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Expert fault diagnosis system for leaching process in zinc hydrometallurgy①

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[Abstract] Leaching process is the first step in zinc hydrometallurgy, which involves the complex chemical reactions for dissolving zinc-bearing material in dilute sulfuric acid. Ensuring the safe running of the process is a key point in the operation. An expert fault diagnosis system for the leaching process was proposed, which has been implemented in a nonferrous metals smeltery. The system architecture and the diagnosis procedure were presented, and the rule models with the certainty factor were constructed based on the empirical knowledge, empirical data and statistical results on past fault countermeasures, and an expert reasoning strategy was proposed which employs the rule models and Beyes presentation and combines forward chaining and backward chaining.

[Key words] zinc hydrometallurgy; leaching process fault diagnosis; expert systems rule models; Beyes presentation
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1 INTRODUCTION

The three basic processes in zinc hydrometallurgy are leaching, purification and electrolysis[1,2]. Leaching is the first process, which involves the complex chemical reactions for dissolving zinc-bearing material in dilute sulfuric acid to form a neutral zinc sulfate solution. In the leaching process, a little fault on the leaching equipment may be led to the variances of the flow rates and temperatures, which seriously influence the safe running. It is important to ensure the safe running of the leaching process and limit the influence of faults that occur. This requires a fault diagnosis method. However, it is difficult to perform effective fault diagnosis for the process because of the complexity of the chemical reactions.

Recent advances in expert systems provide a way for diagnosing faults in the leaching process. Expert systems have been widely studied and applied to the fault diagnosis of chemical processes[3~10]. Empirical knowledge to solve the fault diagnosis problems of complex processes are used in such systems. Since the complex relationships in the leaching process can be expressed by rule models based on the experience of experts and operators and on accumulated empirical knowledge, it is possible to implement fault diagnosis of the process by expert system techniques.

An expert fault diagnosis system for the leaching process (EFDSL) is described in this paper, which has been implemented in a nonferrous metals smeltery. EFDSL uses an expert reasoning strategy based on the rule models with the certainty factor and Beyas presentation, and combining forward chaining and backward chaining, to perform on-line and off-line fault diagnosis. This paper deals mainly with the design of EFDSL, especially the system architecture, the diagnosis procedure, the rule models, and the reasoning strategy, the system application is also presented.

2 SYSTEM ARCHITECHTURE AND DIAGNOSIS PROCEDURE

The leaching process, which is shown in Fig.1, uses neutral and acid continuous leach technology[2]. It consists of one series of neutral leach and two identical series of acid leach. Each series has four tanks and a thickener.

The zinc-bearing material was delivered to a flotation cell and mixed with oxidized iron solution, and the spent electrolyte that contained sulfuric acid was returned from the electrolytic process. The mixed solution was delivered to four water-power classifiers. The overflow was pumped to the first neutral leach tank, and the underflow was milled by four ball mills and pumped to the first tank of each acid leach series. The spent electrolyte was also added to the neutral and acid leaches.

The chemical reactions were carried out in the tanks. The solution was then sent to thickeners. The overflow from the neutral leach was sent to the purification process in the form of a neutral zinc sulfate solution, and the underflow was added to the first tank of each acid leach series. The overflows from the acid

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leach were pumped to the first tank of the neutral leach, and the residues are sent to the residue treatment process.

An important requirement was to ensure safe running of the process. When a fault occurred, information about the cause and location of the fault as well as the appropriate countermeasure should be provided to operators, which means that on-line fault diagnosis for the process should be performed. In addition, off-line fault diagnosis was also required for the leaching process.

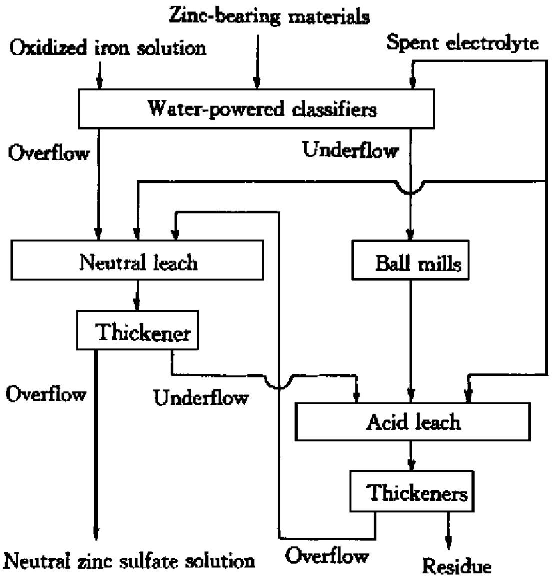

Fig.1 Leaching process

2.1 System architecture

EFDSL uses the architecture shown in Fig.2 to satisfy the requirement of the fault diagnosis for the process. The main components of EFDSL are a knowledge base, a database, an inference engine, a user interface and a process measurement and control interface.

