An Effective Control Method of The Coke Calcining Kiln

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Abstract—The process of calcining petroleum coke in a rotary kiln for the production of anodes is a very complicated exothermic reaction. Mathematically modeling the rotary kiln used for the calcination of the coke is very difficult, because the main problem is that the relationships between input variables and control variables are complex, nonlinear, containing time lags and interrelationships, and that the kiln's response to control inputs depends on the prevailing kiln conditions. A set of fuzzy control rules, which has successfully been used in controlling the petroleum coke calcining rotary kiln in a practical aluminum plant of China, is presented in this paper. A practical distributed control system of the coke calcining kiln is also described.

I. INTRODUCTION

Green petroleum coke is normally calcined in large rotary kilns before being used for electrode manufacturing. There are many processes occurring in the kiln during calcination such as moisture and volatile, coke-dust generation, volatile and coke combustion, etc. The calcining process is schematically shown in Fig. 1.

In reference to the physical processes in the kiln, the kiln can be divided into three zones, i.e., the preheating zone, the calcining zone, the cooling zone.

The overall calcination process is exothermic and self-sustaining due to injection of secondary air and thirdly air.

The main problem in mathematically modeling a control strategy is that the relationships between input variables (measured characteristics of the process) and control variables are complex, nonlinear, containing time lags and inter-relationships, and that the kilns response to control inputs depends on the prevailing kiln conditions.

Although a few papers related to modeling the coke calcining kilns were published[1] [2], the results of these models can not be put into practice, due to too many crude simplifying assumptions.

This effective fuzzy control method presented in the paper has successfully been used in a coke calcining kiln for two years.

II. ANALYSIS OF THE CALCINING PROCESS

The key issue in calcination technology is to control coke quality. Heating rate and calcination temperature strongly affect the quality of the calcined coke. Too high a heating rate increases coke porosity and decreases its bulk density, which is highly undesirable. Too low the heating rate will bring about the need for more sizable kilns which are more costly to build and to operate. A lower heating rate results in a bulk density improvement which can yield substantial savings. Similarly a high enough calcining temperature results in an appropriate crystalline thickness and an increase in coke quality. The challenge is to reach a high calcining temperature with a low heating rate without unduly lengthening the kiln.

Feedrate constitutes another challenge. A low feedrate decreases the dust generation proportionately but affects productivity.

Secondary air and thirdly air may be the most sensitive elements in the control of the process. Their locations, flowrates, velocities and directions strongly affect the degree of mixing of the gas, which in turn can either improve the process or bring it to a halt.

From the above illustration, the coke calcination is a complex process in which several physical phenomena occur in a tightly manner.

From many possible input and control variables, the follows are chosen as particularly relevant. Input variables:

- Exhaust gas temperature — back end temperature(BT);
- Calcining zone temperature (CT).

The process is controlled by varying the following:

- Coke feedrate (CF);
- Kiln rotation speed (in proportion to the coke feedrate);
- Secondary air (SA);
- Thirdly air( TA).
III. CONTROL METHOD

A block diagram of the coke calcining kiln’s fuzzy control is shown in Fig. 2.

A. Selection of fuzzy subsets[3]

The fuzzy subsets of the input variables (i.e., the measured variables):
CT: {DL L SL OK SH H DH};
BT: {DL L SL OK SH H DH};
where DL is drastically low, L is low, SL is slightly low, OK is okay, SH is slightly high, H is high, and DH is drastically high. Their simple symbolic expressions are:
CT: \( \{ X_1^1 X_1^2 X_1^3 X_1^4 X_1^5 X_1^6 X_1^7 \} \);
BT: \( \{ X_2^1 X_2^2 X_2^3 X_2^4 X_2^5 X_2^6 X_2^7 \} \).

The fuzzy subsets of the control variables are as follows:
CF: {VN N SN OK SP P VP};
SA: {VN N SN OK SP P VP};
TA: {VN N SN OK SP P VP};
where VN is very negative, N is negative, SN is small negative, OK is okay, SP is small positive, P is positive, and VP is very positive. Their simple symbolic expressions are:
CF: \( \{ Y_1^1 Y_1^2 Y_1^3 Y_1^4 Y_1^5 Y_1^6 Y_1^7 \} \);
SA: \( \{ Y_2^1 Y_2^2 Y_2^3 Y_2^4 Y_2^5 Y_2^6 Y_2^7 \} \);
TA: \( \{ Y_3^1 Y_3^2 Y_3^3 Y_3^4 Y_3^5 Y_3^6 Y_3^7 \} \).

