AN EXPERT CONTROL SYSTEM FOR PURIFICATION PROCESS①

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ABSTRACT For the purification subprocess of the hydrometallurgical process of zinc, an expert control system(ECS) has been designed and applied in a nonferrous metals smeltery. It consists of an expert control computer system and an I/A series distributed control system. Based on not only knowledge model but also mathematical model, the system completed expert optimization control for the purification process. The theory and techniques in the system design involve the control requirements, hierarchical model, design framework, expert optimization control and system implementation.

Key words hydrometallurgical process of zinc process control expert systems expert optimization control distributed computer control systems

1 INTRODUCTION

The hydrometallurgical technology is extensively used to produce zinc (Zn) in the nonferrous metals industry[1]. Because of the complexity of dynamic behaviour, the hydrometallurgical process of Zn is mostly controlled manually, or partly supported by single control device and local control system[2]. It is important to develop a way of controlling the hydrometallurgical process to improve the quality and output quantity of the product Zn and to reduce its cost. Recent advances in control techniques and artificial intelligence provided the means for control of the nonferrous metallurgical process[3-5]. Expert systems have formed a rapid expanding area within the field of artificial intelligence. Expert control systems(ECS) integrated expert system techniques and engineering control techniques[6]. The expert control system techniques can be applied in the control of hydrometallurgical process of Zn.

The purification process is an important subprocess in hydrometallurgical process of Zn. For the purification process in a nonferrous metals smeltery, an expert control system has been designed. The design uses not only the knowledge representation but also the numerical representation. The knowledge representation comes from the knowledge and reasoning procedure used by human experts. The numerical representation is a mathematical model and can be obtained by using physical modelling from behaviour description and process identification. This paper mainly deals with the design theory and techniques of the mathematical model based on expert control system for purification process.

2 PROCESS DESCRIPTION AND CONTROL REQUIREMENTS

According to the dynamic behaviour and control requirements of the purification process, expert control system techniques can be considered in the control of purification process.

2. 1 *The Purification Process*

The input of purification process is a solution of $ZnSO_4$ which contains such impurities as Cu, Cd, Co, Ni, As, Sb, Ge and Fe. Through

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the purification process, the impurities can be removed from the solution and controlled within an allowable standard by adding powdery Zn and $KSbC_4H_4O_7$ into the chemical reaction process of a boiling vat. At the input side of the purification process, the contents of impurities in solution are shown in Table 1. At the output side, the requirements for contents are shown in Table 2.

Especially, so long as the contents of Cu, Cd and Co in solution are controlled within a given standard, other impurities are also removed and thus the required solution of $ZnSO_4$ can be obtained at the output side of the purification process. The main chemical reaction equations are as follows:

$$CuSO_4 + Zn = ZnSO_4 + Cu\downarrow$$

$$CdSO_4 + Zn = ZnSO_4 + Cd\downarrow$$

$$CuSO_4 + Cd = CdSO_4 + Cu\downarrow$$

To complete above chemical reaction processes, some chemical reaction conditions must be satisfied.

2.2 *The Control Requirements*

The chemical reaction conditions are influenced by the quantity of powdery Zn to be added, the flow, temperature and pH value of the solution, and the contents of impurities at the input side of the purification process. In general, the requirements on temperature, pH value and contents of impurities at the input side can

Table 1 The contents of the impurities at the input side (mg/L)

Cu	Cd	Co	Ni
200~ 400	400~ 1000	8~ 25	8~ 15
As	**Sb**	**Ge**	**Fe**
0.4~ 1.0	0.2~ 0.4	0.14~ 0.3	20~ 30

Table 2 The contents of the impurities at the output side (mg/L)

Cu	Cd	Co	Ni
< 0.1	< 0.7	0.2~ 1.0	< 0.5
As	**Sb**	**Ge**	**Fe**
< 0.1	< 0.2	< 0.032	20~ 35

esily be achieved in the required ranges. Therefore, the control objective of the purification process is to keep an optimal chemical reaction condition by controlling the quantity of powdery Zn to be added and the flow of solution. In particular, the control requirements of the purification process can be described as follows:

(1) Automatic control of the input quantity of powdery Zn. Provided the contents of impurities in solution after making purification processing satisfy the given standard, minimize the input quantity of powdery Zn. This is the main control objective of the purification process.

(2) Optimal control of the flow of solution. This means that the flow of solution must be regulated on an optimal value according to the requirements on output quantity of solution and chemical reaction time so that the stable purification process can be obtained.

