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INTELLIGENT CONTROL METHOD AND APPLICATION OF HOT METAL DESULFURATION PROCESSES

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Abstract: This paper presents an intelligent control method of hot metal co-inject desulfuration which includes the expert setup model of desulfuration (ESMD) and the generalized feedback control mechanism (GFCM). ESMD is applied to the confirmation of the setup for the injection control system according to the experience data, and GFCM is applied to the reduction of the setup errors due to the changes of boundary conditions. The method has been implemented in the desulfuration control system design of certain steel plants and the results have satisfied the production demand. *Copyright©2002 IFAC*

Keywords: intelligent control, process control, expert system, optimization, qualitative analysis

1. INTRODUCTION

For the requirement of high purity steel in the market, the worldwide iron and steel industries have been making great efforts to increase the product quality by reducing the impurities in steel, especially by reducing the sulfur contained in hot metal (Yang and Gao, 1999).

The present widely used desulfuration method is Cao-Mg reagent co-inject hot metal desulfuration. Comparing with other continuous industry processes, the desulfuration method by Cao-Mg co-inject has the control characteristics listed as following:

1) Diversity of control target. The control design has to satisfy the technics requirement and reduce the production costs. Too much desulfuration reagents waste not only raw materials, but also energy with the unnecessary temperature loss of hot metal as well. On the other hand, excessive less desulfuration reagents may bring desulfuration process repetitions, increase working time, and influence next working sequence. An integrated target of the optimal process operation is needed to determine for the process control design.

2) Uncertainty of controlled objectives. The desulfuration process is mainly a chemical reaction process. The uncertain factors, such as, the initial sulfur value contained in hot metal, temperature of hot metal, appointed desulfuration aim value, operation condition of equipments, desulfuration reagent component status, and various man-made factors, affect the final result of desulfuration processes directly or indirectly, and make the control complex.

3) Dependence on the experiences. Since there is no on-line measure for the desulfuration process results with present technics condition, the control structure of the process appears open-looped. For shoot straight of desulfuration, the control system should have a predictive ability according to experience data.

Motivated by the above problems, this paper proposes an intelligent control method of co-inject hot metal desulfuration with combining traditional and intelligent control technologies, and its design is applied to the hot metal desulfuration projects in the certain steel plants.

2. ANALYSIS OF CO-INJECTION DESULFURATION SYSTEM

2.1. Technics and Mathematical Mode

The flow of the co-inject desulfuration is shown in Fig. 1.

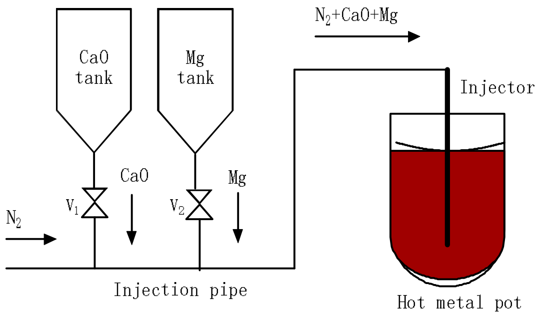

Fig. 1. Co-inject desulfuration flow diagram

The reagents from the Mg tank and CaO tank are mixed in the injection pipe and then are injected into the hot metal pot by the injector. Because the mouth of the injector is near the bottom of the pot, the hot metal is fully stirred with N_2 during it rises. Injected Mg powder is melted into [Mg] which is combined with [S] in the hot metal and becomes solid MgS, then rises into the scruff. The desulfuration process is to set up a set of reagent injecting volumes and rates according to the technics target, and then get the desired rates by adjusting throat valves and inject the desired volume of reagents into the hot metal in order to make the sulfur quantity of the hot metal below technics target. The desulfuration process is described in mathematics as the following:

$$Y = f_1(U_1, U_2, R, X, \Omega); \qquad (1)$$

Where, $Y=(Y_1,Y_2)^T$, Y_1 denotes the sulfur quantity in the hot metal; Y_2 denotes the hot metal temperature (℃); R denotes the desulfuration target value by technics; $X = (X_1, X_2, X_3)^T$ denotes the measurable boundary conditions, X_1 is the initial sulfur of the hot metal to be deal with, X_2 is the hot metal temperature, and X_3 is the weight of the hot metal; $\Omega = (\Omega_1, \Omega_2, \Omega_3, \Omega_4)^T$ denotes the immeasurable boundary conditions, Ω_1 is the Mg purity, Ω_2 is the season difference in temperature, Ω_3 represents the situation of the Mg and CaO powders, and Ω_4 represents the situation of equipment and precision of meters; $U_1=(U_{11},U_{12})^T$ is the output of Mg inject systems, U_{11} and U_{12} are respectively the injected volume and the inject rate of the Mg powder into the hot metal through the throat valve V_1; $U_2=(U_{21},U_{22})^T$ is the output of the CaO inject system, U_{21} and U_{22} are respectively the injected volume and the inject rates of the CaO powder into the hot metal through the throat valve V_2.

