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A DISTRIBUTED EXPERT CONTROL SYSTEM FOR A HYDROMETALLURGICAL ZINC PROCESS

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Abstract. A distributed expert control system (DECSHZ) has been built for a hydrometallurgical zinc process, whose basic steps are leaching, purification and electrolysis. It consists of a central computer management system and three local expert control systems, one for each of the basic steps. This paper deals with the design and application of DECSHZ, especially its distributed architecture and main functions; expert control strategies based on rule models and a combination of rule models and steady-state mathematical models; system implementation; and the results of actual runs. DECSHZ has been found to provide not only a very pure product, but also significant economic benefits.

Keywords. Hydrometallurgical zinc processes, expert systems, distributed computer control systems, process control, rule models, mathematical models.

1. INTRODUCTION

Nowadays, hydrometallurgical technology is used extensively in the nonferrous metals industry to produce zinc. The basic steps in the process are

(1) leaching: the dissolving of zinc-bearing materials in dilute sulfuric acid to form a zinc sulfate solution;

(2) purification: the purification of the zinc sulfate solution to obtain a satisfactory electrolyte; and

(3) electrolysis: the recovery of very pure metallic zinc from the electrolyte (Mathewson, 1959; Zhuzhou Smeltery, 1973).

Precise control of the process is essential to obtain a high-grade product and reduce costs. Conventionally, it is controlled manually because of its large-scale, complex, chemical nature and the fact that there are many factors that influence the chemical reactions involved. In recent years, some digital control systems based on mathematical models have been developed for it. However, it is difficult to achieve the desired control performance because the complexity of the process does not lend itself to exact expression by mathematical models alone (Gui and Wu, 1995).

Recent advances in control engineering and artificial intelligence techniques provide a means of controlling the hydrometallurgical zinc process. Since the early 1980s, distributed computer control systems (DCCS) and expert systems (ES) have been widely studied and applied to many areas of process control (Rodd, 1983; Åström, et al., 1986; Efstathiou, 1989; and Gupta and Sinha, 1996). For the real-time control of processes with decentralized fields, a DCCS is a pragmatic choice. If an ES is designed to emulate the expertise of experts and operators in performing control activities, it is called an expert control system (ECS). An ECS can solve the problem of controlling complex processes with time-variance, nonlinearity and uncertain factors (Cai, et al., 1996). The hydrometallurgical zinc process can be considered to be a steady-state chemical process because it is generally run at a specific operating point, or within a specific operating range. Moreover, the complex relationships among the factors influencing the process can be expressed by rule models, and a combination of rule models and steady-state mathematical models. Both types of models are based on the experience of experts and operators and accumulated empirical knowledge of the process. This makes it is possible to control the process through a combination of DCCS and ECS.

In this study, a DCCS and an ECS were integrated to construct a distributed expert control system for the hydrometallurgical zinc process (DECSHZ). The system employs a distributed architecture and expert control strategies based on rule models, and a combination of rule models and steady-state mathematical models to achieve real-time control of the process. This paper is mainly concerned with the design and application of DECSHZ. First, the distributed architecture and main functions of DECSHZ are described. Secondly, the expert control strategies based on rule models and a combination of rule models and steady-state mathematical models are outlined. Thirdly, the implementation is described, and the results of actual runs are presented. Finally, some conclusions are given.

2. DISTRIBUTED ARCHITECTURE AND MAIN FUNCTIONS

DECSHZ is designed for the hydrometallurgical zinc process in a nonferrous metals smeltery. This section describes the process, and explains the distributed architecture and main functions of DECSHZ.

2.1. Process description

The hydrometallurgical zinc process that was studied is shown in Fig. 1 (Zhuzhou Smeltery, 1973). The zinc-bearing materials are obtained from calcine produced by the roasting of zinc sulfide concentrates, and from zinc fume obtained by the treatment of

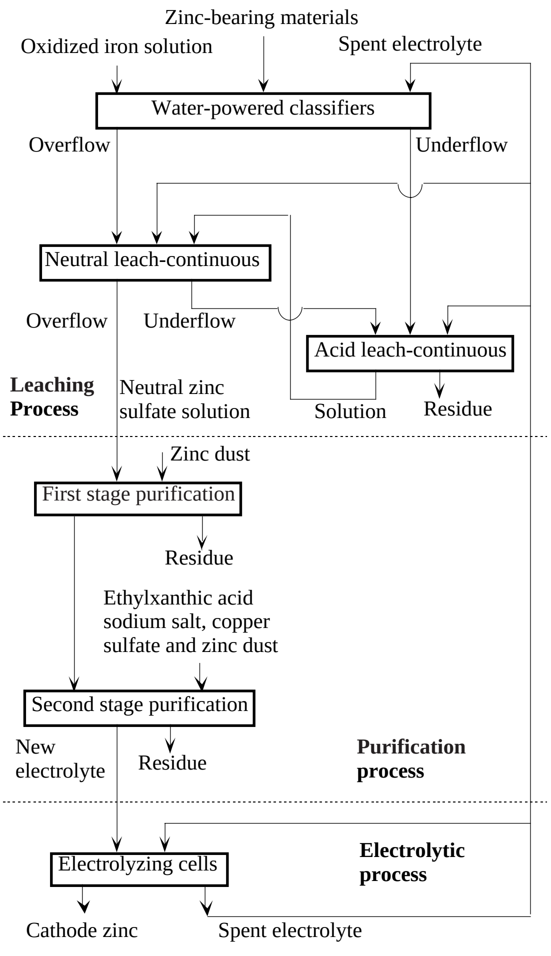

Fig. 1. Hydrometallurgical zinc process.

zinc-bearing residues.

The primary purpose of leaching is to dissolve as much of the soluble zinc in the zinc-bearing materials as possible. A technology of neutral and acid leach-continuous is used. The zinc-bearing materials are delivered to four water-powered classifiers, and dissolved in an oxidized iron solution and spent electrolyte which contains sulfuric acid. The overflow is processed in one series of neutral leach tanks, and the underflow is processed in two series of acid leach tanks. The spent electrolyte is also added to the neutral and acid leach tanks. The overflow from the neutral leach-continuous goes to the purification process in the form of a neutral zinc sulfate solution; the underflow goes to the acid leach tanks. The solution obtained from acid leach-continuous is fed back into the neutral leach tanks.

The neutral zinc sulfate solution requires purification because it contains impurities (mainly copper, cadmium and cobalt, with small amounts of nickel, arsenic, antimony, germanium, iron, etc.). A two-stage purification method is used. The main objective of the first stage is to remove copper and cadmium through the addition of zinc dust; and that of the second stage is to remove cobalt and the remaining cadmium through the addition of ethylxanthic acid sodium salt, copper sulfate and zinc dust. The second stage is a batch process. The purification also removes other impurities.