The knowledge base stores the rule models and Beyes presentation for the fault diagnosis, the empirical data of the process, and the fault reasons and associated actions to be taken, etc. The database stores data measured from the process and inputted by operators, statistical data of the process, and the reasoning results from the inference engine, etc. The inference engine acquires data from the database, and then uses the knowledge in the knowledge base and a reasoning strategy that combines forward chaining and backward chaining to perform fault diagnosis. The user interface is used to display the reasoning results, execute the fault alarm, send the commands of removing faults, and configure and edit the knowledge base and database, etc. The process measurement and control interface transfers the process data to the database and execute the commands from the user interface.

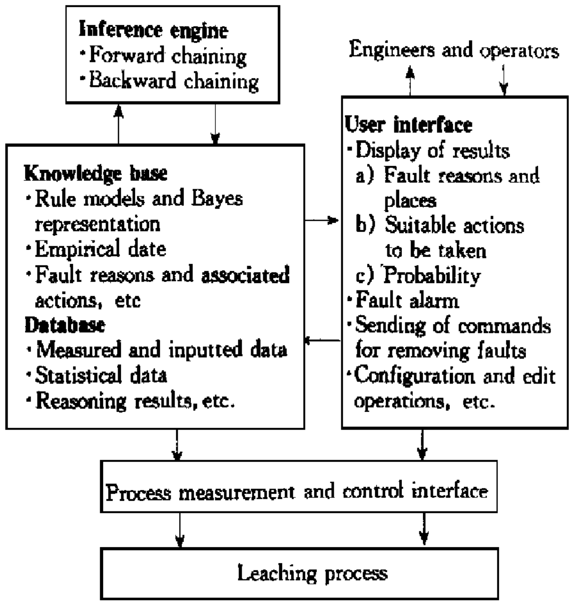

Fig.2 Architecture of EFDSL

2.2 Diagnosis procedure

The main functions of fault diagnosis for the leaching process are to detect and diagnose faults in important equipment such as the leach tanks, pumps, etc, and to indicate the causes and locations of faults as well as suitable countermeasures. EFDSL is designed to provide support for the safe running of the process. By real-time monitoring the process, EFDSL detectes the unusual states such as excessive flow rate, temperature and pH that is too low, etc. In addition, EFDSL also accepts fault facts and data inputted by operators. Based on the unusual states or fault facts and data, EFDSL performs on-line or off-line fault diagnosis. As a result of the diagnosis result, the reason and place of the fault as well as the suitable actions are provided to operators.

The fault diagnosis of the leaching process is implemented in EFDSL that uses an expert system strategy based on rule models with certainty factors and Beyes representation, and combining forward chaining and backward chaining. The fault diagnosis procedures used by FDML are:

1) Obtain data from process through the process measurement and control interface to capture any unusual process states, or accept fault facts and data inputted by operators through the user interface.

2) Store the unusual states or fault facts and data in the database.

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

4) For off-line fault diagnosis, select one fault mode from the possible fault modes using a backward

chaining strategy.

5) Display the reasoning results with certainty factors on the screen, and/or give off an alarm through a bell and lights.

Based on the diagnosis, the operators find the cause and location of the fault by checking the site, and take suitable countermeasures to remove the fault. According to type of the fault, operators can also send some commands for removing fault through the user interface as well as the process measurement and control interface.

3 RULE MODELS AND REASONING STRATEGY

The knowledge base and inference engine are two important components of EFDSL. Two key points in the design of the knowledge base and inference engine are to construct the rule models and develop a reasoning strategy for fault diagnosis.

3.1 Rule models

The knowledge base was designed mainly to facilitate the construction of rule models for fault diagnosis based on the empirical knowledge of engineers and operators as well as the empirical data and statistical results on past fault countermeasures of the process. The procedure for constructing rule models is shown in Fig.3, which contains four steps.