2.2. Design Aims and Control Points of Desulfuration Control Systems

In order to implement the optimal operation of systems, the control design of the hot metal desulfuration must approach following aims:

1) The technics aim. Suppose that R is the aim sulfur, T_1 is the sampling time before the injection, T_2 is the final sampling time after the injection, $Y_1(t)$ is the actually measured sulfur in the hot metal during the desulfuration, and $Y_1(T_2)$ is the measure value of sulfur in the hot metal after the desulfuration, then technics aim is:

$$(Y_1(T_2) - R) \leqslant 2 \text{ (ppm)} \qquad (2)$$

2) The optimal operation aim. Suppose that U_{11} is the actually injected volume of Mg powder per pot of hot metal during the desulfuration, U_{21} is the actually injected volume of CaO powder, and t is the time taken to reach the technics aim, then the optimal operation aim of control systems is:

$$\text{Minimum } (U_{11}+U_{21}) \wedge \text{Minimum } (t)$$
$$\text{st. } (Y_1(T_2) - R) \leqslant 2 \text{ (ppm)} \qquad (3)$$

In the desulfuration process, the quality, turnout and cost of steel are associated with the injection ratio and wastage of the reagents. Although it is good for the quality of steel that the content of sulfur in steel is less, it increases the cost of steel and takes more time and makes the hot metal temperature lower due to use excessive reagent, so as to reduce steel turnout and waste energy supply. So, it is vary significant to implement the optimal operation aims

The hot metal co-inject desulfuration is a complicated dynamic process, which is mainly represented as following:

1) The open-loop characteristics of control. Due to the technics limitation, the sulfur content of hot metal Y_1 and hot metal temperature Y_2 cannot be measured on line. The effect of desulfuration all depends on the experience setups that are decided on the measurable boundary condition gotten before the desulfuration. There have been various qualitative analyses to the desulfuration up to now, but not a certain universal arithmetic to quantify it owing to the limitation of experiment condition and the complexity of transaction. The desulfuration process can only be controlled depending on the experiential knowledge gotten from the results of each

desulfuration.

2) The uncertainty of desulfuration reaction. In desulfuration reaction process, Mg liquating ({Mg} ↔ [Mg]), and desulfuration reacting ([S] + [Mg] ↔ ⟨MgS⟩) are affected by many factors, which cannot be shown with the mathematic expressions.

3) The uncertainty of boundary condition. The boundary conditions of the co-inject desulfuration process, X and Ω, include some uncertain factors. The uncertain factors of measurable boundary conditions mainly are measure errors of operators; those of immeasurable boundary conditions mainly come from the purity change of the Mg powder.

4) The diversity of control target. For the co-inject desulfuration, it means that many optimal targets need to be met to implement production aim, which are shown in expressions (2-3). Except for the parameters mentioned in (2-3) such as the final sulfur $Y_1(T_2)$, the reagent dosages U_{11} and U_{12}, and the inject time t, the hot metal temperature fall is also important to the production. These factors are affected one and another in the desulfuration process.

On basis of the above analysis to the complexities, the design demands of desulfuration process control as follows must be contented:

1) The capacity of setting up volume and injection rate of the reagents. For the uncertainty of desulfuration, the volume and injection rate of desulfuration reagents cannot but be set up on the practical experience and the result of qualitative analysis.

2) The capacity of reducing the error between the final sulfur and aim sulfur on account of the uncertainties. For the change of the immeasurable boundary condition in the system there may be setup error of the desulfuration, the unavoidable difference between final sulfur and aim sulfur, so that an optimization mechanism to adjust the setup has to be included in the desulfuration control design.