A low-zinc, low-acid electrolysis technology is used in the electrolytic process. The electrolyte added to the electrolyzing cells is a mixture of new electrolyte from the purification process and spent electrolyte. The recovery of zinc by electrolysis is accomplished by the application of an electrical current through insoluble electrodes, causing a decomposition of the aqueous zinc sulfate electrolyte and the deposition of metallic zinc on the cathode. In addition, oxygen is released at the anode, and sulfuric acid is formed by the combination of hydrogen and sulfate ions.

To ensure a product of high purity, the concentrations of zinc and the impurities in the solution after the neutral leach and after each stage of purification must meet the standards shown in Table 1. This requires that the optimal conditions for the chemical reactions involved must be maintained.

The key points in the control of the hydrometallurgical zinc process are: first, to determine the optimal pHs of the overflows from the neutral and acid leach-continuous, the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate added to the purification tanks, and the optimal concentrations of zinc and sulfuric acid in the electrolyte; and second, to track them so as to achieve the desired standards and reduce costs as much as

Table 1. Concentration standards for neutral leach and both purification stages (mg/l).

Elements	Zn(g/l)	Cu	Cd	Co
Neutral leach	140-165	160-450	400-1000	8-25
First stage	140-165	<0.2	<100	<10
Second stage	140-165	<0.2	<1.0	<1.0

Elements	Ni	As	Sb	Ge	Fe
Neutral leach	8-15	0.4-1.0	0.2-0.5	0.14-0.5	20-35
First stage	<6	<0.36	<0.5	<0.1	<30
Second stage	<1.0	<0.24	<0.3	<0.05	<20

possible. The empirical knowledge and data on the process show that the following constraints must be satisfied to obtain the optimal conditions for the chemical reactions:

(1) pHs of overflows
  from neutral leach-continuous: 4.8 - 5.2
  from acid leach-continuous: 2.5 - 3.0
(2) Additives for purification process.
  first stage
    zinc dust: 2.0 - 6.0 g/l
  second stage
    ethylxanthic acid sodium salt: ≤2.0 g/l
    copper sulfate: ≤1.5 g/l
    zinc dust: ≤0.5 g/l
(3) Electrolyte.
  zinc concentration: 45 - 60 g/l
  sulfuric acid concentration: 150 - 200 g/l
  ratio of hydrogen ion concentration to zinc ion concentration: 3.0 - 3.8

DECSHZ is designed to satisfy the above control requirements.

In addition, the temperature of the electrolyte must be between 30 and 38 ^{o}C, which is achieved by cooling the returning spent electrolyte; and the current density at the cathode must be between 450 and 600 A/m^2, which is achieved by a hierarchical control system for the electrical load (Wu, et al., 1993).

2.2. Distributed architecture

The important considerations in the selection of the architecture for DECSHZ were the application environment and the main functions of the control system. In view of the particular nature and control requirements of the hydrometallurgical zinc process, DECSHZ uses a star distributed architecture with three levels: real-time control, control optimization and quality optimization, as shown in Fig. 2. It consists of a central computer management system (CCMS) and three local expert control systems for leaching (ECSL), purification (ECSP) and electrolysis (ECSE). ECSL, ECSP and ECSE are allocated to levels 1 and 2; CCMS is at level 3.

CCMS collects on-line data from ECSL, ECSP and ECSE to perform the quality optimization. ECSL, ECSP and ECSE complete the control optimization and provide real-time control of each process in accordance with the quality requirements sent from CCMS. CCMS, ECSL, ECSP and ECSE are connected in a star-shaped local-area network. Data communication interfaces (DCI) provide long-distance data transmission between CCMS, ECSL, ECSP and ECSE.

ECSL consists of an expert controller (ECL), three 761-series single-loop controllers (761SLC), signal amplifiers and converters (SA/SC), and control and measurement mechanisms (CM/MM). A wiring concentrator and converter (WCC) handles data communication between ECL and 761SLCs. Taking the quality of the zinc-bearing materials being used and the temperature of the solution into account, ECL uses a forward-chaining strategy based on rule models to determine the optimal pHs of the overflows of the neutral and acid leach-continuous, and to obtain the target flows of the spent electrolyte added to the neutral and acid leach tanks. There are three 761SLCs: one is allocated to the neutral-leach series, and one is allocated to each of the two series of the acid leach. PI control algorithms are used to track the target flows.

ECSP has an expert controller (ECP) and an I/A-series distributed control system (IADCS). ECP determines the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate to be added to the purification tanks on the basis of the concentrations of the main impurities in the solution by using a reasoning strategy that combines forward chaining and model-based reasoning. The reasoning strategy is based on a combination of rule models and steady-state mathematical models of the process. The values of the optimal amounts thus determined are sent to a control processor (CP10) in IADCS through a note bus interface (NBI). CP10 is connected through a field bus to ten field-bus modulars (FBM), ten control mechanisms (CM), an intelligent measurement system (IMS) and associated measurement mechanisms (MM) to form ten control loops that track the optimal amounts of additives to the first and second purification stages, and to control the flow of the neutral zinc sulfate solution pumped into the first-stage purification tanks. PI control algorithms are used in the control loops. In IADCS, an application processor (AP20) handles the storage, display and printing of the on-line data from the purification process. A workstation processor (WP30) handles the man-machine interface used to configure the functions of IADCS. External equipment is connected to IADCS through a communication processor (CP40), which employs a manufacturing automation protocol.

