The Application of Multivariable Fuzzy Control Based on Multidimensional System to Hot Metal Desulphurization

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Abstract—**Hot metal desulphurization is a very important step in the process of steel production. The production process can not be well controlled by use of traditional control methods. This paper introduced the application of multivariable fuzzy control technology to hot metal desulphurization. Using the features of fuzzy controller, the coupling in multivariable fuzzy system can be eliminated from the perspective of control structure through decomposing fuzzy relation equations. The problems of large delay, nonlinear, and the difficulty to establish precise mathematical model can be well overcome. This technology has achieved remarkable control effect on hot metal desulphurization.**

Keywords-multivariable; fuzzy control; hot metal desulphurization

I. INTRODUCTION

With the continuous advancement of production technology and increasing promotion of the requirement to steel product's quality, more and more stringent limit was made to reduce the sulfur content of steel. In order to improve product quality in converter steelmaking, reducing the sulfur content in the molten iron has become an important issue to be urgently solved in metallurgical industry. However, there are still many limitations and is difficult to operate in the converter to perform desulfurization process, which prompted hot metal pretreatment. And then hot metal is sent to converter to achieve the purpose of desulfurization.

Since a variety of complex physical and chemical reactions occur during the course of desulfurization, and this process is non-linear and with a lot of uncertainty and ambiguity, so currently, it is still necessary to rely on experienced workers to operate in most cases. As a result, it is difficult to ensure the quality of desulfurization. Obviously, the conventional control method is not suitable for the pretreatment of hot metal desulfurization. Therefore, multivariable fuzzy control technology and expert systems which is fused fuzzy control are applied to perform this complex process control in this paper.

II. THE PROCESS OF HOT METAL DESULPHURIZATION

Desulfurization station mainly consists of four parts: pouring station, desulfurization body, dust removal and water process devices. So as to facilitate adding desulfurizing agent, when the ladle is sent from the blast furnace, the ladle which weight is not the same is first turned into equal weight by weighing. And then, the gun is inserted in the molten iron. Next, nitrogen gas and magnesium powder are blown into molten iron to make it boiling. Under the condition of high temperature, dramatic chemical reactions take place between magnesium agent and sulfur in the molten iron, and produces magnesium sulfide[2]. At this point, hot metal desulfurization is completed. The whole process is shown in Figure 1.

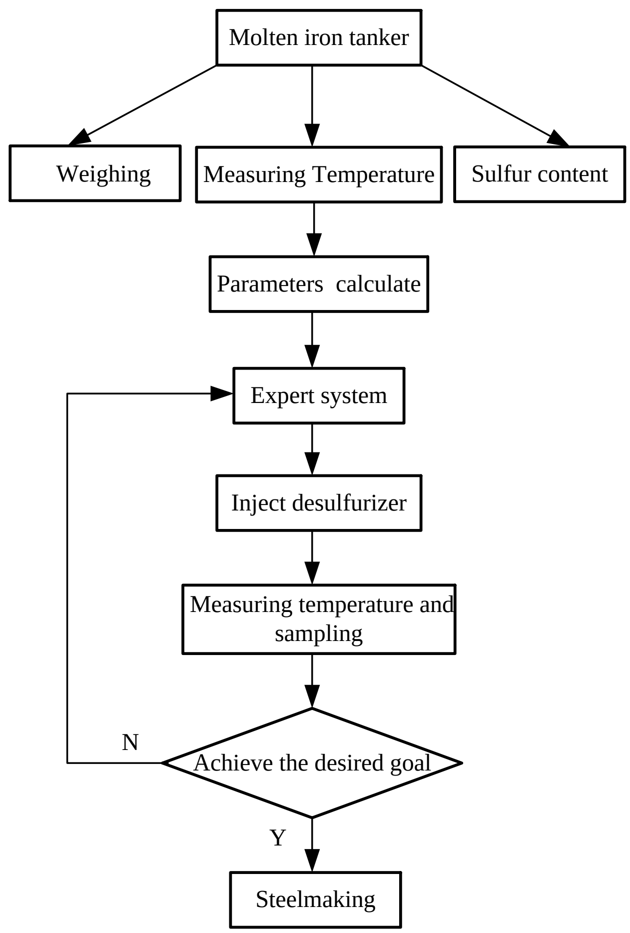

Figure 1. Flow chart of desulfurization process

Since very complex physical and chemical reactions occur in molten iron during the desulfurization process, and this process involves many factors. Therefore, in practical operations, it is extremely difficult to perform qualitative and quantitative control to all of these factors. It is necessary to continue to accumulate experience in a long period of time for operators. As a result, this requirement creates the feasible conditions for the application of expert system.