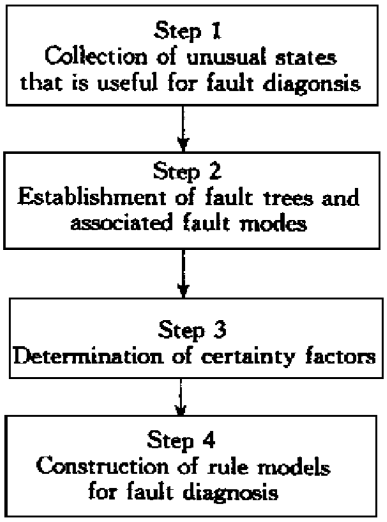

Fig.3 Procedure for constructing rule models

Step 1: Collect all unusual states that are useful for fault diagnosis. The unusual states are mainly collected through the on-line measurement and off-line inputs. The main variables that can be measured on-line are as follows: 1) The flow rate of the spent electrolyte, zinc-bearing materials, oxidized iron solution, overflows and underflows of the classifiers, leach tanks and thickeners; 2) The temperatures of the solutions in the acid and neutral leaches; 3) The pH of the overflows and underflows of the classifiers, leach tanks and thickeners; 4) The running states of the flow regulation valves and the pumps.

Unusual states are represented by +1 (above the allowable range) and - 1 (below the allowable range). The unusual states for flow valves and pumps are represented by +1 (closed for a valve and stopped for a pump).

Step 2: Establish fault modes using the fault tree analysis method[5,6], as shown in Fig.4. The unusual states from the basis for constructing fault trees, which connect these states to hypotheses and fault causes. Moreover, 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 the past fault countermeasures of the process. A name and a number are assigned to each fault mode, as in the example in Table 1.

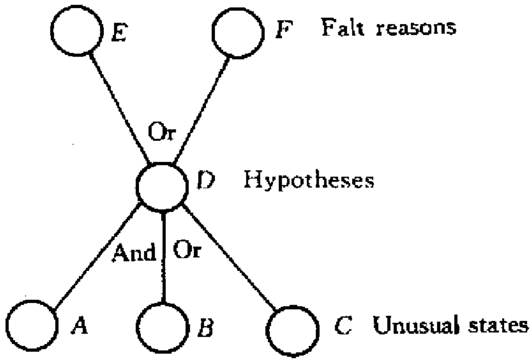

Fig.4 A fault tree

Table 1 Items contained in a fault mode

Number: Yl06
Name: First neutral leach tank is blocked
Fault reasons:
a) The residue at the bottom is overstocked.
b) The pipe at the bottom is blocked.
c) The amount of the flow opening at the bottom is too small or broken.
Place: First neutral leach tank
Suitable actions should be taken:
a) Remove the residue at the bottom.
b) Dredge the pipe at the bottom.
c) Increase the amount of the flow valve opening at the bottom or repair the flow valve.

Step 3: Determine the certainty factors that represent the probability of fault causes. It is desirable to assign a probability to each fault cause because there might be several fault cause for one fault mode. The probability is given by a certainty factor that depends on the failure rate of the equipment, and empirical knowledge and statistical data on past safe recovery.

Step 4: Construct the rule models for fault diagnosis based on the unusual states, fault modes and certainty factors. Based on the unusual states, the fault modes, and certainty factors, thus obtained, rule models for fault diagnosis are represented in form[3,4]

$$R^{\#}: \text{If Condition Then Action} \quad (1)$$

where $R^{\#}$ is the number of the rule model, Condition is the unusual state, or their logical combination, or the medium reasoning result, and Action is the medium or final reasoning result.

Some typical rule models are shown in Table 2, where the values in parentheses are the certainty factors, and the following notations are used.

UC: the underflow from the classifier;
OC: the overflow from the classifier;
FM: the fault mode;
FSA: the flow rate of the spent electrolyte added to the acid leach tank;
PHA: pH of the solution from the acid leach;
UN: the underflow of the neutral leach tank.

Table 2 Some typical rule models for fault diagnosis

R^{FD1}	: If UC is -1 and OC is +1 Then FM J101 appears (0.95)
R^{FD2}	: If FM J101 appears Then the residue at the bottom of the classifier overstocked (0.95), or the classifier broken (0.15)
R^{FD3}	: If FSA is +1 and PHA is -1 Then FM S101 appears (0.95)
R^{FD4}	: If FM S101 appears Then the spent electrolyte-regulating valve broken (0.95)
R^{FD5}	: If UN is -1 Then FM Y100 appears (0.95)
R^{FD6}	: If FM Y100 appears Then the residue at the bottom of the neutral leach tank overstocked (0.60), or the pipe at the bottom of the neutral leach tank blocked (0.20), or the amount of valve opening is too small or the valve broke (0.15)
R^{FD7}	: If the residue at the bottom of the neutral leach tank overstocked Then remove the residue

3.2 Reasoning strategy

A two-step forward chaining strategy[3] is used for on-line fault diagnosis. First, select the fault mode from the knowledge base based on the unusual states, then extract the cause and location of the fault and take a suitable countermeasure from the knowledge base.

