The safety thickness of blast furnace hearth lining and simulation analysis for different interventions

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Abstract. In the late period of the blast furnace operation, the residual thickness of the hearth lining is insufficient. To avoid the burning through of hearth, intervention measures with variable operating conditions are needed. Plugging wind gap, adding Titanium ore and controlling production are frequently used at the scene of the project. A 1-D method is used to determine the safe thickness of the hearth lining. A general CFD software FLUENT is used to simulate the iron tapping of the hearth model under different interference conditions. The influence of different conditions on erosion state of the hearth is explored.

1. Introduction
During the lifecycle of blast furnace hearth, physical and chemical erosion occurs when the hot surface of the lining contacts with molten iron directly. With the development of erosion, the thickness of the hearth lining decreases gradually. The erosion of hearth lining is affected by operating conditions to a great extent. Because the life of hearth is closely related to the residual thickness of lining, it is crucial to adjust operating conditions reasonably to delay the erosion of hearth.

Currently, the lining erosion diagnosis technology based on heat transfer theory is ripe at domestic and foreign countries. Zhang et al. [1] considered four possible situations and calculated the hot face position in the side wall by using a 1-D heat transfer model. A 2-D inverse method for identifying erosion boundary was proposed [2].

The previous method for calculating safe thickness was based on the thermal stability strength of cooling stave [3]. This paper puts forward a new calculation method of the safe thickness based on the strength theory.

In recent years, as Tachimon [4] and Ohno et al. [5] attempted to study the relationship between molten iron flow and lining heat transfer, various comprehensive models have been developed to simulate the flow of molten iron in the hearth and lining heat transfer. Kouji et al. [6] established a mathematical model for estimating the transient erosion process of blast furnace lining, which can simulate the flow and heat transfer of molten iron and the erosion of carbon brick. Chenn et al. [7] proposed a comprehensive computational fluid dynamics model to simulate the flow of hot metal in blast furnace hearth and heat transfer in the lining. Sun [8] discussed the influence of different dead porosity of dead coke column, convective heat transfer coefficient and volume utilization factor on hearth tapping and theoretical operation furnace type. Previous studies mainly focused on modeling the original model of blast furnace hearth, but few on modeling the hearth model under erosion condition.

Gas flow is weak, and there is no dripping slag iron when the wind gap is plugging. Titanium compounds with a high melting point are efficiently accumulating at the bottom of hearth and can form
a viscous substance with molten iron. This substance can repair the corroded hearth to some degree [9]. High productivity is very adverse to the stability and smooth operation of the furnace. Controlling productivity can delay the erosion of the lining. Plugging wind gap, adding titanium ore and controlling production are commonly used for furnace protection in the late period of blast furnace [10].

Using the 1-D theory to calculate the safe thickness of hearth, and taking measures to intervene after the hearth is eroded to the safe thickness. This is of great significance for realizing the safety and longevity of the blast furnace.

2. The calculation model of safety thickness

The hearth structure is generally composed of lining, cooling stave, filler, and shell. When there is no gap between the layers and the shell has a good tighten action, the circumferential stress of the lining shows compressive stress. Take the single layer cylinder structure as the object, shown in Figure 1. The inner and outer radius of the structure are respectively \( r_1 \) and \( r_E \). The lining hot surface temperature takes the iron equilibrium solidification temperature 1150° C. The outer surface of the lining is convective heat transfer boundary. The convective heat transfer coefficient and temperature are respectively \( h_c \) and \( T_c \). The thermal conductivity, linear expansion coefficient and elastic modulus of the lining are respectively \( k_l, \alpha_l, E_l \). The reference temperature of thermal strain is \( T_0 \) the interface pressure of lining structure are respectively \( p \) and \( p_k \).

![Figure 1. Single layer lining structure.](image)

According to the calculation method of the heat transfer of the cylinder, the temperature of the outer surface of the lining can be calculated by the following formula

\[
T_E = \frac{T_i + r_l R_{E1} h_c T_c}{1 + r_l R_{E1} h_c} \tag{1}
\]

where \( R_{E1} \) is thermal resistance of lining

\[
R_{E1} = \frac{1}{k_l \ln \frac{r_E}{r_1}} \tag{2}
\]

The circumferential stress of the inner surface of the lining is

\[
\sigma_{\theta} = \frac{(1 + \alpha_l^2) p - 2 p_{r1} + 2 p - E_l \alpha_l \Delta T_i}{1 - \alpha_l^2} \tag{3}
\]

where \( p_{r1} = \frac{\theta}{2} (\Delta T_T - \alpha_l^2 \Delta T_i) - \frac{\theta}{4} (1 + \alpha_l^2) \ln \alpha_l - \alpha_l s \), \( \alpha_l = \frac{r_1}{r_E}, \Delta T_i = T_i - T_0 \).

