Calculation and Analysis the Influence on the Cooling Water Velocity and Hot Metal Circulation to the Long Life Blast Furnace

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Abstract: Based on the result of the blast furnace dissection and the optimization of hearth heat transfer boundary conditions, the hearth heat transfer mathematical model was established, and then the equivalent heat transfer coefficient of hot metal was proposed, which characterized the iron circulation strength. The dynamic conditions which promoted the viscous layer formation on the brick lining heat face were analyzed. Reducing smelting intensity was the most significant measure which was pointed out quantitatively. The smelting rhythm should be controlled in the condition of blast furnace intensification. The hearth reasonable requirement of critical water velocity was given, that was, the cooling water body temperature should be below the water quality stability temperature and the pipe wall temperature of the boundary layer should be under the cooling water boiling temperature. According to the given condition, the water velocity of the hearth should be greater than 1.2 m/s.

Key words: Hearth, equivalent heat transfer coefficient of hot metal, rational cooling water velocity, film boiling.

1. Introduction

In the current new BF (blast furnace) operating conditions of the high-intensity smelting and the use of low-grade ore, the cases of hearth breakout were occurred frequently [1-3]. Analysis of the reason was mostly concentrated in the insufficient cooling capacity, so as to increase the cooling intensity to extend the life of blast furnace which was an important measure, and sparking a “large amount of water, a small temperature difference” and “small amount of water, a large temperature difference”, two different operating conception [4-5]. Ning Xiaojun et al [6] in the study of rational cooling water system for a large blast furnace hearth pointed out that the rational cooling system of the initial and the final were raised qualitative, but a reasonable quantification of water for a specific blast furnace did not give. Wang Zhijun et al [7] in the analysis and calculation of the demand of Angang hearth cooling water stated that a

method of allowing maximum heat flux intensity was used, but the case of higher heat flux intensity was not considered. Currently, the extent of the influence on hot metal was ignored. The potential of the cooling water circulation and the hot metal transfer in the hearth were not analyzed.

In the existing mathematical models and numerical analysis [8-10], there were still some shortcomings of the boundary conditions selection, such as the impact of the cooling water temperature for cooling water boundary, the first boundary condition was not considered. There was a big temperature difference between the pipe wall boundary layer and the body temperature of the water. As to the hot metal and brick lining interface, some used the 1150 °C solidified as first boundary condition, some used the experience convective heat transfer coefficient of hot metal as third boundary conditions. In this paper, the mathematical model was built on the basis of optimized the boundary conditions. The influence on the blast furnace hot metal cylinder and cooling water

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circulation for the formation of the viscous were calculated under the different operating conditions. A reasonable blast furnace hearth cooling water velocity was given.

2. Calculation Model

2.1 Physical Model

In the blast furnace hearth heat transfer model, the heat transfer theory usually was used for calculating. Blast furnace hearth cooling system structure generally included the following sections: cooling water, cooling wall, ramming mix, carbon brick, ceramic cup, hot metal, etc., as shown in Fig. 1 [11].

Heat flux intensity was deduced by the third boundary condition of thermal heat transfer. The formula was showed as below.

$$q = \frac{T_{HM} - T_{CW}}{\frac{1}{\alpha_{HM}} + \sum \frac{s_i}{\lambda_i} + \frac{1}{\alpha_{CW}}} \quad (1)$$

In the formula,

T_{HM} — the temperature of hot metal.

T_{CW} — the temperature of cooling water.

α_{HM} — the convective heat transfer coefficient of hot metal.

α_{CW} — the convective heat transfer coefficient of cooling water.

s — the thickness of hearth lining.

λ — the thermal conductivity of hearth lining.

2.2 The Convective Heat Transfer Coefficient of Cooling Water

In the formula (1), The variable α_{CW} , t_{rCW} , α_{HM} should be determined. The convective heat transfer coefficient of cooling water could be deduced by Dittus-Boelter [12], as shown in formula (2).

$$Nu_u = \frac{h_w \cdot d_1}{\lambda_w} = 0.023 \left(\frac{V \cdot d_1}{\nu} \right)^{0.8} \left(\frac{\nu}{h_w} \right)^{0.4} \quad (2)$$

In the formula,

V — water velocity, m/s.

λ_w — water conductivity, W/(m·°C).

d_1 — Pipe diameter, m.