3. INTELLIGENT CONTROL METHOD OF CO-INJECT DESULFURATION (ICMCD)

The intelligent control is the control provided with certain intelligent characteristics including (1) the design way in which human experiences and control theories are associated together; (2) the ability of learning on line and obtaining new knowledge; （3） the ability of dealing with the qualitative fuzzy information or quantitative precise information, and (4) the ability of reasoning logically and making decision (Wu and Xie, 1999). In the control demands described in the previous section, an outstanding point is that, due to the complexity of co-inject desulfuration, especially, the open-loop characteristic, the controlled object can not be described by precise mathematical expressions. For the purpose of controlling the desulfuration production, the control design should be finished by the combination of traditional control methods and intelligent control technologies. Therefore, the desulfuration control is divided into two parts: one is to use traditional PID scheme to precisely control the injection facilities; the other is to use expert control techniques to simulate the intelligent activities of metallurgy experts to set up the value and injection rates of the desulfuration reagents to be injected. Since the result of qualitative analysis of desulfuration is clear, and problems that are unable to be solved in traditional way are mainly that how to make decision on the various factors, a kind of intelligent control method including an injection control expert setup model and an intelligent feedback control mechanism is presented according to the system analysis result and the design demands. The logical thought expression of the control is:

$$\text{ICMCD} = \text{ESMCD} + \text{CFC} + \text{IMC} + \text{ISL} \qquad (4)$$

In expression (4), ICMCD stands for Intelligent Control Method of Co-inject Desulfuration; ESMD for Expert Setup Model of Desulfuration; CFC for Co-inject Facility Control; IMC for Intelligent Measure Control; and ISL for Intelligent Setup Learning.

3.1. The Mainframe of ICMCD

The main framework of ICMCD is shown in Fig.2. The control modules in Fig.2 means:

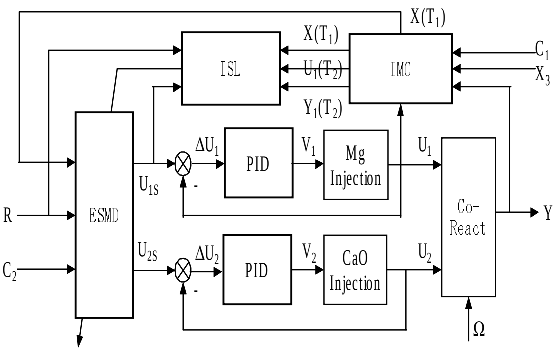

Fig.2. Main framework of co-inject desulfuration control

1) Co-Inject Control Expert Setup Module (ESMD). Inputs contain aim sulfur R, initial sulfur X_1, initial hot metal temperature X_2, hot metal weight X_3, operating command C_2; outputs contain the setups U_{1S} and U_{2S} to the Mg and CaO powder injection systems, respectively.

2) Co-injection Facilities Control (CFC) consists of the Mg powder injection control (setup input is U_{1S} and output is U_1) and CaO powder injection control (setup input is U_{2S} and output is U_2). Because the powder injection outputs can be measured by making use of the weight difference of the inject tanks during control, and controlled quantity is only injection rates, two sets of injection facilities are separately controlled by PID schemes.

3) The tasks of intelligent measure control are to measure all measurable values. During desulfuration, the way to get data is quite complicated, and the manual work is needed in course of measure, so that an important function of IMC is to coordinate the relationship between human and machines and reduce the influence of uncertainties. The kernel of IMC is the Intelligent Feedback Method (IFM), with which the reliability of measured data are confirmed, and then supplied to the Intelligent Setup Learning (ISL) model.

4) The Intelligent Setup Learning (ISL) module and IMC make up of the intelligent feedback control mechanism together. It is difficult for the control system to overcome the errors due to the open-loop characteristic of desulfuration processes, so it is necessary to estimate what happen by means of data from IMC, and then adjust the parameters in ESMCD so as to adapt the change of conditions and meet the control demands. In Fig.2, $X(T_1)$ is the measured boundary condition at T_1; Ω is immeasurable boundary condition; Y is the system output.

3.2 Design of ESDCM

According to the control demands, the co-injection control setup is a sticking point of the control design. The reason is that the uncertainties in the reaction process of desulfuration directly affect the desulfuration effect, and no certain universal parameters can be confirmed for the control design. The solution is to obtain experience rules from the qualitative analysis and to confirm the parameters by means of accumulative data in former productions, then establish ESDCM.