B. Identification of the fuzzy model

The method of reasoning and composition[4] is used for identifying the kiln’s fuzzy control rules based on the data of input variables and output variables. The stages are:

1). Define the values of the fuzzy sets
In domains of input variables and control variables, the values of these fuzzy sets are defined respectively. Every value of the fuzzy subsets may be defined by Normal distribution. For example, Table I shows the values of the CT variable fuzzy set.

2). Data-acquisition and fuzzy filter: Collecting N groups of input data and their corresponding output data, and then processing them with fuzzy filtering, finally getting M(M<N) groups.

3). Determine fuzzy control rules of every dual inputs and single output (i.e., \( (X_1 X_2 Y_i) (X_1 X_2 Y_i) (X_1 X_2 Y_i) \))

First, calculating the fuzzy relation \( \tilde{R}_{x_2 \times x_1} \) on input variables according to the following equation:
\[
\tilde{R}_{x_2 \times x_1} = \tilde{X}_{x_2} \cap \tilde{X}_{x_1},
\]
where \( \tilde{X}_{x_2} \) is No. i fuzzy set of input variable \( x_2 \), \( \tilde{X}_{x_1} \) is No. i fuzzy set of input variable \( x_1 \), “\( \cap \)” denotes the intersection operator or the min-operator, \( i=1,2,\ldots,M \).

For example,
\[
\tilde{X}_{x_2} (1250^\circ C) = \begin{cases} 0 & \frac{0}{x_1^1} + \frac{0}{x_1^2} + \frac{0.8}{x_1^3} + \frac{0.1}{x_1^4} + \frac{0.3}{x_1^5} + \frac{0}{x_1^6} + \frac{0}{x_1^7} \\ 0 & \frac{0}{x_2^1} + \frac{0}{x_2^2} + \frac{0.2}{x_2^3} + \frac{0.9}{x_2^4} + \frac{0.3}{x_2^5} + \frac{0}{x_2^6} + \frac{0}{x_2^7} \end{cases},
\]

\[
\tilde{X}_{x_1} (900^\circ C) = \begin{cases} 0 & \frac{0}{x_1^1} + \frac{0}{x_1^2} + \frac{0}{x_1^3} + \frac{0.8}{x_1^4} + \frac{0.1}{x_1^5} + \frac{0}{x_1^6} + \frac{0}{x_1^7} \\ \frac{0}{x_2^1} + \frac{0}{x_2^2} + \frac{0}{x_2^3} + \frac{0.2}{x_2^4} + \frac{0.9}{x_2^5} + \frac{0.3}{x_2^6} + \frac{0}{x_2^7} \end{cases}.
\]

TABLE 1. THE VALUES OF THE CT VARIABLE FUZZY SET

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<tr>
<th>Quantization</th>
<th>DL</th>
<th>L</th>
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TABLE 2. FUZZY CONTROL RULES OF DUAL INPUTS-SINGLE OUTPUT (\( (X_1 X_2 Y_i) \))

<table>
<thead>
<tr>
<th>CF</th>
<th>( X_1^i )</th>
<th>( X_2^i )</th>
<th>( X_1^i )</th>
<th>( X_2^i )</th>
<th>( X_1^i )</th>
<th>( X_2^i )</th>
<th>( X_1^i )</th>
<th>( X_2^i )</th>
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</thead>
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<td>( \tilde{X}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
<td>( \tilde{Y}_1 )</td>
</tr>
<tr>
<td>( \tilde{X}_2 )</td>
<td>( \tilde{Y}_2 )</td>
<td>( \tilde{Y}_2 )</td>
<td>( \tilde{Y}_2 )</td>
<td>( \tilde{Y}_2 )</td>
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<td>( \tilde{Y}_2 )</td>
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<td>( \tilde{Y}_2 )</td>
</tr>
</tbody>
</table>

Fig. 2. A block diagram of the coke calcining kiln's fuzzy control system
\[ R_{X_3 \times X_1, i} = 0.2 \left[ \begin{array}{cccccc} 0 & 0.8 & 0.3 & 0 \\ 0.9 & 0 & 0 & 0 \end{array} \right] \]

\[ = \left[ \begin{array}{cccccc} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right] \]