III. THE DESIGN OF FUZZY CONTROLLER

The design of fuzzy controller generally includes the following several parts: describe input and output variables set of word, define subsets of fuzzy variables and formulate fuzzy control rules[5]. Of which the design of control rules is the key to fuzzy controller.

A. Selection of language variables

During the course of desulfurization, the commonly used language variable values are as follows: negative large, negative middle, negative small, zero, positive large, positive middle, positive large. Namely, $\{NL, NM, NS, NZ, PS, PM, PL\}$.

In this paper, five major variables are taken into account: namely, original sulfur content in molten iron (V_{FS}), original hot metal temperature (V_T), the amount of molten iron to be processed (V_M), expected percentage of desulfurization (V_{LS}) and magnesium content in desulfurizer ($V_{Mg\%}$). In order to facilitate processing for computer, these variables need to be converted into such variables that the computer can be identified by taking error:

$$V_{FS} \in \{NL, NM, NS, NZ, PS, PM, PL\}$$
$$V_T \in \{NL, NM, NS, NZ, PS, PM, PL\}$$
$$V_M \in \{NL, NM, NS, NZ, PS, PM, PL\}$$
$$V_{LS} \in \{NL, NM, NS, NZ, PS, PM, PL\}$$
$$V_{Mg\%} \in \{NL, NM, NS, NZ, PS, PM, PL\}$$

B. Determination of membership function

Determining membership function of fuzzy subset means that these subsets are implemented discrete process. And then the membership belonging to a finite number of points can be solved. All these memberships constitute the corresponding fuzzy subsets. In this paper, the fuzzy domain of input and output is taken as [-6, 6].

C. Formulation of Fuzzy control rule table

Fuzzy control rule table can be obtained by synthesizing fuzzy conditions and fuzzy relations. In term of the corresponding rules, input and output are carried out matching each other through "if $\cdots$ and $\cdots$, then$\cdots$"conditional statement. The fuzzy logic controller can be obtained as follows:

$$R_1 : IF\ V_{FS} = NL\ AND\ V_T = NL\ AND\ V_M = NL\ AND\ V_{LS} = NL\ AND\ V_{Mg\%} = NL,$$
$$THEN\ U_M = PL\ U_{FM1} = PL\ U_{FM2} = PL;$$
$$R_2 : IF\ V_{FS} = NM\ AND\ V_T = NL\ AND\ V_M = NL\ AND\ V_{LS} = NL\ AND\ V_{Mg\%} = NL,$$
$$THEN\ U_M = PL\ U_{FM1} = PM\ U_{FM2} = NZ;$$
$$R_3 : IF\ V_{FS} = NS\ AND\ V_T = NL\ AND\ V_M = NL\ AND\ V_{LS} = NL\ AND\ V_{Mg\%} = NL,$$
$$THEN\ U_M = PM\ U_{FM1} = NM\ U_{FM2} = NS;$$
$$\cdots \quad \cdots \quad \cdots$$
$$R_n : IF\ V_{FS} = NS\ AND\ V_T = NL\ AND\ V_M = NL\ AND\ V_{LS} = NL\ AND\ V_{Mg\%} = NL,$$
$$THEN\ U_M = PM\ U_{FM1} = NM\ U_{FM2} = NS.$$

Consequently, the total fuzzy relation can be written as:

$$R = R_1 \cup R_2 \cup R_3 \cup \cdots\cdots \cup R_n = \bigcup_{i=1}^{n} R_i \tag{1}$$

Here, the five chiefly variables V_{FS}, V_T, V_M, V_{LS} and $V_{Mg\%}$ are taken as inputs, then, the output of fuzzy controller B satisfies this relation.

$$B = R\left(V_{FS} \times V_T \times V_M \times V_{LS} \times V_{Mg\%}\right) \tag{2}$$

