Abstract

Regenerative rotary reheating furnace is a new type furnace. It can reduce cost and low contamination exhaust. But it is hard for the temperature setting. This paper makes the repository of temperature setting based on mathematics models of the regenerative rotary reheating furnace, and develops regional discrete method for temperature setting. According the contrast results between tube's measured temperature and target temperature, the temperature setting method is accuracy, and it is useful for regenerative rotary furnace.

Keywords: Regenerative Rotary Reheating Furnace; Regional Discrete Method; Mathematics Model

1 Introduction

The reheating technology is very important for the subsequent steel tube rolling production. The quality of steel products can be controlled by the temperature setting of the reheating furnace [1-3]. Rotary reheating furnace is widely used for reheating steel tubes. Currently, the rotary furnace usually uses such kind of fuels that release high calorific value during combustion [4]. Regenerative rotary reheating furnace refers to those kinds of furnaces which not only have a rotary hearth but also utilize regenerative combustion technology [5-7]. It is a new type of furnace in metallurgical industry, which makes use of low calorific value fuels such as the exhaust gas from the burners. However, the wide application of this kind of technology requires detailed studies of temperature setting due to its unique structure [8-9].

This paper focuses on a large regenerative rotary furnace, analyzes the mathematical model which is used for optimal control in the regenerative rotary furnace, and validates the mathematical model in the end.
2 Summarize

The temperature setting is based on structure of regenerative rotary reheating furnace. We made the repository of temperature setting based on mathematics models of the regenerative rotary reheating furnace, and we made the single setting of temperature setting using differential method, lastly, we accommodate the final temperature setting values based on tubes’ distribution. Fig. 1 is the flow chart of temperature setting for regenerative rotary reheating furnace.

![Flow chart of temperature setting for regenerative rotary reheating furnace](image)

Fig. 1: The flow chart of temperature setting for regenerative rotary reheating furnace

3 The Repository

According to mathematical model of rotary reheating furnace for the typical kind of steel, the typical specifications, we do heating tube simulation, select the best temperature setting when the temperature curve is best, while adding furnace temperature setting in some special circumstances, then we constitute the basic values of the fuzzy knowledge database.

The mathematical models of rotary reheating furnace include furnace heat transfer model, the internal heat mathematical model of tube, heat transfer mathematical model of furnace bottom, the heat transfer mathematical model of furnace walls and roof. The detailed models are as followed.

(1) Assumptions of the mathematical model [10]

1) The temperature distribution doesn’t change with time. The temperature is uniform in each control section, and radiation heat transfer between different sections is ignored;

2) The temperature of each section approximately equals the value of thermocouple of each section;

3) Roof and wall of furnace are adiabatic radiation heat transfer;

4) The heat resistance between different materials of furnace bottom is ignored;

5) The temperature distribution of tube is symmetric along the pipe axis;

6) Tube’s temperature is equal with bottom’s temperature at the contact point position.

(2) Mathematical model of Furnace radiation heat transfer
The radiation heat transfer is happened between gas and tubes, gas and roof, gas and walls, gas and bottom, walls and tubes, roof and tubes, bottom and tubes, walls and roof, walls and bottom, roof and bottom. The status of Furnace is shown in Fig. 2, the radiation heat transfer Relationship chart is signed in Fig. 3.

![Fig. 2: The status of furnace](image)

1: The unknown tube; 2: The known tube; 3: Furnace bottom; 4: Furnace roof and Furnace walls; 5: Furnace gas

![Fig. 3: The radiation heat transfer relationship chart](image)

The equation of each point in Fig. 3 is followed.

\[
\frac{E_{b1} - J_1}{K_1} + \frac{J_2 - J_1}{R_{1,2}} + \frac{E_{bg} - J_1}{R_{1,g}} + \frac{J_3 - J_1}{R_{1,3}} + \frac{J_4 - J_1}{R_{1,4}} = 0 \quad (1)
\]

\[
\frac{E_{b2} - J_2}{K_2} + \frac{J_1 - J_2}{R_{1,2}} + \frac{E_{bg} - J_2}{R_{2,g}} + \frac{J_3 - J_2}{R_{2,3}} + \frac{J_4 - J_2}{R_{2,4}} = 0 \quad (2)
\]

\[
\frac{E_{b3} - J_3}{K_3} + \frac{J_1 - J_3}{R_{1,3}} + \frac{E_{bg} - J_3}{R_{3,g}} + \frac{J_2 - J_3}{R_{2,3}} + \frac{J_4 - J_3}{R_{3,4}} = 0 \quad (3)
\]

\[
\frac{J_1 - J_4}{R_{1,4}} + \frac{E_{bg} - J_4}{R_{4,g}} + \frac{J_2 - J_4}{R_{2,4}} + \frac{J_3 - J_4}{R_{3,4}} = 0 \quad (4)
\]
where: $E$ is the radiation intensity of black body, $J$ is the availability radiation intensity, $K$ is the exterior thermal resistance, $R$ is the interspaces thermal resistance.

