = 8$ and f_t = low,
Then $C_N = C_{N18l}$;

R^{EC4}: If f_{Ncz} = large, Then $C_{Nopt} = C_N - \Delta C_{Nzl}$;

R^{EC5}: If f_{Nci} = large, Then $C_{Nopt} = C_{Nopt} + \Delta C_{Nil}$.

Where f_{Ncz} and f_{Nci} denote the concentration levels (large, medium or small) of zinc and impurities, respectively, in the overflow from the neutral leach; C_{Nopt} is the optimal pH of the overflow from the neutral leach; C_N is the initial value of C_{Nopt}; and C_{N84m}, C_{N101h}, C_{N18l}, ΔC_{Nzl} and ΔC_{Nil} are empirically determined values.

The rule models for the acid leaches are similar to those for the neutral leach. The following algorithm determines the optimal pHs.

Step 1 Compute f_c f_{ps} and f_t from the zinc content and particle size of the zinc-bearing material, and the temperature of the solution, respectively.

Step 2 Determine the initial pHs, such as C_N, by rule models $R^{EC1} \sim R^{EC3}$.

Step 3 Compute the concentration levels of zinc and impurities in the overflows (f_{Ncz} and f_{Nci}).

Step 4 Determine the optimal pHs, such as C_{Nopt}, by rule models such as R^{EC4} and R^{EC5}.

3.2 Computing the target flow rates

Leaching can be considered to be a steady-state chemical process. To obtain the target flow rates corresponding to the optimal pHs, steady-state mathematical models are first constructed, which are based on the assumptions that the zinc-bearing material and the solution in the tanks are agitated and completely mixed, and that the temperature of the solution is uniform. For the sulfuric acid in the steady-state neutral leach, the mass balance principle[10] yields

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

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 ith acid leach series, respectively; x_{Nhe} is the concentration of sulfuric acid in the spent electrolyte; F_{Co} and F_{iAo} are the flow rates of the overflows from the classifiers and the ith acid leach series; F_{Ne} is the flow rate of the spent electrolyte; V_N is the total volume of the leach tanks; and r_{Nh} is the reaction rate of sulfuric acid.

Suppose f_{Nzo} denotes the particle reaction rate of zinc oxide with sulfuric acid and it is estimated based on the empirical knowledge and data. This estimate is denoted by $\hat{f}_{Nzo}$. The mass balance of zinc oxide and a simple calculation yield

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

where

$$K_{Nh} = \frac{M_{H_2SO_4}}{M_{ZnO}} \eta_{Czo} \mu_{Czb} V_N. \quad (3)$$

k_{Co} is the ratio of liquid to solid in the overflow from the classifiers; $M_{H_2SO_4}$ and M_{ZnO} are the molecular weights of sulfuric acid and zinc oxide; and η_{Czo} and μ_{Czb} are the zinc oxide content and the specific gravity of the zinc-bearing material.

Let x^g_{Nh} denote the target concentrations corresponding to the optimal pH. From empirical knowledge, the target flow rates $F^g_{Ne}(k)$ of the spent electrolyte during the kth period are given by

$$F^g_{Ne}(k) = \alpha_N(k)F_{Ne}(k) + \sum_{l=0}^{k}\beta_N(l)[x^g_{Nh} - x_{Nh}(l)], \tag{4a}$$

$$F_{Ne}(k) = \frac{1}{x_{Nhe}(k) - x^g_{Nh}}\{K_{Nh}(k)\frac{F_{Co}(k)}{1+k_{Co}(k)}\hat{f}_{Nzo}(k) - \sum_{i=1}^{2}F_{iAo}(k)[x_{iAh}(k) - x^g_{Nh}] - F_{Co}(k)[x_{Ch}(k) - x^g_{Nh}]\}, \tag{4b}$$

where $\alpha_N(k)$ and $\beta_N(l)$ are empirical coefficients.

The rule models for determining $\hat{f}_{Nzo}$, $\alpha_N(k)$ and $\beta_N(l)$ are constructed by a method similar to those for the optimal pHs. The following algorithm computes the target flow rate for the neutral leach.

Step 1 Select $\hat{f}_{Nzo}$, $\alpha_N(k)$ and $\beta_N(l)$ based on f_c, f_{ps} and the concentrations of sulfuric acid in the overflow of the neutral leach and in the solutions added to the neutral leach by rule models.