ν — Cooling water kinematic viscosity, m²/s.

h_w — Convective heat transfer coefficient, W/(m²·°C).

2.3 The Interfere of the Water and Pipe

Blast furnace cooling water was turbulence which was fully developed. The boundary layer were existed at the interface between the cooling water and the wall, so the cooling water temperature could be divided into two types, one for the cooling water body temperature T_1 , that was a certain temperature after heating by heat flux intensity, the other was the boundary layer temperature, that was the pipe wall temperature T_2 .

2.4 The Interfere of the Iron and Brick

There were two possible states between the hot metal and the brick lining interface. When the hot metal was stationary, that was the first boundary condition. While the hot metal was flowing at a certain rate, that was the third boundary condition [13].

Fig. 1 Physical models of BF heat transfer.

Table 1 The convection heat transfer under different water velocity.

Water velocity, m/s	0.2	0.5	0.8	1	1.2	1.5	2
Convective heat transfer W/(m ² ·K)	1054	2194	3195	3820	4420	5284	6651

Fig. 2 Physical models of cooling water and pipe.

Fig. 3 Physical models of hot metal and hearth lining.

The thermal conductivity of hot metal changed with temperature as shown in Equation (3) [14], the thermal conductivity of hot metal at 1200 °C was 9.5 W/(m²·°C) by calculation. Therefore, the temperature in the thinner boundary layer under a continuous high intensity smelting conditions, the convective heat transfer played a decisive role in thermal resistance.

$$\lambda_{HM} = 45.14 \exp(-0.0013T_{HM}) \quad (3)$$

In the formula,

λ_{HM} — the convective heat transfer of hot metal, W/(m·°C).

T_{HM} — the temperature of hot metal, °C.

2.5 Equivalent Hot Metal Heat Transfer Coefficient Based on the Presence Viscous Layer

A layer thickness of about 2mm on the hot face brick lining in hearth was found in a blast furnace dissection, which played a role in protecting brick lining [15]. After laboratory analysis, the main component of the viscous layer was iron with a large amount of graphite. Its color had a big difference to normal hot metal. So the viscous layer was existed in the normal production process. Thus, assuming in a brick lining thickness and cooling water velocity condition, the viscous layer forming temperature was T, the thick of viscous boundary layer was 2mm, then the equivalent hot metal convective heat transfer coefficient in different cooling intensity and different furnace service period could be calculated. The calculation process of the equivalent hot metal convective heat transfer coefficient based on the existing of the viscous layer could be realized. Fig. 4 was a configuration diagram of the calculation

method.

3. Calculation Results and Analysis

3.1 Equivalent Heat Transfer Coefficient of Hot Metal

The flowing strength of hot metal was characterized by the equivalent heat transfer coefficient of hot metal, reflecting the intensity of hot metal. The service life of blast furnace was divided into four stages according to the heat transfer model. That was: the remaining brick lining thickness was 1.1 m, 0.55 m, 0.2 m and 0.1 m. Through calculation of the various service periods, the equivalent heat transfer coefficient of hot metal changed with the cooling water velocity was shown in Fig. 5. As can be seen from the figure, with brick lining thickness thinning, the equivalent heat transfer coefficient of hot metal increased at the same cooling intensity conditions. That was, in the early service, when the brick lining was thick, the viscous layer of hot metal generated at a lower intensity, with brick lining thinning, the total thermal resistance of the cooling system decreased, the cooling effect was highlighting, the temperature of the brick lining hot face decreased, at that time, the strength of the hot metal circulation might be appropriate increased, which could ensure the presence of a viscous layer and maximize productivity.

In the final service of the furnace, viscous layer of hot metal could generate at higher circulation intensity. However, the viscous layer would be fall off for the unstable and fluctuate of hearth smelting conditions. In this case, the brick lining could contact directly with the hot metal, and the safety factor decreased. Therefore, the hot metal circulation intensity should be controlled in the final service furnace. The change of the equivalent heat transfer coefficient of hot metal with the cooling water velocity was not obvious, which indicated that increasing the cooling intensity for viscous layer formation was very limited in the same service furnace and the same hot metal circulation intensity.

Fig. 4 The configuration diagram of iron equivalent coefficient of heat transfer.