IV. THE REALIZATION OF MULTIVARIABLE FUZZY CONTROLLER

Hot metal desulfurization possesses such features as large delay, nonlinear, difficult to establish accurate mathematical model, etc. and involves a number of control variables. It is a typical multivariable control system. If this project is placed in the framework of the multidimensional system control theory and taken into consideration, then the system is a MIMO system [1, 5-10]. For a given multidimensional system, the description of its state-space is expressed as:

$$\begin{aligned} x'\left(i_1,\cdots, i_n\right) &= Ax\left(i_1,\cdots, i_n\right) + Bu\left(i_1,\cdots, i_n\right) \\ y\left(i_1,\cdots, i_n\right) &= Cx\left(i_1,\cdots, i_n\right) + Du\left(i_1,\cdots, i_n\right) \end{aligned} \tag{3}$$

Where $u\left(i_1,\cdots, i_n\right)$ and $y\left(i_1,\cdots, i_n\right)$ are input and output vectors respectively; $x\left(i_1,\cdots, i_n\right)$ is state vector in the form of

$$x\left(i_1,\cdots, i_n\right) = \begin{bmatrix} x_1\left(i_1,\cdots, i_n\right) \\ x_2\left(i_1,\cdots, i_n\right) \\ \vdots \\ x_n\left(i_1,\cdots, i_n\right) \end{bmatrix},$$

$$x'\left(i_1, i_2,\cdots, i_n\right) = \begin{bmatrix} x\left(i_1+1, i_2,\cdots, i_n\right) \\ x\left(i_1, i_2+1,\cdots, i_n\right) \\ \vdots \\ x\left(i_1, i_2,\cdots, i_n+1\right) \end{bmatrix};$$

and A, B, C, D are all real coefficient matrices.

Applying n-D z-transform to (3) gives

$$\begin{aligned} Z^{-1}X(z_1,\cdots,z_n) &= AX(z_1,\cdots,z_n)+BU(z_1,\cdots,z_n) \\ Y(z_1,\cdots,z_n) &= CX(z_1,\cdots,z_n)+DU(z_1,\cdots,z_n) \end{aligned} \tag{4}$$

where,

$$Z=\begin{bmatrix} I_1z_1 & & & \\ & I_2z_2 & & \\ & & \ddots & \\ & & & I_nz_n \end{bmatrix}$$

when the boundary conditions are zero.
According (4), we have

$$X(z_1,\cdots,z_n)=(I-ZA)^{-1}ZBU(z_1,\cdots,z_n) \tag{5}$$

And

$$Y(z_1,\cdots,z_n)=\left\{C(I-ZA)^{-1}+D\right\}U(z_1,\cdots,z_n) \tag{6}$$

Then, the transfer matrix of the n-D system can be obtained

$$H(z_1,\cdots,z_n)=C(I-ZA)^{-1}+D \tag{7}$$

In view of the fact that fuzzy control shows better control effect for systems with lag and random interference, fuzzy control which is fused expert system is applied to hot metal desulfurization in this paper. If the open loop transfer matrix of system can be determined, the decoupling in multivariable fuzzy system can be achieved from the control structure through decomposing fuzzy relation equations. That is to say, a multi-input multi-output fuzzy controller is decomposed into a number of multi-input single-output fuzzy controllers, the coupling influence of multi-variable fuzzy system can be eliminated by this way[4]. For the sake of illustration, a two input two output system (Fig. 2) is taken as an example.

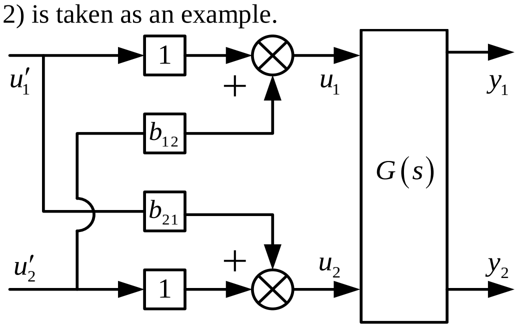

Figure 2. A two input two output system

According to Fig 2, we will get (8)

$$\begin{aligned} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} &= G\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}=\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \\ &=\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}\begin{bmatrix} 1 & b_{12} \\ b_{21} & 1 \end{bmatrix}\begin{bmatrix} u'_1 \\ u'_2 \end{bmatrix} \\ &=\begin{bmatrix} G_{11}+G_{12}b_{21} & G_{11}b_{12}+G_{12} \\ G_{21}+G_{22}b_{21} & G_{21}b_{12}+G_{22} \end{bmatrix} \end{aligned} \tag{8}$$

If the condition (9) holds true,

$$\left.\begin{aligned} G_{11}b_{12}+G_{12}=0 \\ G_{21}+G_{22}b_{21}=0 \end{aligned}\right\} \tag{9}$$

It is not difficult to get (10)

$$\left.\begin{aligned} b_{12}=-\frac{G_{12}}{G_{11}} \\ b_{21}=-\frac{G_{21}}{G_{22}} \end{aligned}\right\} \tag{10}$$

So, the problem of coupling in multivariable fuzzy system can be solved.