ECSE contains an expert controller (ECE) and three

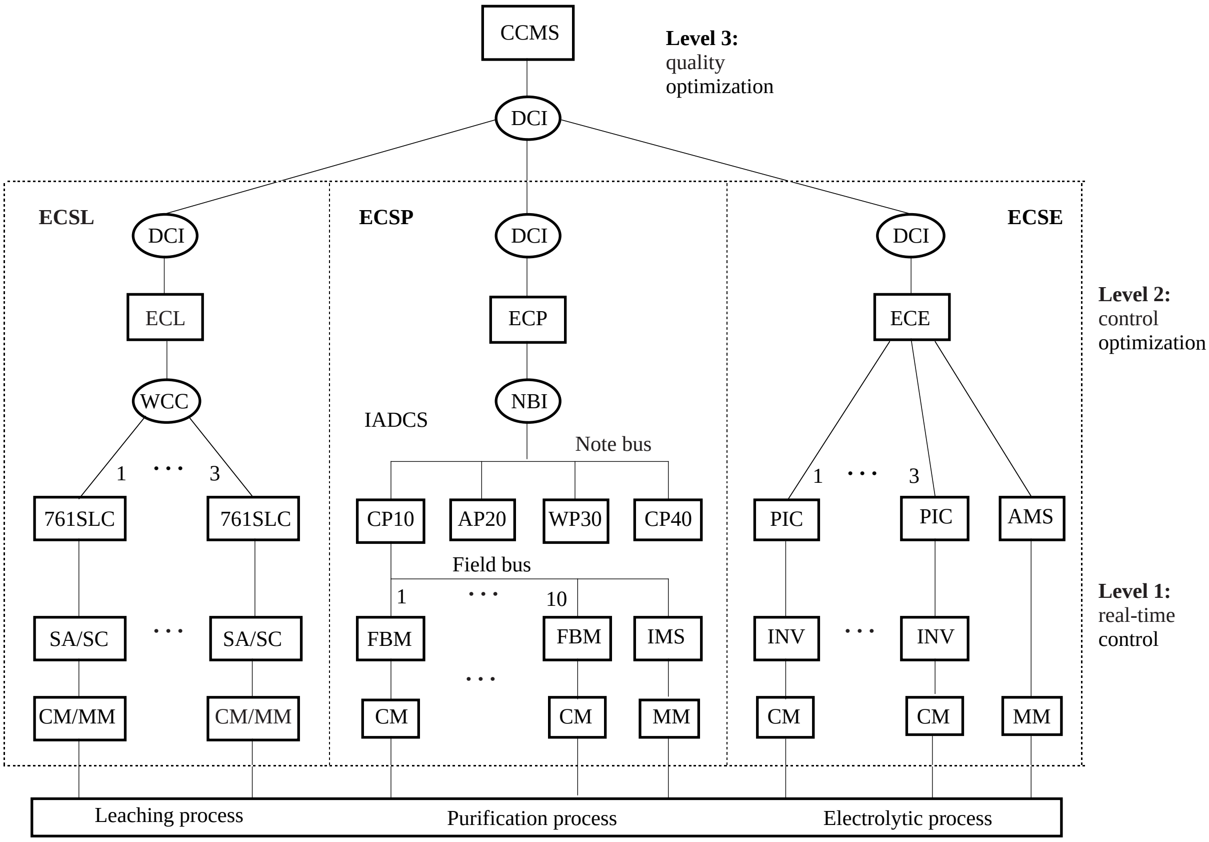

Fig. 2. Distributed architecture of DECSHZ.

PI controllers (PIC). ECE determines the optimal concentrations of zinc and sulfuric acid in the electrolyte, based on the temperature of the electrolyte and the current density at the cathode, and employs a forward-chaining strategy based on rule models to compute the target flow of the new electrolyte added to the electrolysis cells, so as to yield the maximum efficiency for the current being used. There are three flow-control loops. The PICs control the speeds of three pumps by means of inverters (INV) to track the target flow. An automatic measurement system (AMS) measures the concentrations of zinc, sulfuric acid and impurities in the solution, as well as the temperature and flow of the solution, etc.

2.3. Main functions

DECSHZ has six primary functions:

(1) Control optimization, which is the determination of the optimal pHs, optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate, and optimal concentrations of zinc and sulfuric acid.

(2) Real-time control, which includes tracking control of the optimal target values obtained from the control optimization.

(3) Quality optimization, which determines the quality requirements for leaching, purification and electrolysis.

(4) On-line centralized supervision of leaching, purification and electrolysis, which is implemented in a primary control room (for managers) and three secondary control rooms (for engineers and operators).

(5) On-line fault diagnosis, which ensures the safe running of the hydrometallurgical zinc process and DECSHZ.

(6) Information management, such as accumulation, storage, statistical analysis, classification, query, reporting and trend analysis of the process data, as well as quality prediction, cost estimation, etc.

3. STRUCTURES OF THE EXPERT CONTROLLERS AND CONTROL STRATEGIES

The key point in the design of DECSHZ is the design of ECL, ECP and ECE. This section describes the structure and control strategies of these three controllers.

3.1. Structures of the expert controllers

ECL, ECP and ECE have a similar structure (Fig. 3), which consists of a characteristics-capturing mechanism, a database, a knowledge base, an inference engine and a user interface. (Items in brackets "[ ]" are for ECP only.)

The characteristics-capturing mechanism handles process data from the real-time control level, to obtain

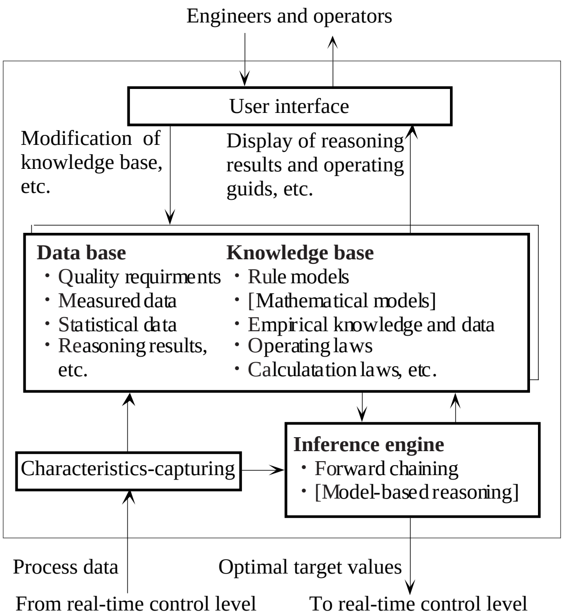

Fig. 3. Structure of an expert controller.
Fig. 3. Structure of an expert controller.

data on characteristics. These data are stored in a working memory, and are used by the database, knowledge base and inference engine.

The database stores the quality requirements, measured data and statistical data on the process, and the reasoning results from the inference engine, etc.

The knowledge base stores the rule models, steady-state mathematical models (for use by ECP only), empirical knowledge and data, and operating laws for the process, as well as calculation laws, etc.

The inference engine acquires the data related to the process characteristics from the working memory, and then uses the knowledge in the knowledge base and a forward-chaining strategy (for ECL and ECE) or a reasoning strategy that combines forward chaining and model-based reasoning (for ECP) to determine optimal target values for the real-time control level.

The user interface is used to edit and modify the knowledge base, as well as to display and print the reasoning results and operating guidelines, etc.

3.2. Knowledge representation

ECL, ECP and ECE use the empirical knowledge of veteran engineers and operators, and empirical data on the process, to solve control problems for leaching, purification and electrolysis. How empirical knowledge and data on the process is obtained and represented is an important aspect of the design of ECL, ECP and ECE.

Empirical knowledge is culled from experienced engineers and operators. The following empirical methods were extracted from interviews with them.

(1) Method of determining a) the optimal pHs of the overflows from the neutral and acid leach-continuous according to the quality of the zinc-bearing materials and the temperature of the solution, and b) the appropriate target flows of the spent electrolyte to be added to the neutral and acid leach tanks.

(2) Method of determining the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate to be added to the purification tanks from the concentrations of the main impurities in the solution.