Fig. 5 Equivalent heat transfer coefficient of hot metal changed with water flow velocity.

Fig. 6 showed the brick lining hot face temperature changed with the cooling water velocity and the equivalent heat transfer coefficient of hot metal in the brick thickness of 0.55 m. As can be seen from the figure, with the cooling water velocity increased, the

brick lining hot face temperature reduced, that was, the formation of the viscous layer was promoted by increasing the cooling intensity. However, the temperature of the brick lining hot surface changed very little when the water velocity was greater than 1.2 m/s or more. There was little effect that the cooling water intensity continued to increase. While the brick lining hot face temperature had a big change with the equivalent heat transfer coefficient of hot metal. It was concluded that reducing the hot metal circulation was an effective measure for reducing the temperature of the brick hot face and reducing the erosion of the hearth brick lining. However, it was very limited to reduce the temperature of the brick hot face by increasing the cooling intensity.

3.2 The Reasonable Cooling Water Velocity of Hearth

In normal production, the cooling water inlet

temperature was far below the boiling temperature, which was less heat water [16]. Cooling water pressure was higher, the greater the water velocity, and the greater less heat water. Water velocity changed with the cooling water pressure as shown in formula (4) [17], the boiling temperature of the cooling water with the pressure variation as shown in formula (5). And the heat transfer coefficient between the pipe and the cooling water maintained at a high level, so the cooling water temperature will quickly bring away the heat by water temperature elevated itself.

The body temperature of the cooling water, water temperature of inner pipe and the boiling temperature of the inner wall changed with the cooling water velocity as shown in Fig. 7.

$$v = \mu \sqrt{2gP} \quad (4)$$

$$T = -1.109P^2 + 19.434P + 84.204 \quad (5)$$

In the formula,

v — cooling water velocity.

P — cooling water pressure.

μ — Water flow coefficient, 0.6.

T — the boiling temperature of cooling water.

The stove need to work under conditions without overheating, and the peak heat flux intensity of cast iron was generally 150-200 kW/m². The calculation results of the peak heat flux intensity in 150 kW/m² and 200 kW/m² condition were shown in Fig. 7, respectively. As can be seen from the figure, when the heat intensity was 150 kW/m², the pipe wall temperature was lower than the conditions of film boiling if the cooling water velocity was greater than 1.0 m/s. When the heat flux intensity was 200 kW/m², the cooling water velocity must be greater than 1.2 m/s which would effectively prevent the occurrence of film boiling. When the cooling water temperature was greater than 1.2 m/s, there was no significant change of the body cooling water and the pipe wall temperature. So in the actual production, the cooling water velocity should be controlled at 1.2 m/s or more. It was worth mentioning that the body temperature of the cooling water must be less than the stability of the

cooling water temperature to prevent the formation of scale.

Fig. 6 The influence on forming viscous layer by equivalent heat transfer coefficient of water flow velocity (a) and hot metal (b).

(a) Thermal heat flux intensity 150kW/m²

(b) Thermal heat flux intensity 200kW/m²

Fig. 7 The water temperature changes with water flow velocity.

4. Conclusions

The hearth heat transfer mathematical model was established based on the optimization of the boundary conditions. Including the cooling water temperature, water temperature boundary layer and convective heat transfer coefficient of hot metal and the brick. The equivalent heat transfer coefficient of hot metal was proposed, which characterized the strength of the hearth state.

Improving the cooling strength and reducing the hot metal circulation intensity could promote the viscous layer formation. Some calculations showed that, there was limited effect on forming the viscous layer by improving the cooling strength when the cooling water velocity was greater than 1.2 m/s, while reducing the intensity of hot metal circulation had a remarkable effect.

The smelting rhythm should be controlled. In the early service, the equivalent heat transfer coefficient of hot metal could be controlled at 30 W/(m²·°C) or so, with the brick lining thinning, the cooling effect was increasingly prominent, the circulation of hot metal strength might be appropriate increased. In the final furnace service, the equivalent heat transfer coefficient should be controlled at 80 W/(m²·°C) or less.

The reasonable water demand of blast furnace hearth was that the body temperature was lower than the water stability temperature and the cooling water pipe temperature was below the boiling temperature. The calculations showed that the cooling water velocity was greater than 1.2 m/s which could prevent the film boiling.

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