Step 2 Obtain $x_{Nhe}(k)$, $x_{Ch}(k)$, $x_{iAh}(k)$, $k_{Co}(k)$, $F_{Co}(k)$ and $F_{iAo}(k)$ from the measurement equipment.

Step 3 Compute x^g_{Nh} corresponding to the optimal pH, and $K_{Nh}(k)$ based on process data.

Step 4 Compute the target flow rate $F^g_{Ne}(k)$ from steady-state mathematical model (4). If the value is outside the allowable range, it is set to an allowable value by firing suitable rule models.

An algorithm similar to the one of the neutral leach computes the target flow rates for the acid leaches.

4 Design of fault diagnosis module

The fault diagnosis module is designed to provide support for the safe running of the process. Based on unusual states, fault facts and data on the process, the module performs on-line or off-line fault diagnosis.

4.1 Fault diagnosis procedure

The procedure is as follows:

Step 1 Obtain data on the process to capture any unusual process states, and accept fault facts and data input by operators. Then store the unusual states, fault facts and data in the database.

Step 3 Based on data in the database, select either a fault mode for on-line fault diagnosis using rule models and a forward chaining strategy, or possible fault modes for off-line fault diagnosis using a Bayes representation.

Step 4 For off-line fault diagnosis, select one of the possible fault modes using a backward chaining strategy.

Step 5 Display the reasoning results with certainty factors, and/or give off an alarm.

Based on the diagnosis, the operators find the cause and location of the fault by checking the site, and take suitable countermeasures to correct the fault. According to the type of the fault, operators can also send commands through the user interface to the expert controller to correct it.

4.2 Rule models and reasoning strategy design

An important aspect of the fault diagnosis module design is the construction of rule models. It contains four steps.

Step 1 Collect all unusual states, which are represented by +1 (within the allowable range) and −1 (beyond the allowable range), e.g. flow valves and pumps by +1 (closed for a valve and stopped for a pump).

Step 2 Establish fault modes using a fault tree analysis method[6,7]. Using fault trees connect unusual states on the bottom to hypotheses in the middle and fault causes at the top. The fault modes are captured from the hypotheses. The cause and location of a fault as well as suitable countermeasures are contained in a fault mode extracted from empirical knowledge and statistical data on past fault countermeasures.

Step 3 Determine the certainty factors that represent the probability of fault causes and depend on the failure rate of the equipment, and empirical knowledge and statistical data on past safe recovery.

Step 4 Construct the rule models in the If-Then form based on the unusual states, fault modes and certainty factors. Two typical rule models are listed as follows:

R^{FD1}: If the underflow from the classifier is −1 and the overflow from the classifier is +1,
Then the fault mode is J101 (0.95).

R^{FD2}: If the fault mode is J101,
Then there is too much residue at the bottom of the classifier (0.85), or the classifier is bro-

ken (0.10).

A two-step forward chaining strategy is used for on-line fault diagnosis: First, select the fault mode based on the unusual state; and then extract the cause and location of the fault and a suitable countermeasure.

A backward chaining strategy is used for off-line fault diagnosis. The inference procedure contains four steps.

Step 1 Select possible fault modes from the fault facts by using a Bayes representation

$$P(X_i/Y) = \frac{P(Y/X_i)P(X_i)}{\sum_{j=1}^{n} P(Y/X_j)P(X_j)}, \qquad (5)$$

where Y and X_i denote a fault fact and the ith fault mode; $P(X_i)$ and $P(Y/X_i)$ denote the a priori probability of X_i and the conditional probability of Y with respect to X_i; $P(X_i/Y)$ is the a posteriori probability of X_i with respect to Y. The possible fault modes are the ones that satisfy $P(X_i/Y) \geqslant \beta$, where β is an empirical coefficient.

Step 2 Test each fault mode by checking the data and states of the process.

Step 3 If the test is successful, the fault mode is selected, and the cause and location of the fault and a suitable countermeasure are displayed as reasoning results on a screen. If not, go to the next step.

Step 4 See if all possible fault modes have been tested. If yes, select the most probable fault mode and display the associated reasoning results. If not, select the next fault mode and return to Step 2.

5 Real-world application

The designed expert control and fault diagnosis scheme were used in the leaching process of a nonferrous metals smeltery. It is an important part for the control of the overall hydrometallurgical zinc process.