In this paper, the design of fuzzy controller is determined through the five mainly variables, namely, V_M, V_{LS} V_{FS}, V_T and $V_{Mg\%}$ .The running mechanism is as follows. Fuzzy controller first extracts applicable control rules from the library, and then does fuzzy inference operations with input variables according to these rules. Next, the results of reasoning are turned into output.

The process consists of three parts: fuzzification, fuzzy reasoning and fuzzy solution, just as shown in Figure 3.

First, the value of control variables is acquired by sampling. Compared these sampled values with the set values, error signals can be obtained; Then the precise quantity of error signals is converted into fuzzy variables; Next these obtained fuzzy variables are performed operating and reasoning according to fuzzy relations, and decisions can be made based on synthetic rules. Finally, the variables of fuzzy control are carried out fuzzy solution [3].

Specifically in this paper, the control output B is firstly solved through the relationship set R and control input V, and then implemented fuzzy solution and reverted into corresponding analog and digital signal. According to these signals, the spray speed of magnesium powder and the amount of carrying nitrogen gas in different periods, total spray time as well as the total amount of magnesium consumption are calculated. Finally, the rotational speed of feeder motor and the opening degree of flow control valve are well under control through module outputs to achieve the running of this system.

V. THE EFFECT OF APPLICATION AND CONCLUSION

TABLE I. THE COMPARISION OF FUZZY AND EMPIRICAL CONTROL METHOD

Parameters	**Fuzzy Control**	**Empirical control**
Mg powders (kg・ t-1)	0.53	1.38
Other reagents (kg・t-1)	0.62	1.85
The quantity of slag(kg・t-1)	2.10	3.30
Iron loss /(kg・t-1)	0.81	1.38
Temperature drop/℃	5~7	10~12

Table 1 shows the comparative results of several important parameters between fuzzy control and empirical control method in the desulfurization process. As can be seen from the table, the parameters have significantly dropped. Especially, the amount of Mg powder consumption is about reduced by half. Compared with the conventional control methods, the application of fuzzy control technology is more reliable and easier to operate, and possesses stronger fault tolerance.

This paper introduced the application of multivariable fuzzy control technology to hot metal desulphurization. Using the features of fuzzy controller, the coupling in multivariable fuzzy system can be eliminated from the control structure through decomposing fuzzy relation equations. The problems of large delay, nonlinear, and the difficulty to establish precise mathematical model can be well overcome. Furthermore, fuzzy control also greatly reduces the complexity of control system and improves the fault tolerance of system. It is more reliable and easier to operate. This technology has achieved remarkable control effect on hot metal desulphurization.

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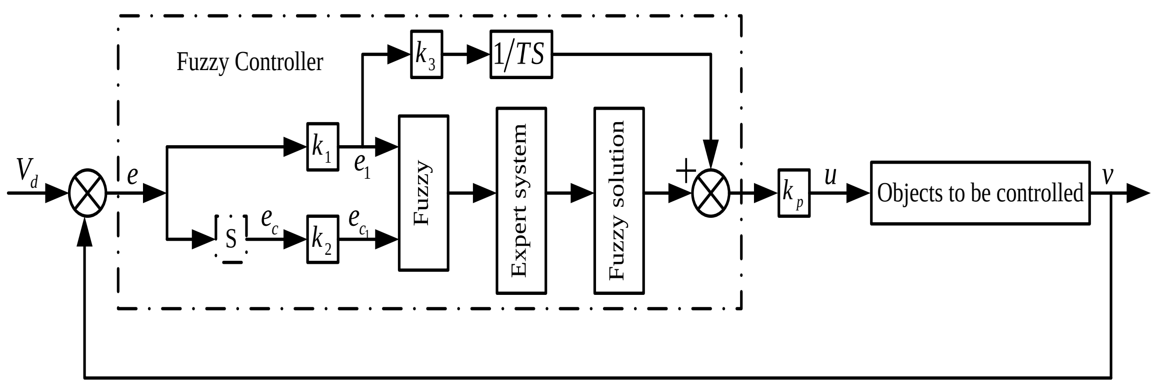

Figure 3. The realization of fuzzy controller