(3) On line monitoring of the dynamic parameters in the purification process. These parameters include the input quantity of powdery Zn, the flow, temperature and pH value of solution, and the contents of impurities etc.

(4) Fault diagnosis and substance balance computation. The system will discriminate and give warning in cases of system trouble, dynamic parameters exceeding bounds of given values and large equipment breakdown etc, while the substance balance computation is for the purpose to keep a balance relation between input and output of the purification process.

(5) Process information management, such as accumulation, reservation, statistics and query for all process information, as well as displaying and printing of reports and loading curves with Chinese characters.

The above control requirements can be achieved by using expert control system technique. An expert control system, which has been established in a nonferrous metals smeltery, completed the control and management of purification process.

3 HIERARCHICAL MODEL AND DESIGN FRAMEWORK

The expert control system must perform the tasks of expert optimization control, expert fault diagnosis and expert real time management for the purification process in order to obtain required solution of $ZnSO_4$ and guarantee the safe run of the control system. To achieve this purpose, a three level hierarchical model is used in expert control system design.

3. 1 *The Hierarchical Model*

The expert control system for purification process contains six parts. They are characteristic information processing mechanism, knowledge base and data base, inference engine, synthetic processing mechanism, user interface and distributed controllers respectively.

The functions of the six parts mentioned above are described respectively as follows:

(1) The characteristic information processing mechanism characterizes all collected information from purifications process. The characterized information can be received by synthetic processing mechanism, inference engine, knowledge base and data base.

(2) The knowledge base and data base consist of facts and heuristics. The facts constitute a body of information of purification process that is widely shared, publicly available and generally agreed upon by experts in the field of hydrometallurgical process of Zn. The heuristics are mostly private, little-discussed rules of good judgement that characterize expert-level decision making in the field. The knowledge is composed of external and internal knowledge which can be obtained from human experts and technical references in the field and the self-learning of expert control system.

(3) The inference engine uses the reasoning strategies of forward chaining and the knowledge from knowledge base and data base to solve practical control problems and draw a conclusion.

(4) The synthetic processing mechanism obtains an optimal given value by utilizing the conclusion from inference engine and the mathematical model of purification process and according to a synthetic algorithm.

(5) The user interface contains an input interface and output interface, which provide the methods for information input and output respectively.

(6) The distributed controllers are consisted in an I/A series distributed control system, which contain a powdery Zn controller and a flow controller.

A hierarchical model including six parts of an expert control system is shown in Fig. 1. The frist level is the distributed controllers and the input interface. The characteristic information processing mechanism and the synthetic processing mechanism are contained in the second level. The third level has inference engine, knowledge base, data base and output interface. All knowledge representation and numerical representation are stored in knowledge base and data base.

3. 2 *The Design Framework*

The expert control system for purification process is parted into expert optimization subsystem, expert fault diagnosis subsystem and expert real time management subsystem to perform the system functions. The block diagram of the overall control system is shown in Fig. 2.

In Fig. 2, the given index contains given range of contents of impurities in solution and optimal chemical reaction conditions of purification process, the given values are optimal given values of powdery Zn quantity to be added in purification process and the flow of solution at the input side of purification process respectively, the controlled outputs have powdery Zn quantity and the flow which are feedbacked to the input side of the distributed controllers by measurement interface, which performs on line measuring of the contents of impurties and the temperature, flow and pH value of the solution.

The design of expert optimization control subsystem involves three aspects which are the computation of optimal given values of powdery Zn input quantity and the flow, the internal design of each subsystem and its implementation. A numerical representation which is a mathematical model described the purification process and a knowledge representation which is a rule model, are used in computation of optimal given values of powdery Zn input quantity and flow. The powdery Zn input quantity is computed by given index and measured values of impurity contents,

Fig. 1 The hierarchical model of the expert control system for the purification process

Fig. 2 The block diagram of the overall control system

and the flow of solution which is determined by chemical reaction conditions. The optimization control for purification process can be achieved by powdery Zn quantity control loop and the flow control loop.

An expert fault diagnosis technique based on the Bayes respresentation and fuzzy selecting principle is used to detect and diagnose the faults of two control loops, expert control computer system and three on line analyzers measuring the contents of Zn, Cu, Cd and Co in $ZnSO_4$ solution. The substance balance computation is also used in the expert fault diagnosis, of which the design procedure is as follows:

(1) Find a fault transfer decision table by analysing the reliability relations between the components of expert control system.