The unit of aim sulfur $R \in [2,15]$ and initial sulfur X_1 are density, ppm. When $Y_2 \in$ [1250℃, 1350℃], the change of hot metal temperature hardly affects desulfuration effect. A set of formulae of which the output is U_S and the input is X_1, can be described by the equation (5). Where, U_{11S} and U_{12S} are respectively the volume setup and rate setup of Mg powder injection; U_{21S} and U_{22S} are respectively the volume setup and rate setup of CaO powder injection; K_1 is the experience constant set up on the operation displays.

$$\begin{aligned} U_S &= (U_{11S}, U_{12S}, U_{21S}, U_{22S})^T; \\ U_{11S} &= f_{1R}(X_1)\times X_3 + f_2(X_2)\big|_{R=1,\cdots,20} \\ U_{12S} &= K_1 \\ U_{21S} &= 4\times U_{12S} \\ U_{22S} &= 50 - K_1 \end{aligned} \tag{5}$$

The common characteristic of immeasurable boundary conditions is that they change slowly, witch can be found in the description of immeasurable boundary condition; therefore, when setup parameter are decided, the change of immeasurable boundary conditions can be ignored and its affections will be dealt with by means of the intelligent feedback mechanism. According as the desulfuration dynamics principle, for each aim sulfur, the relationship between initial sulfur and injection volume of Mg powder can be considered as linear, and the experience formulas are simplified by

$$f_{1i}(x) = a_i x + b_i \qquad i = 2,3,\cdots,10 \tag{6}$$

$$f_2(x) = \begin{cases} 1+\varepsilon & x \le 1250 \\ 1 & 1250 < x < 1350 \\ 1+\varepsilon & 1350 < x \end{cases} \tag{7}$$

In the expression (6) and (7), a_i, b_i and ε are the parameters to be ascertained.

ESDCM is an experience module on the basis of the theories and experiences, which cannot be precisely proved by scientific methods, and only be judged by its facticity by means of the experience data. After a desulfuration process, the actual injection volumes and injection rates of Mg powder and CaO powder and final sulfur are saved. Through mining (Zheng and Zheng, 1999) these data, ESDCM is validated and the initial parameters of the model is set up and modified.

For the final sulfur and actual injection volume of once injection, whether or not that injection hit the control target, they are reusable. Though the desulfuration effect is not good enough for current injection, it can be as an anticipant setup to the target sulfur equaled to the current final sulfur. This property of final data makes itself useful to parameter learning.

The arithmetic of data mining is following (see also Fig.3, where R=3):

1) Let K_1=10 Kg/min (according to experience).

2) According as expression (6), let R= Y_1 (T_2) and confirm the position (X_1, U_{11}) on the plan for R (see also Fig.3).

3) Make use of step 2) to map all the samplings to the relevant plans.

4) Form the regression curves of samplings by computer.

5) Adjust the parameters a_i and b_i in expression (6) according to the regression curves by the operators.

6) Repeat step 3) - 5).

When the samplings are few, the arithmetic depends on the human experience, but after lots of samplings are gathered, the human effect is less and less, and the precision of formulas is up.

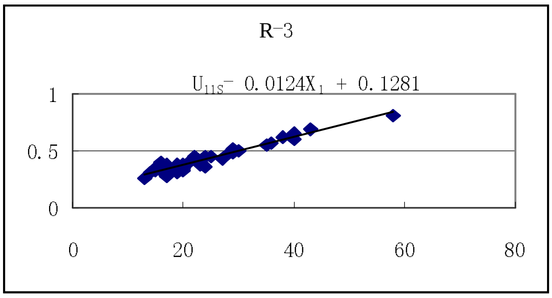

Fig. 3. Plan for parameter confirmation

Because of $R \in [2,15]$, $X_1 \in [15,80]$, in order to be convenient for the setup optimization, the experience formulas of which the parameters have to be confirmed are transformed into a matrix of which the element, $SU(i, j)$, is a setup of injection volume of Mg powder per tone of hot metal when $R = i$ and $X_1 = j$, and expression (5) can be changed as follows:

$$\begin{aligned}
&\text{IF } (i = R) \text{ and } (j = X) \text{ THEN}\\
&\quad f_{1R}(X_1) = SU(i, j);\\
&\quad U_{11S} = f_{1i}(X_1) \times X_3 + f_2(X_2)\\
&\quad U_{12S} = K_1\\
&\quad U_{21S} = 4 \times U_{11S}\\
&\quad U_{22S} = 50 - K_1
\end{aligned} \qquad (8)$$

3.3. The Generalized Feedback Control Mechanism

As above, due to the uncertainties as well as open-loop characteristic of desulfuration there will be the overrun system output error, $R\text{-}Y_1(T_2)$, and the control system must be able to reduce the error by itself for the production therefore.