(3) Method of determining a) the optimal concentrations of zinc and sulfuric acid in the electrolyte from the temperature of the electrolyte and the current density at the cathode, and b) the appropriate target flow of the new electrolyte to be added to the electrolyzing cells.

The empirical data was culled from past operating runs, measured values and statistical data on the hydrometallurgical zinc process. This kind of data is a key element in process control.

All empirical knowledge on the process is represented by production rule models of the following form (Efstathiou, 1989)

$$R^{\#}: \text{If } \textit{condition} \text{ Then } \textit{action}, \qquad (1)$$

where $R^{\#}$ is the number of the rule model, *condition* is the operating state of the process or a logical combination of operating states, and *action* is the conclusion or the operation. These rule models are stored in the knowledge base.

For process control, *condition* includes the predetermined standards, quality, temperature, pHs, flows, concentrations, current density, etc., and *action* includes the determination of optimal target values, the adjustment of reasoning results, etc.

3.3. Expert control strategies

The expert control strategy for the control of leaching and electrolysis is based solely on rule models; that for the control of purification is based on a combination of rule models and steady-state mathematical models.

It follows from the discussion in Section 3.1 that the inference engines of ECL and ECE employ a forward-chaining strategy based solely on the rule models for leaching and electrolysis, and that the inference engine of ECP employs a reasoning strategy based on a combination of the rule models and steady-state mathematical models for purification.

4. EXPERT CONTROL STRATEGY BASED SOLELY ON RULE MODELS

Both ECL and ECE use the same expert control strategy, which is based solely on rule models; but ECE has a somewhat more complicated design. This section explains only the design of ECE. ECL was designed by the same method.

4.1. Empirical knowledge and data

Empirical knowledge is acquired mainly from interviews with experienced engineers and operators working on the process. For instance, an efficient empirical method of determining the optimal concentrations of zinc and sulfuric acid in the electrolyte is used. More specifically, the optimal ranges of the concentrations of zinc and sulfuric acid are first determined from the temperature of the electrolyte and the current density at the cathode. Next, an initial concentration of zinc is selected from the optimal range, and the appropriate target flow is computed for the new electrolyte, added to the electrolyzing cells. Then, the concentration of sulfuric acid in the electrolyte is estimated under the assumption that new electrolyte is supplied at the computed target flow. If the estimate is in the optimal range of sulfuric acid concentrations, the selected concentration of zinc and the estimated concentration of sulfuric acid are used as optimal values. If this is not the case, the selection, computation and estimation procedures are repeated until the optimal concentrations of zinc and sulfuric acid are finally obtained.

The following empirical expressions are used to compute the target flow of the new electrolyte, and to estimate the concentration of sulfuric acid in the electrolyte.

$$Q_1 = k_1 \frac{x_1 - x_{O1}}{x_{N1} - x_1} Q_2 \tag{2}$$

$$x_2 = k_2 \frac{Q_2}{Q_1 + Q_2} x_{O2}\,, \tag{3}$$

where Q_1 is the target flow of the new electrolyte, Q_2 is the flow of the returning spent electrolyte, x_1 is the selected concentration of zinc, x_2 is the estimated concentration of sulfuric acid, x_{O1} and x_{O2} are the concentrations of zinc and sulfuric acid in the spent electrolyte, respectively, and k_1 and k_2 are empirically determined coefficients.

It is important to obtain empirical data on the electrolytic process. This is mainly statistical data concerning the relationships between the concentrations of zinc and sulfuric acid in the electrolyte, the temperature of the electrolyte, the current density at the cathode, and the current efficiency.

4.2. Construction of rule models

The empirical knowledge and data are represented using the form (1) in Section 3.2. As shown in Table 2, some typical rule models are used to determine the optimal concentrations of zinc and sulfuric acid in the electrolyte. The allowable variation in the temperature of the electrolyte and the current density are classified into m real sets $\tilde{T}_i$ $(i = 1,\ 2,\ \cdots,\ m)$ and n real sets $\tilde{I}_j$ $(j = 1,\ 2,\ \cdots,\ n)$, respectively. x_T is the temperature of the electrolyte, x_I is the current density, x_{1opt} and x_{2opt} are the optimal concentrations of zinc and sulfuric acid, respectively, $\tilde{X}_1$ and $\tilde{X}_2$ are the optimal ranges of the zinc and sulfuric acid concentrations in the electrolyte, respectively, $\tilde{A}_{ij}$ and $\tilde{B}_{ij}$ $(i = 1, 2, \cdots, m,\ j = 1, 2, \cdots, n)$ are the corresponding empirical ranges, and Δx is an empirical value.

Table 2. Some typical rule models for concentration control

R^{E1} : If $x_T \in \tilde{T}_i$ and $x_I \in \tilde{I}_j$	Then $\tilde{X}_1 = \tilde{A}_{ij}$ and $\tilde{X}_2 = \tilde{B}_{ij}$
R^{E2} : If $x_1 \in \tilde{X}_1$ and $x_2 > \max(\tilde{X}_2)$	Then $x_1 = x_1 + \Delta x$
R^{E3} : If $x_1 \in \tilde{X}_1$ and $x_2 < \min(\tilde{X}_2)$	Then $x_1 = x_1 - \Delta x$
R^{E4} : If $x_1 > \max(\tilde{X}_1)$	Then $x_1 = \max(\tilde{X}_1)$
R^{E5} : If $x_1 < \min(\tilde{X}_1)$	Then $x_1 = \min(\tilde{X}_1)$
R^{E6} : If $x_1 \in \tilde{X}_1$ and $x_2 \in \tilde{X}_2$	Then $x_{1opt} = x_1$ and $x_{2opt} = x_2$

4.3. Determination of optimal concentrations

The concentrations of zinc and sulfuric acid in the electrolyte are determined by a forward-chaining strategy (Efstathiou, 1989) based on the rule models. An algorithm for determining the optimal concentrations and computing the target flow of new electrolyte are derived as follows:

(1) Measure x_T, x_I, x_{N1}, x_{O1}, x_{O2} and Q_2.

(2) Determine $\tilde{X}_1$ and $\tilde{X}_2$ by rule model R^{E1} and select k_1 and k_2.

(3) Set

$$x_1 = \frac{\max(\tilde{X}_1) + \min(\tilde{X}_2)}{2}. \tag{4}$$

(4) Compute Q_1 from expression (2) and estimate x_2 from expression (3).

(5) Test if $x_2 \in \tilde{X}_2$. If it is true, determine the optimal concentrations x_{1opt} and x_{2opt} from rule model R^{E6}. If not, modify x_1 according to rule models R^{E2} - R^{E5} and return to step (4).

5. EXPERT CONTROL BASED ON RULES AND MATHEMATICAL MODELS

This section describes steady-state mathematical models of the purification process, which are based on both the chemical reactions involved and empirical data on the process, and are modified in accordance with the empirical knowledge of veteran engineers and operators, and empirical data on the process.