(2) Establish a fault mode information base, which is composed of fault transfer decision table and its causality explanation and processing stratigies.

(3) Design a fault diagnosis inference engine using Bayes decision theory and fuzzy selecting principle, which computes the probability of the fault arised when expert control system is running in some states and selects a fault mode from the fault mode information base, and then the reasons and their solutions of the fault are found.

The expert real time management subsystem completes the task of the process information management, which is a real time data base management system and designed by using data base management technique.

4 EXPERT OPTIMIZATION CONTROL TECHNIQUE

Fig. 3 shows the connections between the components of expert optimization control subsystem. Using the communication interface, the expert control computer system transfers the optimal given values of powdery Zn quantity and the flow determined by mathematical model and the rule model of purification process to powdery Zn quantity control loop and the flow loop realized in I/A series distributing control system respectively. The charateristic information processing mechanism receives the given index from keyboard input and the process parameters provided by the measurement interface including three on line analyzers.

4.1 *The Computation of Optimal Given Values*

Fig. 4 shows the computation procedure of optimal given values of powdery Zn quantity and the flow denoted by u_{G1} and u_{G2}.

The rule model is a production rule model. All production rules contained in the knowledge base determine the actions of expert optimization subsystem. The procedure from choosing a rule to execute the rule includes three steps: matching, clash solving and action. The action can add a new entry into the knowledge base or modify other entries, or present an activation of the distributed controllers or a computation algorithm.

The purification process has four boiling vats, each of which has a dynamic mathematical model obtained by physical modelling from behaviour description and process identification as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{F}{\varepsilon V} & 0 \\ 0 & -\frac{F}{\varepsilon V} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} -\frac{Af_1}{\varepsilon V M_B} \\ -\frac{Af_2}{\varepsilon V M_B} \end{bmatrix} s + \begin{bmatrix} -\frac{1}{\varepsilon V} F x_{10} \\ -\frac{1}{\varepsilon V} F x_{20} \end{bmatrix}$$

where f_1 and f_2 satisfy the following two constraint equations respectively.

$$f_1^3 + \left(\frac{1}{s} hP_1 x_1 - \frac{9}{8}\right) f_1^2 - \frac{3}{s} hP_1 x_1 \left(3 - \frac{1}{s} hP_1 x_1\right) f_1 + \frac{27}{8} - \left(\frac{3}{2} - \frac{1}{s} hP_1 x_1\right)^3 = 0$$

$$f_2^3 + \left(\frac{1}{s} hP_2 x_2 - \frac{9}{8}\right) f_2^2 - \frac{3}{s} hP_2 x_2 \left(3 - \frac{1}{s} hP_2 x_2\right) f_2 + \frac{27}{8} - \left(\frac{3}{2} - \frac{1}{s} hP_2 x_2\right)^3 = 0$$

Fig. 3 The connections between the components of expert optimization control subsystem

Fig. 4 The computation procedure of optimal given values

where x_1 and x_2 are the contents of Cu^{2+} and Cd^{2+} of the solution at the output side of boiling vat, and x_{10} and x_{20} are those at the input side respectively. F is the flow at the input side. s denotes the powdery Zn input quantity. ε, V, A, M_B and h are constants involved in the dynamic behaviour of purification process and the construction of boiling vat.

It is clear that a static mathematical model of the boiling vat is as follows:

$$x_1 = x_{10} - \frac{Af_1}{FM_B}s,$$

$$x_2 = x_{20} - \frac{Af_2}{FM_B}s$$

Therefore, s can be computed by given x_1, x_{10}, x_2, x_{20} and F, where F is determined by the chemical reaction time in boiling vat. Based on the computed s and determined F, u_{G1} and u_{G2} can be obtained by synthetic processing mechanism using the rule model.

4.2 *The Rule Model and the Inference Engine*

The following states are chosen in the design of rule model and inference engine:

(1) The content of Cu^{2+} is not in given range (denoted by CuNR).

(2) The content of Cd^{2+} is not in given range (CdNR).

(3) The content of Co^{2+} is not in given range (CoNR).

(4) The error between computed value and measured value of powdery Zn quantity is less than the maximum allowable value (ELT).

(5) The error between computed value and measured value of powdery Zn quantity is greater than the maximum allowable value (EGT).

(6) The flow is not in given range (FNR).

(7) The temperature is not in given range (TNR).

(8) pH value is not in given range (pHNR).

(9) The error of the flow at input side and output side is not in given range (EFNR).