(3) Heat transfer mathematical model of tube

Control equations:

$$
\rho C_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial r} \left( \lambda_s(T) \frac{\partial T}{\partial r} \right) + \frac{1}{r} \lambda_s(T) \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( \lambda_s(T) \frac{\partial T}{\partial \theta} \right)
$$

(5)

Initial conditions:

$$
\tau = 0, \quad T(r, \theta, 0) = T_0(r, \theta)
$$

(6)

Boundary conditions:

$$
\begin{align*}
& r = R, \quad -\frac{\pi}{2} < \theta \leq \frac{\pi}{2} \quad \lambda_s(T) \frac{\partial T}{\partial r} = q_s(\theta) \\
& r = R, \quad \theta = -\frac{\pi}{2} \quad \lambda_s(T) \frac{\partial T}{\partial \theta} = q' \\
& 0 \leq r < R, \quad \theta = \frac{\pi}{2} \quad \lambda_s(T) \frac{\partial T}{\partial \theta} = 0 \\
& 0 \leq r < R, \quad \theta = -\frac{\pi}{2} \quad \lambda_s(T) \frac{\partial T}{\partial \theta} = 0
\end{align*}
$$

(7) (8) (9) (10)

where $R$ is the radius of the tube, $\rho$ is the density of the tube, $C_p$ is the Specific heat capacity of the tube, $\lambda_s$ is the coefficient of heat conductivity of the tube, $q_s$ is the radiation thermal flux of the tube, it will be solved by Eq. (1) to Eq. (4), $q'$ is the conductive thermal flux between the tube and furnace bottom.

(4) Heat transfer mathematical model of furnace bottom

Furnace bottom is divided into two parts which are signed section A and section B. Section A is contact with the tube and Section B is contact with the gas. Heat transfer of furnace bottom is signed in Fig. 4.

![Fig. 4: Heat transfer of furnace bottom](image)

Control equations of Section A:

$$
\rho c_p(T_A) \frac{\partial T_A}{\partial \tau} = \frac{\partial}{\partial y} \left( \lambda_d(T_A) \frac{\partial T_A}{\partial y} \right) + Q_A
$$

(11)
Initial conditions: 
\[ 0 \leq y \leq Y, \tau = 0 \quad T_A(y, 0) = T_A(0) \]  
(12)

Boundary conditions: 
\[ y = 0, \tau > 0 \quad - \lambda_d(T_A) \frac{\partial T_A}{\partial y} = q_A^0 \]  
(13)
\[ y = Y, \tau > 0 \quad - \lambda_d(T_A) \frac{\partial T_A}{\partial y} = q_A^Y \]  
(14)

Control equations of Section B: 
\[ \rho c_p(T_B) \frac{\partial T_B}{\partial \tau} = \frac{\partial}{\partial y} \left( \lambda_d(T_B) \frac{\partial T_B}{\partial y} \right) + Q_B \]  
(15)

Initial conditions: 
\[ 0 \leq y \leq Y, \tau = 0 \quad T_B(y, 0) = T_B(0) \]  
(16)

Boundary conditions: 
\[ y = 0, \tau > 0 \quad - \lambda_d(T_B) \frac{\partial T_B}{\partial y} = q_B^0 \]  
(17)
\[ y = Y, \tau > 0 \quad - \lambda_d(T_B) \frac{\partial T_B}{\partial y} = q_B^Y \]  
(18)

where \( Q_A \) and \( Q_B \) are heat sources of the furnace bottom, \( \rho \) is the density of the furnace bottom, \( C_p \) is the Specific heat capacity of the furnace bottom, \( \lambda_d \) is the coefficient of heat conductivity of the furnace bottom, \( q_A^0 \) is the conductive thermal flux between the tube and furnace bottom, \( q_B^0 \) is the radiation thermal flux, it will be solved by Eq. (1) to Eq. (4), \( q_A^Y \) and \( q_B^Y \) are the downside thermal flux of the furnace bottom, they will be solved by the followed equation.
\[ q = \alpha(T - T_0) \]  
(19)

where \( T_0 \) is environment temperature, \( T \) is furnace bottom’s temperature, \( \alpha \) is Natural convection coefficient.

(5) Heat transfer mathematical models of furnace roof and furnace wall

Heat transfer mathematical model of furnace roof has the same form with heat transfer mathematical model of furnace wall. Heat transfer of furnace roof and furnace wall is signed in Fig. 5.

Control equations of furnace roof:
\[ \rho c_p(T_f) \frac{\partial T_f}{\partial \tau} = \frac{\partial}{\partial y} \left( \lambda_f(T_f) \frac{\partial T_f}{\partial y} \right) \]  
(20)

Initial conditions: 
\[ 0 \leq y \leq Y, \tau = 0 \quad T_f(y, 0) = T_f(0) \]  
(21)

Boundary conditions: 
\[ y = 0, \tau > 0 \quad - \lambda_f(T_f) \frac{\partial T_f}{\partial y} = q_f^0 \]  
(22)
\[ y = Y, \tau > 0 \quad - \lambda_f(T_f) \frac{\partial T_f}{\partial y} = q_f^Y \]  
(23)
4 The Single Tube Setting

Based on repository, the single tube temperature setting is gained by difference. Fig. 6 show the method of single temperature setting, we divide tubes’ steel grade into Kind 1, Kind 2, Kind 3, and so on, and divide standard into Standard A, Standard B, Standard C, and so on in any steel grade. There is temperature setting in any standard (for example: the temperature setting is $T_{A1}$, $T_{A2}$, $T_{A3}$, ..., $T_{AN}$ in Standard A).

We use the linear differential method to requesting the single temperature setting. For example: when the Standard X is in somewhere between Standard A and Standard B, the difference formula is as follows:

$$T_{X_i}^0 = \frac{A - X}{A - B} \cdot T_{A_i} + \frac{X - B}{A - B} \cdot T_{B_i}$$

(28)
where $T_{X_i}^0$ is the single temperature setting of Standard X, $T_{A_i}$ is the single temperature setting of Standard A, $T_{B_i}$ is the single temperature setting of Standard B, $X$ is the diameter of Standard X, $A$ is the diameter of Standard A, $B$ is the diameter of Standard B.

5 The Final Temperature Setting

Based on the single tube temperature setting, the final temperature setting is requested in using the regional discrete method.

The regional discrete method is based on that the residence time of tube in a section will affect on temperature setting of this section. The different ratios are confirmed according to the residence time of tube in a section. The final temperature setting is confirmed to add that any single tube temperature setting multiply their ratios. The explanation of regional discrete method is showed in Fig. 7, the ratios formula and the final temperature setting formula are followed.

$$\omega_i = \frac{\tau_i}{\sum_{i=1}^{n} \tau_i} \cdot 100\% \quad (29)$$

where $\omega_i$ is the ratios of different tubes ($i$ is 1, 2, ..., $n$), $\tau_i$ is the residence time of tube in a section ($i$ is 1, 2, ..., $n$).

$$T_{sp} = \sum_{i=1}^{n} T_i \cdot \omega_i \quad (30)$$
where $T_{sp}$ is the final temperature setting, $T_{i}$ is the single tube temperature setting, $\omega_{i}$ is the ratios of different tubes ($i$ is 1, 2, $\cdots$, $n$).

6 Validation

In order to test the accuracy of the temperature setting, this paper measures tube’s temperature after discharging. The rotary reheating furnace’ mean diameter is 21 m, and its wide is 5.2 m, there are 9 sections in the furnace, the temperature setting in each section is shown in Table 1. The results of contrast between measured temperature and target temperature is showed in Table 2. The relative error is mostly in 0.2% to 0.8%, the maximum relative error is less than 1%. Therefore, the process of tube heating is reasonable.

<table>
<thead>
<tr>
<th>Section No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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<td>1280</td>
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<td>1295</td>
<td>1290</td>
<td>1285</td>
<td>1275</td>
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<table>
<thead>
<tr>
<th>Measured temperature ($^\circ$C)</th>
<th>Absolute error ($^\circ$C)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
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<tr>
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<td>5</td>
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<td>0.62</td>
</tr>
<tr>
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<tr>
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<td>0.81</td>
</tr>
</tbody>
</table>

Tube Diameter: 310 mm
Tube Length: 3500 mm
Target Temperature: 1265$^\circ$
7 Conclusion

Regenerative rotary furnace is a new kind of furnace in metallurgical industry, which can reduce heating costs, reduces pollutant emission, and has many other advantages, but it is inconvenience to confirm temperature setting because of complex flow field, the special structure of furnace. For regenerative rotary furnace this paper presents a method which using The regional discrete method, using this method, the temperature setting is accuracy, the tube's temperature after discharging will be accordant with the target temperature. The works which we do will be direction for the application of regenerative rotary furnace.

References