ECP employs a combination of modified mathematical models and rule models to determine the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate added to the first- and second-stage purification tanks.

5.1. Steady-state mathematical models

Consider first the steady-state mathematical models of the first stage of purification. Assume that the neutral zinc sulfate solution and zinc dust in the reaction tanks are agitated and completely mixed, and that the temperature of the solution is uniform. For component A in the solution, the following balance equation is obtained by the substance balance principle (Inugita and Nakanishi, 1987)

$$\varepsilon V \frac{\mathrm{d}C_A}{\mathrm{d}t} = F(C_A - C_{A0}) - \int_0^V r_A \mathrm{d}V, \quad (5)$$

where C_{A0} and C_A denote the concentrations of component A before and after the first stage of purification, respectively, V is the volume of the reaction tank, ε is the ratio of the volume of solution to the total volume, F is the flow of neutral zinc sulfate solution, and r_A is the reaction rate.

For the steady-state operating, r_A is the steady-state reaction rate. Let f_A denote the steady-state particle reaction rate of zinc dust with the component A, and let u denote the amount of zinc dust added to the reaction tank. Then

$$\frac{M}{M_A} r_A = f_A u \quad (6)$$

is obtained by the principle of steady-state substance balance, where M_A and M are the atomicities of component A and zinc, respectively.

Combining expression (6) with eq. (5) in the steady state yields the following steady-state balance equation:

$$F(C_A - C_{A0}) = \frac{M_A V}{M} f_A u. \quad (7)$$

The above equation gives the amounts of zinc dust to be added to the first-stage purification tanks for copper and for cadmium:

$$F(x_{\mathrm{Cu}}^1 - x_{\mathrm{Cu}}^0) = \frac{M_{\mathrm{Cu}} V}{M} f_{\mathrm{Cu}} u_1 \quad (8a)$$

$$F(x_{\mathrm{Cd}}^1 - x_{\mathrm{Cd}}^0) = \frac{M_{\mathrm{Cd}} V}{M} f_{\mathrm{Cd}} u_2, \quad (8b)$$

where x_{Cu}^0 and x_{Cu}^1 are the concentrations of copper before and after first-stage purification, respectively, x_{Cd}^0 and x_{Cd}^1 are concentrations of cadmium before and after first-stage purification, f_{Cu} and f_{Cd} are the particle reaction rates for zinc dust with copper and with cadmium, respectively, u_1 and u_2 are the amounts of zinc dust that must be added to remove the copper and cadmium, respectively, and M_{Cu} and M_{Cd} are the atomicities of copper and cadmium, respectively. It is clear that the amount of zinc dust to be added to the first stage purification tanks is the sum of u_1 and u_2. Let that be denoted by u_Σ. Then

$$u_\Sigma = F[K_1(x_{\mathrm{Cu}}^1 - x_{\mathrm{Cu}}^0) + K_2(x_{\mathrm{Cd}}^1 - x_{\mathrm{Cd}}^0)], \quad (9)$$

where

$$K_1 = \frac{M}{VM_{\mathrm{Cu}} f_{\mathrm{Cu}}}, \quad K_2 = \frac{M}{VM_{\mathrm{Cd}} f_{\mathrm{Cd}}}. \quad (10)$$

The coefficients K_1 and K_2 can be estimated by the least-squares identification method (Middleton and Goodwin, 1990) from the steady-state data on the purification process. Using these estimates $\hat{K}_1$ and $\hat{K}_2$, u_Σ can be written as

$$u_\Sigma = F[\hat{K}_1(x_{\mathrm{Cu}}^1 - x_{\mathrm{Cu}}^0) + \hat{K}_2(x_{\mathrm{Cd}}^1 - x_{\mathrm{Cd}}^0)]. \quad (11)$$

The above is the steady-state mathematical model for determining the amount of zinc dust to be added to the first stage purification tanks.

The amount of ethylxanthic acid sodium salt added to the second-stage purification tanks is obtained by the same method. Let v_Σ denote the amount of ethylxanthic acid sodium salt. Then,

$$v_\Sigma = V[\hat{K}_3(x_{\mathrm{Co}}^2 - x_{\mathrm{Co}}^1) + \hat{K}_4(x_{\mathrm{Cd}}^2 - x_{\mathrm{Cd}}^1)], \quad (12)$$

where x_{Co}^1 and x_{Co}^2 are the concentrations of cobalt before and after the second-stage purification, respectively, x_{Cd}^2 is the concentration of copper after the second stage of purification, V is the volume of solution in the reaction tank, and $\hat{K}_3$ and $\hat{K}_4$ are coefficients estimated by the least-squares identification method.

In addition, the amounts of copper sulfate and zinc dust to be added to the second-stage purification tanks are obtained from the following expressions:

$$w_\Sigma = \hat{K}_5 v_\Sigma \quad (13)$$

$$z_\Sigma = V[\hat{K}_6 + \hat{K}_7(x_{\mathrm{Cd}}^2 - x_{\mathrm{Cd}}^1)], \quad (14)$$

where $\hat{K}_5$, $\hat{K}_6$ and $\hat{K}_7$ are empirically determined coefficients.

The steady-state mathematical models (11)-(14) of the purification process are taken as nominal mathematical models because they are concerned only with the removal of copper, cadmium and cobalt from the solution. However, there are also other impurities in the solution, and the chemical reaction conditions may change in allowable ranges. For these reasons, models (11)-(14) need to be modified by the empirical knowledge of engineers and operators, and empirical data on the process, in order to determine the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate to be added to the reaction tanks so that all the impurities are removed from the solution.

Assume that $x_{\mathrm{Cu}}^{1\mathrm{g}}$ and $x_{\mathrm{Cd}}^{1\mathrm{g}}$ denote the target concentrations of copper and cadmium after the first stage of purification, and $x_{\mathrm{Co}}^{2\mathrm{g}}$ and $x_{\mathrm{Cd}}^{2\mathrm{g}}$ denote those of cobalt and cadmium after the second stage. From experience, the optimal amount $u_{opt}(k)$ of zinc dust added to the first-stage purification tanks during the k-th period is given by the following expressions:

$$u_{opt}(k) = \lambda_1(k)u_\Sigma(k) + \sum_{l=0}^{k} \lambda_2(l)\Delta u_\Sigma(l) \quad (15a)$$

$$u_\Sigma(k) = F[\hat{K}_1(x_{\mathrm{Cu}}^{1\mathrm{g}} - x_{\mathrm{Cu}}^{0}(k)) + \hat{K}_2(x_{\mathrm{Cd}}^{1\mathrm{g}} - x_{\mathrm{Cd}}^{0}(k))] \quad (15b)$$