The characteristic information processing mechanism receives the states from purification process and stores it into knowledge base and data base. Based on the states or its logic operation, the inference engine uses the reasoning strategies of foward chaining to determine the corresponding action by production rules got from knowledge base.

The production rules have this form: IF conditions THEN action, which means that if the conditions are satisfied then the action is executed. For example, the following production rules are used to compute the optimal given value of powdery Zn quantity control loop and flow control loop.

(1) IF (CuNR OR CdNR) AND ELT
THEN $u_1(k+1) = k_1 u_1(k)$

(2) IF (CuNR OR CdNR) AND EGT
THEN $u_2(k+1) = k_2 u_2(k)$

(3) IF CoNR AND ELT
THEN $u_1(k+1) = k_3 u_1(k)$

(4) IF CoNR AND EGT
THEN $u_2(k+1) = k_4 u_2(k)$

where k_1, k_2, k_3 and k_4 are the experience values from control experts in the field of purification process, $u_1(k+1)$ and $u_1(k)$ are the given values of powdery Zn quantity at $k+1$ and k control period, $u_2(k+1)$ and $u_2(k)$ are the flows at $k+1$ and k control period.

In addition, the following production rules are used in the expert fault diagnosis subsystem.

(1) IF FNR
THEN the flow warning

(2) IF TNR
THEN the temperature warning

(3) IF pHNR
THEN the pH value warning

(4) IF EFNR
THEN the substance balance warning

5 SYSTEM IMPLEMENTATION

The expert control system is implemented by an expert control computer system and an I/A series distributed control system. The expert control computer system contains the characteristic information processing mechanism, the knowledge base and data base, the inference engine, the synthetic processing mechanism and a part of the user interface. The other part of the user interface and the two control loops are included in the I/A series distributed control system.

5.1 *The Hardware Constituents*

The hardware constituents of the expert control computer system are as follows:

(1) A basic model of the industrial control computer including 4MB of random access memory, where CPU is an Intel 80386 microprocessor.

(2) A 133.3 mm (5.25-inch) and a 76.2 mm (3-inch) floppy disk drives and their interface adaptors for the standard 1.2 MB and 1.44 MB diskettes.

(3) A 100MB hard disk as well as its interface adaptor and drive.

(4) A 101-key keyboard.

(5) A 355.6 mm (14-inch) VGA monitor and its interface adaptor.

(6) A 24-pin line printer and its interface adaptor.

(7) A serial asynchronous communication adaptor.

(8) A timer interrupt board for real time data communication between the expert control computer system and the I/A series distributed control system.

The constituents of the I/A series distributed control system used in expert control system for purification process are as follows:

(1) Ten field bus modulars (FBM), which are used to receive process parameters and output control signals.

(2) A control processor (CP10), which processes the process parameters and control signals.

(3) An application processor (AP20), which completes the processing, reservation, displaying and printing of process information etc.

(4) A workstation processor (WP30), which is used as a man-machine interface to configurate and select the function of the distributed control system.

(5) A communication processor (COMP10), which is connected with the expert control computer system using MAP protocol.

The contents of Zn, Cu, Cd and Co in the solution of $ZnSO_4$ are on line measured by COURIER 30 type X fluorescent analyzer, EC25 type electrochemical analyzer and OTI95 type automatic analyzer.

5.2 *The Applied Software Design*

The applied software of the expert control system is designed only in the expert control computer system. Based on the modular programming, the applied software can be designed by using Microsoft C 7.00 version language and run on a disk operating system version 5.00 or above. It consists of main menu, characteristic information processing, knowledge base and data base, inference and operation guide, optimal given value, fault diagnosis and processing, process information management and Chinese character processing modulars.

The I/A series distributed control system can continuously monitor and control the purification process in accordance with its configured algorithm.

REFERENCES

1 Zhuzhou Smeltery. Zinc Metallurgy, (in Chinese). Changsha: Hunan People's Press, 1973.

2 Fu Z J. In: Proceedings of the Second China National Nonferrous Metals Conference, (in Chinese), 1991, 1: 66–72.

3 Gevarter W B. Artificial Intelligence, Expert Systems, Computer Vision, and Natural Language Processing. New Jersey: Noyes Publications, 1984.

4 Fu K S *et al*. Artificial Intelligent Principle and Applications, (in Chinese). Beijing: Tsinghua University Press, 1987.

5 Astrom K J. In: Proceedings of the First European Control Conference, 1991, 3: 2328–2339.

6 Cai Z X. Intelligent Control, (in Chinese). Beijing: Electronic Industry Press, 1990.

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