A distributed computer control system was constructed based on an IPC 810 industrial control computer and three 761 series single-loop controllers. The functions of the expert controller were implemented by an application written in C++ language, while the functions of the 761 controllers by the configuration. The application for the expert control is specially developed for the leaching process. Compared with the application designed on the expert system development platform, it has the advantages of quick execution speed and high run efficiency, but also the disadvantage of long development time.

Special instruments are used to accurately measure different kinds of process data. More specifically, the pHs are measured with industrial pH meters, concentrations with an X fluorescence analyzer, flow rates with E + H electromagnetic flow meters, etc. The data required for the control system are measured periodically and are collected by a local area network. The fault facts are required for off-line fault diagnosis.

The results of actual runs show that the pHs are kept in the optimal ranges of 4.8 – 5.2 for the neutral leach and 2.5 – 3.0 for the acid leaches. The final results are shown in Figs. 3 and 4, where the dotted lines indicate the standard limits on the concentrations. They show that the concentration of zinc is kept in the range of 140 – 170 g/l, and that of Cu, Cd and Co are less than 450 mg/l, 1000 mg/l and 25 mg/l, respectively, which meet the given standards and means that high-purity metallic zinc is obtained.

However, the conventional control shows that the pHs were in the ranges of 4.0 – 5.8 for the neutral leach and 2.0 – 3.5 for the acid leaches, and the concentration of zinc was in the range of 120 – 150 g/l, and that of Cu, Cd and Co are less than 550 mg/l, 1100 mg/l and 35 mg/l, respectively. It is clear that the pHs can not be kept in the optimal ranges, and the concentration of zinc was so low and that of the impurities were so high for the conventional control.

Statistical data show that costs are considerably lower. Compared with conventional control, the leach rate of the zinc-bearing material is 4.8% higher, and the consumption of zinc-bearing material is dramatically lower. This means that much more of the soluble zinc in the zinc-bearing material is dissolved.

With regards to fault diagnosis, actual runs show that the percentage of hits is over 90% for on-line diagnosis and over 95% for off-line diagnosis. Fault diagnosis reduces the frequency of occurrence of actual faults to quite a low level because it pinpoints the cause and location of faults and suitable countermeasures are taken before the fault occurs.

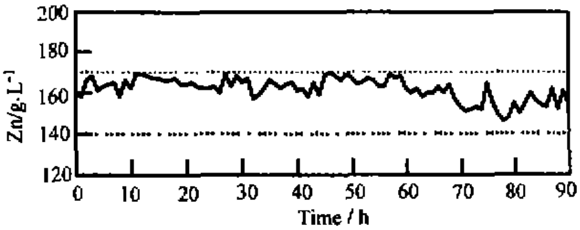

Fig. 3 Concentration of zinc in overflows

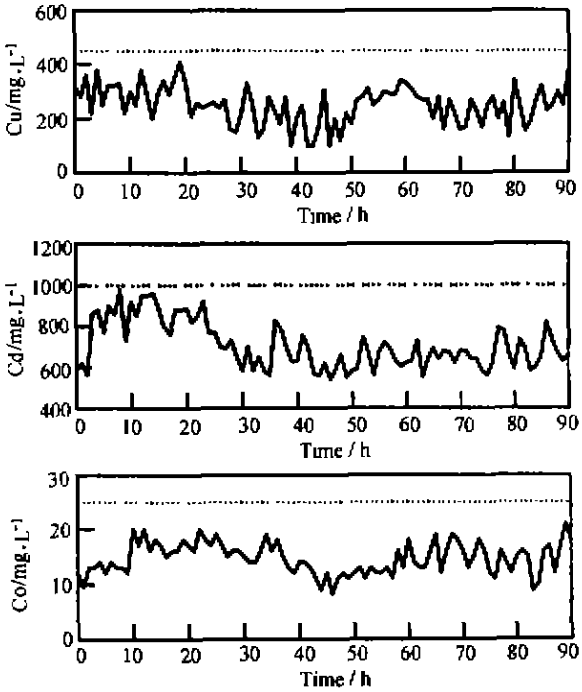

Fig. 4 Concentrations of major impurities in overflows

6 Conclusions

An expert control and fault diagnosis scheme for the leaching zinc process was described. The expert control based on steady-state mathematical models and rule models can determine the optimal pHs and the target flow rates. The conventional single-loop controller can track the target flow rates. The fault diagnosis employing rule models with certainty factors and a Bayes representation can ensure the safe running of the process. A real-world application demonstrates the effectiveness of the scheme.

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