$$\Delta u_\Sigma(k) = F[\hat{K}_1(x_{\mathrm{Cu}}^{1\mathrm{g}} - x_{\mathrm{Cu}}^{1}(k)) + \hat{K}_2(x_{\mathrm{Cd}}^{1\mathrm{g}} - x_{\mathrm{Cd}}^{1}(k))], \quad (15c)$$

where $\lambda_1(k)$ and $\lambda_2(l)$ are empirical coefficients determined from the empirical knowledge of veteran engineers and operators, as well as the concentrations of copper and cadmium before and after the first stage of purification. Similarly, the optimal amounts $v_{opt}(k)$, $w_{opt}(k)$ and $z_{opt}(k)$ of ethylxanthic acid sodium salt, copper sulfate and zinc dust, respectively, added to the second-stage purification tanks during the k-th period, are given by the following expressions:

$$v_{opt}(k) = \begin{cases} \mu_1(k)v_\Sigma(k), & k = 0 \\ \mu_2(k)\Delta v_\Sigma(k), & k > 0 \end{cases} \quad (16a)$$

$$v_\Sigma(0) = V[\hat{K}_3(x_{\mathrm{Co}}^{2\mathrm{g}} - x_{\mathrm{Co}}^{1}) + \hat{K}_4(x_{\mathrm{Cd}}^{2\mathrm{g}} - x_{\mathrm{Cd}}^{1})] \quad (16b)$$

$$\Delta v_\Sigma(k) = V[\hat{K}_3(x_{\mathrm{Co}}^{2\mathrm{g}} - x_{\mathrm{Co}}^{2}(k)) + \hat{K}_4(x_{\mathrm{Cd}}^{2\mathrm{g}} - x_{\mathrm{Cd}}^{2}(k))] \quad (16c)$$

$$w_{opt}(k) = \begin{cases} w_\Sigma(k), & k = 0 \\ \Delta w_\Sigma(k), & k > 0 \end{cases} \quad (17a)$$

$$w_\Sigma(0) = \hat{K}_5 v_\Sigma(0) \quad (17b)$$

$$\Delta w_\Sigma(k) = \hat{K}_5 \Delta v_\Sigma(k) \quad (17c)$$

$$z_{opt}(k) = \begin{cases} \gamma_1(k)z_\Sigma(k), & k = 0 \\ \gamma_2(k)\Delta z_\Sigma(k), & k > 0 \end{cases} \quad (18a)$$

$$z_\Sigma(0) = V[\hat{K}_6 + \hat{K}_7(x_{\mathrm{Cd}}^{2\mathrm{g}} - x_{\mathrm{Cd}}^{1}) \quad (18b)$$

$$\Delta z_\Sigma(k) = V[\hat{K}_6 + \hat{K}_7(x_{\mathrm{Cd}}^{2\mathrm{g}} - x_{\mathrm{Cd}}^{2}(k)), \quad (18c)$$

where $\mu_1(k)$, $\mu_2(k)$, $\gamma_1(k)$ and $\gamma_2(k)$ are empirical coefficients determined from the empirical knowledge of engineers and operators, as well as the concentrations of cobalt and cadmium before and after the second stage of purification.

Expressions (15)-(18) are modified steady-state mathematical models of the purification process that are used to determine the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate to be added to the reaction tanks.

5.2. Description of rule models

The empirical knowledge of experienced engineers and operators is represented as production-rule models of the form (1) in Section 3.2. The main content of the *condition* part is as follows:

(1) Error between target and measured values of the concentrations (large, middle and small).

(2) Variation in the concentrations (large and small).

(3) Control inputs, such as the amount of zinc dust, etc. (larger than the allowable value, large and small).

(4) Reaction conditions (temperatures, flows, and pHs are/are not in the allowable range).

(5) Relationships between the components (e.g., the ratio of copper to cadmium, etc.).

(6) Other process states.

The main content of the *action* part is instructions to increase, reduce or maintain the control inputs, and to display the optimal target values for the batch processing.

Assume that $\lambda_{1\mathrm{H}}$, $\lambda_{1\mathrm{M}}$, $\lambda_{2\mathrm{H}}$, $\lambda_{1\mathrm{L}}$, $\mu_{1\mathrm{M}}$, $\mu_{2\mathrm{L}}$, $\gamma_{1\mathrm{M}}$ and $\gamma_{2\mathrm{L}}$ are the empirical coefficients stored in the knowledge base, OBF and OBS denote the concentrations of other impurities before the first and second stages of purification, respectively, VAF denotes variations in the concentrations of copper and cadmium during the first stage of purification, $u_{\max}$ is the maximum allowable amount of zinc dust added to the first-stage purification tanks, and $v_{\max}$ is the maximum allowable amount of ethylxanthic acid sodium salt added to the second-stage purification tanks. Some typical rule models used in the first and second stages of purification are shown in Table 3.

5.3. Determination of optimal amounts

Through a combination of modified mathematical models and rule models, ECP uses a reasoning strategy that combines forward chaining (Efstathiou, 1989) and model-based reasoning (Ishiduka and Kobayashi, 1991) to determine the optimal amounts u_{opt}, v_{opt}, w_{opt} and z_{opt}. The following algorithm determines the optimal amounts.

(1) Measure the concentrations of impurities in the solution, before and after each stage of purification.

(2) Calculate the error between target and measured concentrations, and the variations of the concentrations.

(3) Determine coefficients λ_1 and λ_2 from rule models, such as R^{P1} - R^{P4}.

(4) Determine the optimal amount $u_{opt}(k)$ from the steady-state mathematical model (15).

(5) Calculate $v_\Sigma(0)$, $w_\Sigma(0)$ and $z_\Sigma(0)$ from the expressions (16b), (17b) and (18b), or $\Delta v_\Sigma(k)$, $\Delta w_\Sigma(k)$ and $\Delta z_\Sigma(k)$ from the expressions (16c), (17c) and (18c).

(6) Determine the optimal amounts $v_{opt}(0)$, $w_{opt}(0)$ and $z_{opt}(0)$ from rule models such as R^{P6};

Table 3. Some typical rule models for the first and second stages of purification.

