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Zonal method solution of radiative heat transfer in a one-dimensional long roller-hearth furnace in CSP

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Abstract: A radiative heat transfer mathematical model for a one-dimensional long furnace was set up in a through-type roller-hearth furnace (TTRHF) in compact strip production (CSP). To accurately predict the heat exchange in the furnace, modeling of the complex gas energy-balance equation in volume zones was considered, and the heat transfer model of heating slabs and wall lines was coupled with the radiative heat transfer model to identify the surface zonal temperature. With numerical simulation, the temperature fields of gas, slabs, and wall lines in the furnace under one typical working condition were carefully accounted and analyzed. The fundamental theory for analyzing the thermal process in TTRHF was provided.

Key words: zonal method; roller-hearth furnace; radiative heat transfer; mathematical model; temperature fields

1. Introduction

In compact strip production (CSP), for example, thin slab continuous casting and rolling, through-type roller-hearth furnace (TTRHF) is the key thermal engineering equipment to connect the continuous caster with the tandem mill. The furnace is divided into hot, soaking, and buffering sections, in which functions, such as, heating, soaking, insulating, delivering, and buffering are realized. Heat transfer is always important for the CSP technical thermal process. Although there are many investigations on heat transfer calculation for soaking [1-3] or continuous furnace, little study [4] is focused on the heat exchange in TTRHF. The basic idea of the zonal method [5-6] is to suppose that the furnace line surfaces and the slab-heated surface are divided into small areas, even as the medium in the furnace is also discredited into small volume zones. In each zone, temperature and physical parameters are uniform. The temperature and heat flux of all the areas and volume zones are calculated by setting-up a close-scheme nonlinear energy-balance equation. This calculation is accessible only when the temperatures of the furnace surface and heated metal surface are known, thus the equation has to be coupled with a solid heat conduction equation set. These two equation sets offer boundary conditions for each other and make up of a general expression for the heat exchange in TTRHF using the zonal method.

According to the CSP structural and thermal engineering characteristics in the roller-hearth heating furnace, a one-dimensional heat transfer mathematical model along the length of the furnace was established with the zonal method in this article. The numerical simulation helped to further analyze the effects of some thermal or operational parameters on heat transfer in TTRHF.

2. Physical model

To simplify the research, heat transfer from rollers to slabs was ignored and the slab was taken as being symmetrically heated [7]. The half-thickness of the slab was 25 mm; the furnace was 180 m long, 1 m high, and 1.5 m wide. Because the length of the furnace was much larger than it's height and width, and the gas temperature along the length, especially in hot section, changed remarkably, whereas, that along the height and width was quite small, a one-dimensional long model was employed. The furnace was divided into small volume zones along its length. The sizes of the volume zones are shown in Fig. 1.

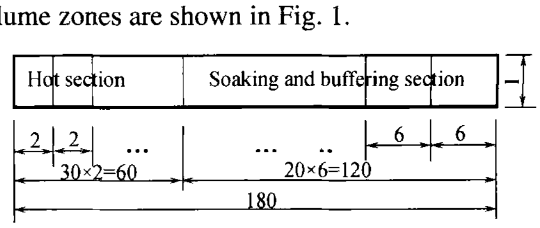

Fig. 1. Physical model. Unit: m.

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3. Mathematical models

3.1. Energy-balance equation in the volume section

As burner nozzles on the walls warmed up by themselves, fuel in the volume zones was burned to release heat. Some of the combustion products refluxed because of flame entrainment; others were drawn out of the exhaust port to preheat air. The burned gas flowed along the furnace width and the heat was transferred by convection from the surface of heated areas and lines. Heat equilibrium in the volume zones is shown in Fig. 2. Ignoring the sensible heat content brought by fuel and the slab's oxidizing heat release [8], the energy equation under steady working condition in the heating furnace is written as

$$m_{fi}Q_{dw}^{y}+(1-\beta)m_{yi}I_{2i}+\sum_{j=1}^{m+n}\overline{(Z_iZ_j)}_{a}E_{bj}=m_{yi}I_{2i}+4a_{gi}V_{gi}E_{bi}+h_{wi}F_{wi}(T_{gi}-T_{wi})+h_{mi}F_{mi}(T_{gi}-T_{mi}) \quad (1)$$