Although, in the desulfuration, control system cannot on line measure sulfur quantity Y_1 in hot metal, the final result can be used for next setup as reference. So, if the desulfuration production is regard as a continuous process, the generalized feedback control mechanism (GFCM) can be built by adjusting the parameters in ESMCD. After once desulfuration, the final sulfur $Y_1(T_2)$, actual injection volume of Mg powder $U_1(T_2)$ and their reliabilities are saved in *ST-LN* (the setup parameter learning matrix) in ISL module for modifying the parameters of ESMCD. As soon as the error overruns, ISL module will modify the parameters of ESMCD to reduce the error according as analysis to the data saved before.

The structure of *ST_LN* is similar to *SETUP*, but its element, *SL* (*i*, *j*), contains not only *SU* (*i*, *j*), but also other data (see also Fig.4). In Fig.4, *SL*(*i*, *j*).*Mg-setup* is current setup; *SL*(*i*,*j*).*modify* is the modification instancy degree of current setup; *SL*(*i*, *j*).*precision* is the entry point of desulfuration precision queue (precision queue for short); *SL*(*i*, *j*).*pastdata* is the entry point of final data saved in past desulfuration (past data queue for short). In the precision queue, each node records the precision and injection final time of once injection to use current setup and reliability of the precision. In the past data queue, each node records the actual injection volume of Mg powder and time and reliability of sampling of once injection, where, final sulfur is equal to *i*.

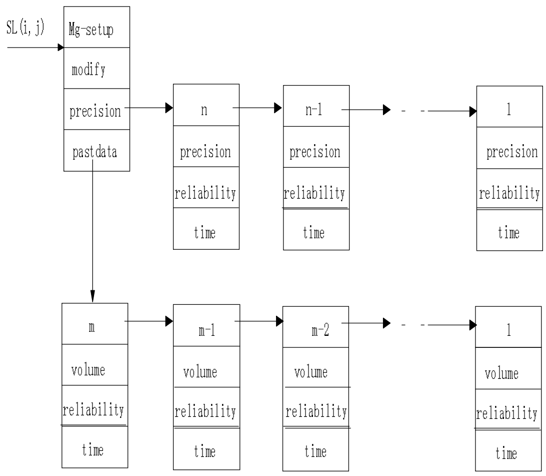

Fig. 4. Elements of *ST_LN*

It is not enough to use the final data of once injection to confirm if the current setup need to be modified, so a queue with the length alterable is designed in *SL*(*i*, *j*). When the new data are added to the queue, ISL module modifies *SL*(*i*, *j*).modify by means of the data of precision queue. If *SL*(*i*, *j*).*modify* $\geq \lambda$ (a constant), the module modified current setup is *SL*(*i*, *j*).*Mg-setup*, according to the data of past data queue. At the same time, all the Mg-setups in *ST-LN* are modified. The arithmetic of ISL module is as follows:

a. FOR *i* = 2 to 15
  FOR *j* = 15 to 80 DO:
    To confirm *SL*(*i*， *j*).*modify*;

b. IF *SL*(*i*， *j*).*modify* $\geq \lambda$ THEN
  SL(*i*， *j*).*Mg_setup* = *f* (*SL*(*i*， *j*).*pastdata*)

c. Repeat step a and b till $SL(i, j).modify < \lambda$

d. FOR i = 2 to 15

FOR j = 15 to 80 DO：

$SU(i, j) = SL(i, j).Mg\_setup$；

4. CONCLUSIONS

The co-inject desulfuration system designed with ICMD has been running up to now. Table 1 shows the result of 500 injections for the desulfuration process.

Table 1 Proportion of target

Target	Inject	Proportion
$\lvert R-Y_1(T)\rvert = 0$	113	22%
$\lvert R - Y_1(T) \rvert <= 1$	158	31%
$1 < \lvert R - Y_1(T) \rvert <= 2$	140	28%
Overrun	89	19%

As showed in Table 1, the proportion of overrun is still a little bit high, so that the study on ICMD should be done further. For the purpose of better desulfuration effect, GFCM will be perfected in the future.

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