Rule	If	Then
First-stage purification:		
R^{P1} :	If $x_{\mathrm{Cu}}^{0}(k)-x_{\mathrm{Cu}}^{1g}$ large and $x_{\mathrm{Cd}}^{0}(k)-x_{\mathrm{Cd}}^{1g}$ large and OBF large and VAF large	Then $\lambda_1(k)=\lambda_{1\mathrm{H}}$
R^{P2} :	If $x_{\mathrm{Cu}}^{0}(k)-x_{\mathrm{Cu}}^{1g}$ middle and $x_{\mathrm{Cd}}^{0}(k)-x_{\mathrm{Cd}}^{1g}$ small and OBF middle and VAF small	Then $\lambda_1(k)=\lambda_{1\mathrm{M}}$
R^{P3} :	If $x_{\mathrm{Cu}}^{1}(k)-x_{\mathrm{Cu}}^{1g}$ large and $x_{\mathrm{Cd}}^{1}(k)-x_{\mathrm{Cd}}^{1g}$ midlle	Then $\lambda_2(k)=\lambda_{2\mathrm{H}}$
R^{P4} :	If $x_{\mathrm{Cu}}^{1}(k)-x_{\mathrm{Cu}}^{1g}$ small and $x_{\mathrm{Cd}}^{1}(k)-x_{\mathrm{Cd}}^{1g}$ large	Then $\lambda_2(k)=\lambda_{2\mathrm{L}}$
R^{P5} :	If $u_{opt}(k)>u_{\max}$ and $u_{opt}(k-1)$ small	Then $u_{opt}(k)=u_{\max}$
Second-stage purification:		
R^{P6} :	If $x_{\mathrm{Co}}^{1}(k)-x_{\mathrm{Co}}^{2g}$ midlle and $x_{\mathrm{Cd}}^{1}(k)-x_{\mathrm{Cd}}^{2g}$ large and OBS small	Then $v_{opt}(0)=\mu_{1\mathrm{M}}v_{\Sigma}(0)$ and $w_{opt}(0)=w_{\Sigma}(0)$ and $z_{opt}(0)=\gamma_{1\mathrm{M}}z_{\Sigma}(0)$
R^{P7} :	If $x_{\mathrm{Co}}^{2}(k)-x_{\mathrm{Co}}^{2g}$ small and $x_{\mathrm{Cd}}^{2}(k)-x_{\mathrm{Cd}}^{2g}$ middle and reaction time over	Then $v_{opt}(k)=\mu_{2\mathrm{L}}\Delta v_{\Sigma}(k)$ and $w_{opt}(k)=\Delta w_{\Sigma}(k)$ and $z_{opt}(k)=\gamma_{2\mathrm{L}}\Delta z_{\Sigma}(k)$ and extend reaction time
R^{P8} :	If $v_{opt}(0)>v_{\max}$	Then $v_{opt}(0)=v_{\max}$

or $v_{opt}(k)$, $w_{opt}(k)$ and $z_{opt}(k)$ from rule models such as R^{P7}.

(7) Modify the optimal amount $u_{opt}(k)$ according to rule models such as R^{P5} if it is outside the allowable range.

(8) Modify the optimal amounts $v_{opt}(0)$, $w_{opt}(0)$ and $z_{opt}(0)$, or $v_{opt}(k)$, $w_{opt}(k)$ and $z_{opt}(k)$ according to rule models such as R^{P8} if they are larger than the maximum allowable value.

6. SYSTEM IMPLEMENTATION AND RESULTS OF ACTUAL RUNS

The methodologies presented in this paper were used in the design of ECSL, ECSP and ECSE. DECSHZ has been running in a nonferrous metals smeltery since 1996. It not only ensures the high purity of the metallic zinc produced, but also yields significant economic benefits.

6.1. Implementation of DECSHZ

DECSHZ was implemented with industrial control computers, single-loop controllers and a distributed control system. CCMS was implemented on an IPC 810 computer, and runs under the WINDOWS 3.2 operating system; ECL, ECP and ECE were implemented on three IPC 610 computers, and run under the MS-DOS 6.22 operating system. The functions of CCMS, ECL, ECP and ECE are implemented in four application software packages written in Borland C++ and 8086-series assembly language. The full implementation of the functions of 761SLC and IADCS was achieved through their configuration.

Special instruments are used to measure various kinds of the process data accurately. More specifically, flows are measured with E+H electromagnetic flow meters, pHs with industrial pH meters, and weights with electronic scales. A COURIER 30 X fluorescent analyzer, an EC25 electrochemical analyzer and an OTI95 automatic analyzer are used for the on-line measurement of the impurity concentrations of the solution during the purification process. An automatic measurement system measures the concentrations of zinc and sulfuric acid in the electrolyte.

6.2. Results of actual runs

The application of DECSHZ to the hydrometallurgical zinc process has proved to be more successful than originally anticipated. Not only has the maintenance of optimal chemical reaction conditions yielded a high-quality product, but the consumption of zinc-bearing material, zinc dust, ethylxanthic acid sodium salt, copper sulfate and power for electrolysis have also been reduced. In addition, general work procedures have been improved.

Figs 4-7 show the results of actual runs of the process. The dotted lines indicate the standard limits listed in Table 1 and the constraints given in Section 2.1.

Fig. 4 shows some results for leaching. The optimal pHs of the overflows of the neutral and acid leach-continuous are determined by ECL and tracked by 761SLCs. As much as possible of the soluble zinc in the zinc-bearing material is dissolved. It is clear that the pHs of the overflows of the neutral and acid leach-continuous satisfy the constraints (1) in Section 2.1, and that the neutral zinc sulfate solution produced by the leaching process meets the standards in Table 1.

The results for the first and second stages of the purification of the neutral zinc sulfate solution obtained from the leaching process are shown in Figs 5 and 6. The control inputs (the optimal amounts of zinc dust, ethylxanthic acid sodium salt and copper sulfate) are determined by ECP and added to the first- and second-stage purification tanks. The results show that the constraints (2) in Section 2.1 are satisfied, and that the concentrations of the major impurities (copper, cadmium, cobalt) are reduced enough to meet the standards in Table 1. In addition, the concentrations of zinc and other impurities (nickel, etc.) also meet the standards in Table 1.

Fig. 7 shows actual results for the electrolytic process.

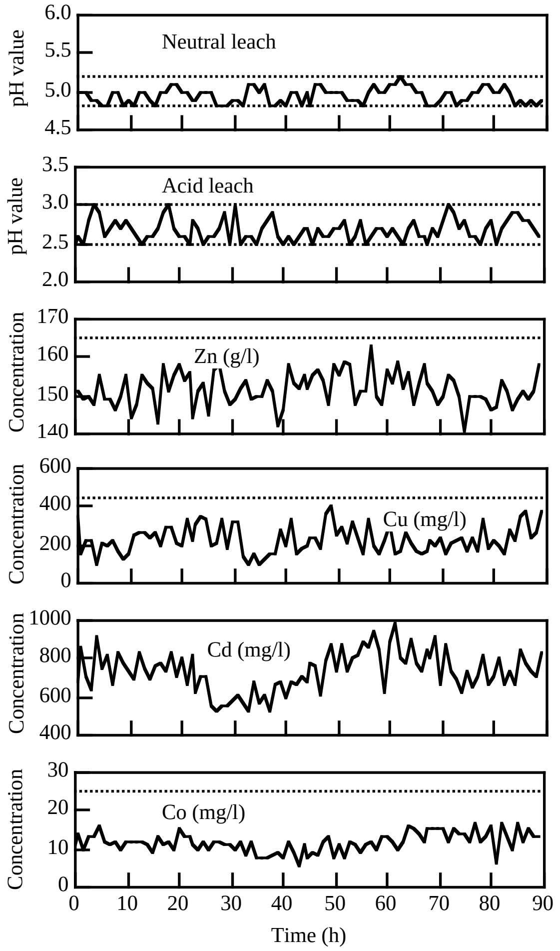

Fig. 4. Results for leaching.