where m and n are the number of surface areas and volume zones, respectively; m_{fi} and m_{yi} are the fuel supply quantity in the volume zone and the fume amount in the discharge volume zone respectively, m^3/s; Q_{dw}^{y} is the net calorific power of fuel, J/m^3; β the heat loss ratio of flue gas to discharging fume heat; I_{2i} the fume enthalpy in the exhaust volume zone, J/m^3; $\overline{(Z_iZ_j)}_{a}$ the total radiation heat exchange area, m^2 [9]; E_{bj} and E_{bi} are the blackbody emissive power, W/m^2; a_{gi} the absorption coefficient of gas, 1/m; V_{gi} the gas volume, m^3; h_{wi} and h_{mi} are the convective heat transfer coefficients of gas from lines and with slabs respectively, $W/(m^2 \cdot K)$; F_{wi} and F_{mi} are the areas of lines and slabs respectively, m^2; T_{gi}, T_{wi}, and T_{mi} the temperature of furnace gas, lines and slabs, respectively, K.

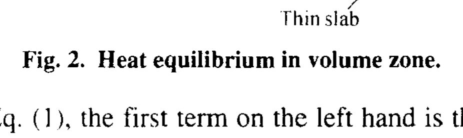

Fig. 2. Heat equilibrium in volume zone.

In Eq. (1), the first term on the left hand is the heat released from complete combustion, the second term is the heat brought by preheated air, the third term is the incidence heat of gas; the first term on the right hand is the entrapped heat by fume, the second term is the emitted heat from gas, the third term is the convective heat transfer from gas to lines and slabs.

The equation for the total heat of gas can be written as

$$\Delta Q_{gi}=4a_{gi}V_{gi}E_{bi}-\sum_{j=1}^{m+n}\overline{(Z_iZ_j)}_{a}E_{bj}+h_{wi}F_{wi}(T_{gi}-T_{wi})+h_{mi}F_{mi}(T_{gi}-T_{mi}) \quad (2)$$

where ΔQ_{gi} is the total gas heat flux in volume zone i, W.

After the mixing of combustion product with recirculating gas flow at the export of the nozzle (Fig. 2), the heat equilibrium equation can be written as

$$R_{ri}m_{yi}I_{1i}=m_{fi}Q_{dw}^{y}+(1-\beta)m_{yi}I_{2i}+(R_{ri}-1)m_{yi}I_{2i} \quad (3)$$

where, the term on the left hand of the equals sign is the total heat amount at the burner nozzle; the third term of right side is the transported heat brought by recirculating fumes to the burner export. In Eq. (3) it is supposed that fuel has been exhausted in the furnace.

Express the average enthalpy I_{gi} of gas by fume enthalpy at the burner export and exhaust port (I_{1i}, I_{2i}):

$$I_{gi}=\zeta I_{1i}+(1-\zeta)I_{2i} \quad (4)$$

where ζ is the weight number.

Then, the total gas heat flux ΔQ_{gi} in the furnace is attained:

$$\Delta Q_{gi}=R_{ri}(m_{fi}Q_{dw}^{y}-\beta m_{yi}I_{gi})/(R_{ri}-\zeta\beta) \quad (5)$$

where I_{gi} is the average enthalpy of gas $I_{gi}=C_{gi}T_{gi}$, J/m^3; C_{gi} the gas mean specific heat capacity, $J/(m^3 \cdot K)$; I_{1i} the fume enthalpy of gas at the burner export, J/m^3; R_{ri} the gas recycling multiplying factor;

Eqs. (2) and (5) represent the solution of gas temperature distribution in volume zones. With supposed gas temperature distribution, specified fuel constitution, and combustion calculation results, heat ΔQ_{gi} is gained by Eq. (5). Then by iteration, the temperature distribution of gas in all volume zones is got by Eq. (2).

3.2. Energy-balance equation for line surface zones

The energy-balance equation for line surface areas is written as follows.

$$\sum_{j=1, j\neq i}^{m+n}\overline{(Z_iZ_j)}_{a}E_{bj}+h_{wi}F_{wi}(T_{gi}-T_{wi})=\Delta Q_{wi}+\varepsilon_{w}F_{wi}E_{bi} \quad (6)$$

where E_{bj} is the blackbody emissive power, W/m^2; ΔQ_{wi} the heat flux transporting to the lines in the furnace, W; ε_{wi} the line surface blackness; E_{bi} the line