It follows from the above two steps that the fault diagnosis using the forward chaining results from selecting the rule models and associated data in the knowledge base according to the unusual states. The procedure from choosing a rule model to executing it includes three steps: marching, clash solving and action. A clash-solving strategy[3] in which the rule model with the most complex conditions is fired first is used to select the fault mode.

A backward chaining strategy[4] is used for off-line fault diagnosis. It is based on the fault facts and data inputted by operators. The inference procedure is shown in Fig.5, which contains four steps: 1) select possible fault modes from the fault facts by using Beyes representation[4,6]; 2) test each fault mode by checking data and states of the process; 3) if the test is successful, the fault mode is selected, and the cause and location of the fault and a suitable countermeasure are shown as reasoning results on a screen. If not, go to the next step; 4) see if all possible fault modes have been tested. If yes, the most probable fault mode is selected and the associated reasoning results are displayed. If not, select the next fault mode and return to step (2).

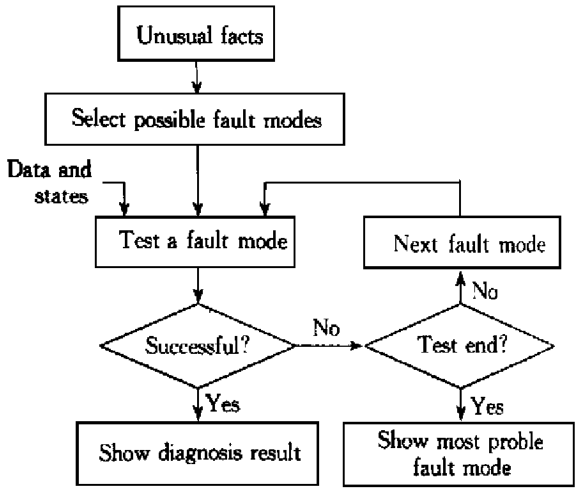

Fig.5 Flow chart using backward chaining

Beyes presentation is used to select the possible fault modes. Assume that all possible fault modes are selected from among n fault modes. Let Y and X_i denote a fault fact and the i-th fault mode; and let $P(X_i)$ and $P(Y/X_i)$ denote the a priori probability of X_i and the conditional probability of Y with respect to X_i, respectively. Then $P(X_i/Y)$, which is the a posteriori probability of X_i with respect to Y, can be obtained from $P(X_i)$ and $P(Y/X_i)$ by using Beyes representation[4,6]

$$P(Y/X_i) = \frac{P(Y/X_i)\,P(X_i)}{\sum_{j=1}^{n} P(Y/X_i)\,P(X_j)} \quad (2)$$

The fault modes that satisfy $P(Y/X_i) \geqslant \beta$ are the possible ones, where β is an empirical coefficient. $P(X_i)$ and $P(Y/X_i)$ are determined from the failure rates of the equipment, and empirical knowledge and statistical data on past safe recovery.

4 SYSTEM APPLICATION

EFDSL has been implemented in a nonferrous metals smeltery. The results of actual runs show that EFDSL is a powerful way to ensure the safe runs of the leaching process.

4.1 System implementation

EFDSL is implemented on an IPC 610 type computer system, and runs under the MS-DOS 6.22 operating system. EFDSL is connected with an expert control system for the leaching process (ECSL)[9], which provides the process data and executes the commands for removing faults from EFDSL.

ECSL contains an expert controller, three control loops composed of 761 controllers, inverter and pumps, and a measurement system. It determines and tracks the optimal pH of overflows of the neutral and acid leaches. As Fig.6, EFDSL implements the fault diagnosis based on ECSL.

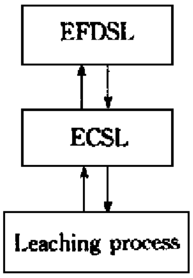

Fig.6 EFDSL and ESCL

Special instruments are used to accurately measure different kinds of process data: E + H electromagnetic flow meters for flow rates, industrial pH meters for pH values, etc.

The functions of EFDSL are implemented in an application software package, which is written in Borland C++ and 8086-series assembly language.

4.2 Results of actual runs

Statistical data on the fault diagnosis using EFDSL in the leaching process show that the percentage of actual hits for on-line diagnosis is over 90% and that for off-line diagnosis is over 95%. EFDSL 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.

5 SUMMARY

The design and application of EFDSL have been presented in this paper. An expert reasoning strategy that employs the rule models with the certainty factor and Beyes presentation, and combines forward chaining and backward chaining were used to perform on-line and off-line fault diagnosis of the leaching process. Rule models for the fault diagnosis was constructed based on empirical knowledge of experts and operators as well as the empirical data and statistical results on past fault countermeasures of the process. The results of actual runs show that EFDSL provided an effective means to ensure the safe runs of the leaching process.

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