It is clear that not only are the constraints (3) in Section 2.1 satisfied, but that the results were optimal under the consideration of those constraints.

6.3. Benefits

Statistical data on the hydrometallurgical zinc process show that not only is the high purity of product guaranteed, but that costs are considerably lower. In particular, a comparison with the results for manual control reveal the following facts:

(1) The leach rate of zinc-bearing materials is about 2% higher, which yields a higher recovery rate of metallic zinc.

(2) The consumption of zinc dust is about 11.5% lower, and the amounts of ethylxanthic acid sodium salt and copper sulfate used are also relatively low.

(3) The current efficiency of the electrolysis is 3.6% higher, which means that the electrical power used by the electrolytic process is reduced to 2,900~3,000 kw-h/ton.

7. CONCLUSIONS

This paper describes the design and application of DECSHZ, which is now running in a nonferrous metals smeltery. Four conclusions can be drawn from

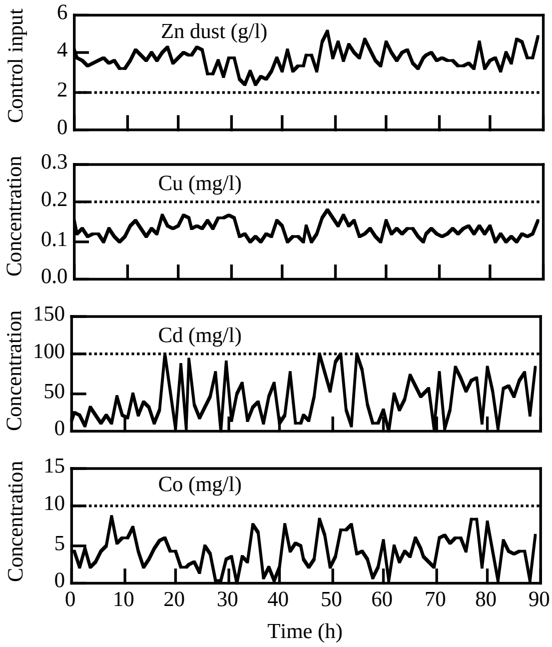

Fig. 5. Results for the first stage of purification.

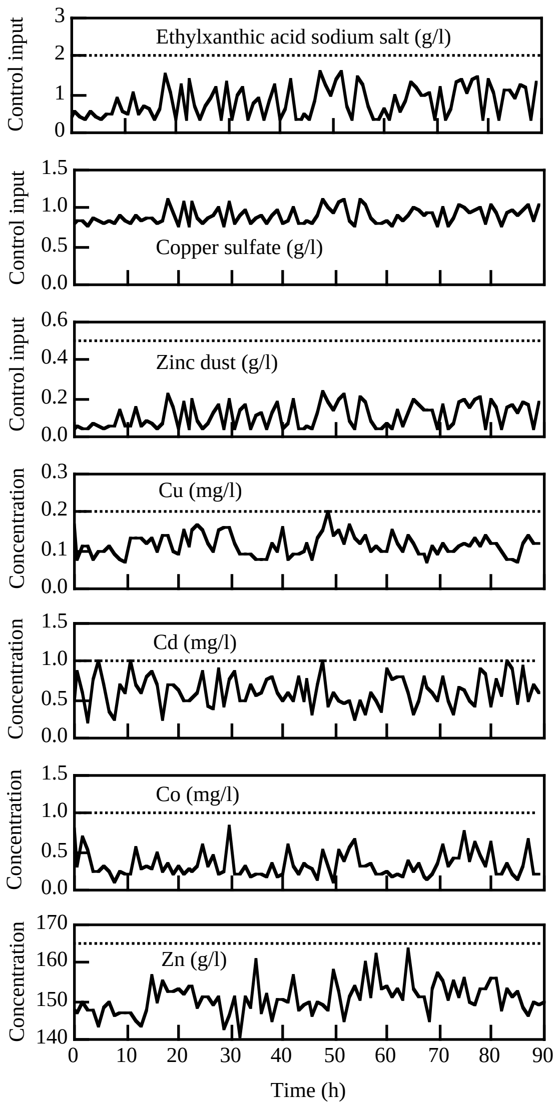

Fig. 6. Results for the second stage of purification.

the results of actual runs:

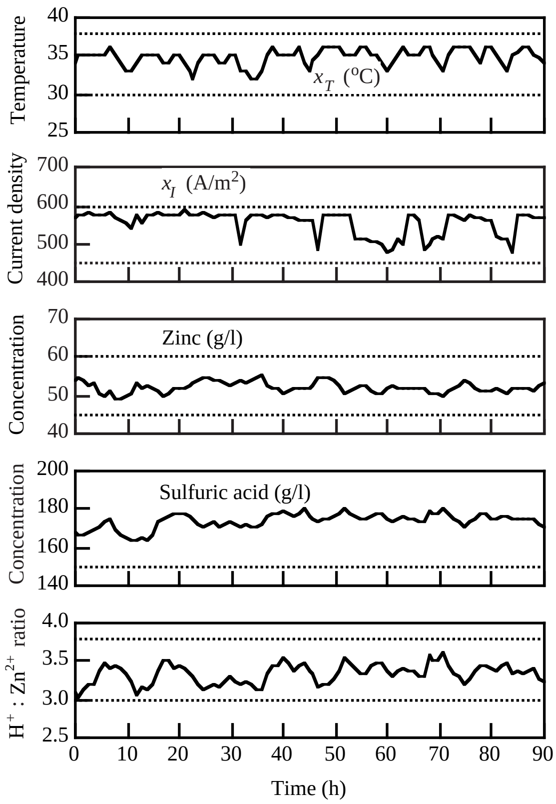

Fig. 7. Results for electrolysis.

(1) Expert control systems and distributed computer control systems can be used to control a hydrometallurgical zinc process, which has decentralized fields and complex behavior.

(2) The steady-state behavior of the process can be expressed in rule models or a combination of rule models and steady-state mathematical models based on the empirical knowledge of engineers and operators and empirical data on the process.

(3) Expert control strategies based on rule models and a combination of rule models and steady-state mathematical models can be used to determine optimal operating points for the process, such as the optimal pHs, control inputs and concentrations for leaching, purification and electrolysis, respectively.

(4) The distributed expert control system for this process was designed using the methodologies described above, and satisfies the practical control requirements. It provides not only a high-quality product, but also significant economic benefits.

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