Second, calculating the output variable's fuzzy relations of No. i data pair of M groups respectively. The equation is:

\[ R_{u_i, u'_i, j} = \tilde{Y}_{i,j} \cap R_{X_3 \times X_1, i} \]

(2)

where \( \tilde{Y}_{i,j} \) is the elements of the output variable's fuzzy set, \( j=1, 2, \ldots, 7, i=1, 2, \ldots, M \). For example,

\[ \tilde{Y}_{i,j} = \left( \frac{8.2 \text{ ton/hour}}{y_1^2 + y_2^2 + y_3^2 + y_4^2} \right) \]

\[ R_{u_i, u'_i, j} = 0.7 \cap R_{X_3 \times X_1, i} \]

\[ = \left[ \begin{array}{cccccc} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right] \]

Third, calculating the fuzzy relations of all M groups data pair according to the following equation:

\[ R_{u_i, u'_i} = \bigcup_{j=1}^{m} R_{u_i, u'_i, j} \]

(3)

where symbol "union" denotes the union operator or the max-operator, \( j=1, 2, \ldots, 7, i=1, 2, \ldots, M \).

Finally, selecting a proper level \( \lambda \) and processing a \( \lambda \)-cut (\( \lambda \)-level set), the control rule \( R_{X_3 \times X_1, i} \) of dual outputs with single input \( (X_1, X_2, Y_1) \) is gotten, shown as Table 2. Similarly, another two control rules \( R_{X_3 \times X_1, i} \) and \( R_{X_2 \times X_1, i} \) may be gotten.

4. Establish the fuzzy model: Synthesizing all the control rules of dual outputs with single input, the coke calcining kiln's fuzzy model may be obtained, shown as Table 3.

IV. A PRACTICAL DISTRIBUTED CONTROL SYSTEM OF THE COKE CALCINING PROCESS

Fig. 3 shows a block diagram of the control system. The system is composed of three levels.

The first level (local control) contains programmable digital controllers, each providing closed loop control of an individual plant process variables(PV). It mainly controls the rotary cooler and the boiler. The controllers may be operated in one of the three modes: manual, automatic, or remote set point. In "manual" mode, the operator sets the output of the controller directly, essentially setting a damper, valve or other device directly. In "automatic" mode, the operator gives the controller a desired PV level or set point(Sp). The controllers may use proportional-integral-derivative action on the PV/SP difference, depending on the programming. When put in "remote set point" mode, the first level controllers no longer take set points from the operator. Instead, they receive set points from the second level or the third level.

The second level contains the fuzzy controller. The fuzzy controller carries out the above fuzzy control algorithms. It is through action of the fuzzy control that several calcining parameters are controlled in coordination to produce a consistent product.

The third level of the system is the supervisory control station. The station provides supervisors with graphics displays of all system process variables and set points. It also displays the results of more complex computer calculations of process consistency and efficiency. Engineers program the first and second level controllers through the station. The fuzzy controller is also directly programmed, because it is an industrial PC itself.

V. CONTROL RESULTS

This control system has been run for two years in the coke

<table>
<thead>
<tr>
<th>CF</th>
<th>SA</th>
<th>TA</th>
<th>CT</th>
</tr>
</thead>
<tbody>
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<td>x_1^1</td>
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<tr>
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<td>x_3^2</td>
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</table>

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calcining of Qingtongxia Aluminum Plant. The coke calcination ratio increases 8.2% (from 64.1% to 73.3%), and the mean productivity of the calcined coke per day increases 12% (from 150 ton/day to 168 ton/day). The quality of the calcined coke is also increased (e.g., its real density increases from 2010 kg/m$^3$ to 2050 kg/m$^3$).

Fig. 4 shows a typical control curve in Oct. 3, 1995.

VI. CONCLUSIONS

Based on the performance of the Qingtongxia installation, we can say that the fuzzy control system can be used in a rotary kiln calcining plant to:

- Successfully maintain maximum throughputs as constrained be desired temperature consistency level.
- Reduce kiln calcining temperature variation and produce calcined coke with less reactivity.
- Coordinate changes in operation on a total plant basis.
- Improve the product quality.
- Maintain steam pressure control for turbine waste heat boiler system.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES


