Numerical Study on Temperature Uniformity of Regenerative Heating Furnace

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Abstract. Using CFD simulation technology, the influence of three kinds of operation modes (air change on the same side mode, cross air change mode and staged air change mode) on the temperature uniformity of regenerative heating furnace was studied. The results show that: 1) in the same side air exchange mode, the high temperature area is easy to form in the middle of the furnace, which makes the local temperature of the billet surface high; 2) in the cross air exchange mode, the high temperature area appears in the middle of the furnace, the heat exchange in the middle of the billet is strong, and the heating speed is fast; 3) in the staged air exchange mode, the high temperature area moves to both ends, and the temperature at both ends of the billet is higher than that in the middle. Therefore, in order to keep the temperature of billet constant, the best operation mode of regenerative heating furnace is alternating operation of cross air change mode and staged air change mode.

1. Introduction

The application of high temperature air combustion technology (HTAC) in the field of steel rolling heating furnace not only has better energy-saving effect, but also because the burners of the furnace are arranged on both sides of the furnace, and the alternative reversing makes the temperature in the width direction of the furnace more uniform, which is conducive to improving the uniformity of billet heating [1]. In order to get the best operation of regenerative heating furnace, scholars at home and abroad have done a lot of research. For example, Tang et al.[2] used the numerical calculation software FLUENT to study the gas temperature distribution in the heating furnace, and by optimizing the combustion mode of the burner, the injection speed and the injection angle to achieve a more uniform temperature distribution in the furnace. Ou et al.[3] studied the influence of different structure of reversing combustion on the entrainment and combustion of multi burner jet in the heating furnace. Qiu et al.[4] established a coupled heat transfer model of the furnace and the aluminum for a representative rectangular regenerative aluminum melting furnace. Based on the above research, this paper proposes a method to determine the temperature uniformity in the furnace through the temperature distribution on the billet surface, and simulates the influence of different operation modes on the temperature uniformity of the furnace.
2. Numerical simulation

2.1 Physical Model
The research object is a regenerative forging furnace with a production capacity of 80 T/h. The furnace size is 4800mm×3850mm×1573mm, the billet specification is Φ550×1500, double row charging, the two sides of the regenerative burner are symmetrically arranged, the total number of burners is 10, and the reversing time is 30s. The unstructured tetrahedron and hexahedron hybrid mesh is used in the simulation, and the mesh is encrypted locally. The number of mesh nodes is 1093798. The main dimensions and section diagram are shown in Figure 1.

Figure 1. Layout of regenerative heating furnace and billet

In actual operation, the heating furnace is a nonlinear and complex time-varying system with many interference factors. To facilitate the calculation, the following assumptions are made for the model:

(1) The internal sealing of the heating furnace is good, there is no escape phenomenon, and there is no heat loss of the furnace wall.
(2) It is assumed that only the furnace gas is coupled to the billet for heat exchange.
(3) The influence of iron oxide scale on billet is not considered for the time being.
(4) It is assumed that the air temperature after the preheating of the regenerator can reach 1073K.
(5) It is assumed that the burner can be commutated at the same time when commutating.

2.2 Mathematical formulations

2.2.1 Flow and energy equations
The basic mathematical equations such as continuity, momentum, energy, turbulent kinetic energy, for gas flow and heat transfer are given by [5]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \sum_{i=1}^{n} \frac{\partial (\rho u_i)}{\partial x_i} = 0$$  \hspace{1cm} (1)

Where: ρ is the fluid density, t is the time the fluid flows, and u_i is the velocity.

Momentum equation:

$$\frac{\partial \rho u_i}{\partial t} + \sum_{j=1}^{n} \frac{\partial (\rho u_i u_j)}{\partial x_j} = F_i - \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$  \hspace{1cm} (2)

Where: p is the static pressure of the control body, F is the volume force, μ is the dynamic viscosity, \(\tau_{ij}\) is the stress tensor.

Stress tensor is given by:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij}$$  \hspace{1cm} (3)

Where \(\delta_{ij}\) is the molecular viscosity

Energy equation:
\[
\frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_i} (u_i (\rho E + P)) = \frac{\partial}{\partial x_i} (k_{\text{eff}} \frac{\partial T}{\partial x_i}) + S_h
\] (4)

Where: \( k_{\text{eff}} \) is the heat conduction coefficient; \( T \) is the thermodynamic temperature; \( E \) is the energy, and \( S_h \) is user-defined.

### 2.2.2 Turbulent combustion model

The \( k-\varepsilon \) model is generally applied to solve the turbulence, which shows a good agreement with the experimental observations. The \( k \) equation and the \( \varepsilon \) equation are expressed as follows:

**Turbulent kinetic energy equation \( k \):**

\[
\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j k) = \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] - \rho \varepsilon + G_k + G_b + S_k
\] (5)

**Turbulent dissipation equation \( \varepsilon \):**

\[
\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j \varepsilon) = \left[ (\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j} \right] - \rho \varepsilon^2 + \frac{C_1 \varepsilon}{k} (G_k + C_3 G_b) + S_\varepsilon
\] (6)

\( C_1, C_2, C_3 \) are constant, \( S_k \) and \( S_\varepsilon \) are user-defined, Prandtl number is average turbulent flow, and \( \mu_t \) is turbulent viscosity. The \( G_k \) formula is as follows:

\[
G_k = -\rho u_i \frac{\partial T}{\partial x_i}
\] (7)

The \( G_b \) formula is as follows:

\[
G_b = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} g_i + \frac{\mu_t}{\rho T} \frac{\partial T}{\partial x_i}
\] (8)

Where: \( g_i \) is gravitational vector, \( P \) is fluid density and \( T \) is thermodynamic temperature.

### 2.3 Burner operation mode

In order to analyze the influence of heating mode on the uniformity of temperature field in the furnace, three typical operating conditions was studied, which are air change on the same side mode, cross air change mode and staged air change mode, and the nozzle reversing cycle is 60s. The layout of specific nozzle operation mode is shown in Figure 2.

![Figure 2. Schematic diagram of burner operation mode](image)

### 2.4 Boundary and initial conditions

The heating furnace uses natural gas as fuel, the calorific value is \( 8300 \times 4.18 \text{ kJ/m}^3 \), and the oxidant is air. The inlet boundary is velocity inlet, the velocity flow of fuel inlet is \( 36 \text{ m}^3/\text{h} \), the inlet pressure is \( 6 \text{ kPa} \), the excess air coefficient is \( 1.13 \), and the air inlet pressure is \( 2 \text{ kPa} \). The outlet boundary is the pressure outlet and the value is 0. The billet is treated according to the boundary condition of heat conduction solid and there is no heat source inside. The surface blackness and furnace wall blackness of billet are taken as 0.8. The thermal conductivity of 7800kg / m3 manganese steel is calculated according to the thermal conductivity solid, and the thermal conductivity and specific heat are set...
according to the reference [6]. During initialization, the air preheating temperature is 1073K, and the initial billet temperature is 1073K.

3. Results and analysis

3.1 Uniformity analysis of furnace

Fig. 3 is a cloud chart of three operation modes at the time of single commutation cycle. It is divided into three groups: temperature field in the furnace, velocity field in the furnace and temperature field on the outer surface of billet. There are three operation modes corresponding to each group from left to right, which are air exchange mode on the same side, cross air exchange mode and staged air exchange mode. It can be seen from Fig. 3 (a) and (b) that at the time of single reversing cycle, the peak value of flame temperature in the same side air exchange mode is low, because the jet direction is in the same direction, the generated air flow is orderly, and there are less vortices between the air flows, forming a low-pressure area in the furnace interior, and the flame air flow is inclined to the inner part, so that large vortices are generated in the furnace center, resulting in the length of the intermediate flame size. On the contrary, the jet direction of cross air exchange mode is staggered, and the jet direction between adjacent jets is opposite, and there will be vortex between each two jets. After that, the original
vortex will be broken up, resulting in vortex in the opposite direction. The vortex increases the degree of disorder in the furnace, making the combustion more complete, the peak temperature higher, the range of high temperature area larger and mainly located in the low-pressure area in the middle of the furnace. There are both the same direction jet and the reverse jet in the staged air exchange mode. The multi direction jet and the multi direction jet interact with each other, resulting in irregular size vortex. The air flow deviates seriously, and the high temperature area deviates to both ends.

According to the analysis of furnace uniformity based on the temperature field on the outer surface of billet, it can be seen from Fig. 3 (c) that a stable and concentrated high-temperature area is formed in the furnace central area of the same side air exchange mode, and the local temperature of billet in the furnace central area is high; the high-temperature area of the cross air exchange mode is enlarged, and the billet is heated and concentrated along the depth of furnace; the air flow of the staged air exchange mode is severely skewed, and the high-temperature area is inclined to both ends.

3.2 Uniformity analysis of billet heating

In order to study the uniformity of billet heating, a coordinate system is established based on the axial center position of furnace and the end face of the third row of billet. The specific location of the origin is shown in Figure 4 (a). Fig. 4 (b) and (c) show the distribution of the axial surface temperature of billet and the axial surface temperature of furnace in three heating modes respectively. It can be seen from Fig. 4 that in the same side air exchange mode, the axial surface temperature of billet changes greatly, the central heat load of furnace is high, and the uniformity of heating is poor; in the cross air exchange mode, the surface temperature of billet along the axial direction of furnace is high and even, but the axial surface temperature of billet changes obviously. On the side deviating from the axial direction of furnace, the surface temperature of billet is low; in the graded air exchange mode, the axial steel along the furnace is low. The surface temperature of billet is high and even, but the temperature is low. The axial surface temperature of billet tends to increase away from the axial side of furnace.

![Figure 4. Surface temperature distribution of billet](image-url)
4. Conclusion
The thermal information in the heating furnace which is difficult to get by common experimental methods can be obtained by numerical simulation, which provides reference for improving the design and operation of HTAC heating furnace and realizing the optimal control of heating furnace. Through numerical simulation, the following conclusions are obtained.

1) At the time of single reversing cycle, the peak value of flame temperature in the same side air exchange mode is lower than that of cross air change mode and staged air change mode.
2) In the same side air exchange mode, the axial surface temperature of billet changes greatly, the central heat load of furnace is high, and the uniformity of heating is poor; in the cross air exchange mode, the surface temperature of billet along the axial direction of furnace is high and even, but the axial surface temperature of billet changes obviously.
3) In order to keep the temperature of billet constant, the best operation mode of regenerative heating furnace is alternating operation of cross air change mode and staged air change mode.

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