According to the strength condition of lining,

\[
|\sigma_{\theta}| \leq \sigma_y \tag{4}
\]

where \( \sigma_y \) is the allowable compressive strength of lining.

Given the radius of the outer edge and the compressive strength, the radius \( r_1 \) of the inner edge of the liner can be obtained by iteration calculation from the formulas (3) and (4). The safety thickness of lining is calculated by Equation (5).

\[
L_s = r_E - r_1 + L_0 \tag{5}
\]

where \( L_0 \) is the deterioration thickness of lining.
3. The numerical simulation model

The erosion model of the hearth is studied, because of the symmetry of the model, taking half of the hearth model as the calculation model. The erosion model is established as shown in Figure 2. Furnace hearth is round-shaped erosion as a whole, and local mushroom-shaped erosion occurs at -45° azimuth. The most severe erosion has reached to a safety thickness of 0.3m. The dimensions of the hearth are as follows: the diameter of the hearth is 6m, the height of the hearth is 5.2m, the average thickness of the side wall of the hearth is 0.65m, the average thickness of the hearth bottom is 1.3m, the height of the iron tap is 4.1m, and the diameter of the iron tap is 0.1m. The hearth is composed of a mixture of iron and slag and a central dead coke zone, and they are porous media with a porosity of 0.8 and 0.3 respectively. The combination of iron and slag is mixed by the mass ratio of 3:1. The properties of carbon brick are shown in table 1.

![mushroom-shaped erosion](image1)
![round-shaped erosion](image2)

**Figure 2.** The hearth erosion model. **Figure 3.** Sketch of wind gap number.

| Density | Heat capacity | Thermal conductivity |
|---------|---------------|----------------------|
| / kgm⁻³ | / kgK⁻¹       | / Wm⁻¹K⁻¹            |
| 1600    | 700           | 14                   |

The simulation of plugging different wind gap above the hearth is realized by changing the boundary conditions. Under the condition of supplying air normally, the top of the hearth is the velocity boundary. Under the condition of blocking wind gap, the area without blocking wind gap is velocity boundary; and the area of blocking wind gap becomes wall boundary. As shown in figure 3, the wind gaps are numbered from 1 to 12, the site of occurring local depression is under the 3# and 4# wind gap. The tapping process of supplying air normally and blocking single wind gap are simulated respectively.

The simulation of adding titanium ore is realized by changing the initial erosion morphology of the lining. The residual thickness of the lining is 0.3m on the area of occurring mushroom erosion without adding titanium ore, according to the amount of titanium ore, the minimum thickness values of lining are 0.4, 0.5, and 0.6m. The simulation of the hearth model with different thickness is carried out respectively.

The simulation of controlling production is realized by changing the volumetric utilization coefficient [11]. According to the daily tapping quantity, the inlet speed above the hearth can be calculated according to Equation (6). In this paper, the volume utilization coefficients are equal to 2.4, 2.6, 2.8, 3.0, 3.2, and 3.4 t-m⁻³-d⁻¹, respectively. The inlet velocities of different volume utilization coefficients are listed in table 2.

\[ v = \frac{1000(M_{\text{iron}} + M_{\text{slag}})}{3600 \times 24 \pi r^2 \rho} \] (6)
where \( M_{\text{iron}} \) is the daily iron quantity, \( M_{\text{slag}} \) is the daily slag quantity, \( r \) is the inner radius of lining, \( \rho \) is the density of the iron and slag mixture.

The general CFD software FLUENT is used to simulate the iron tapping of the hearth model, assuming that the iron-slag is a viscous incompressible liquid, the k-ε model is used to simulate the turbulence. The solver settings of FLUENT: the inlet is velocity boundary, and keeps a constant temperature of 1500\(^\circ\)C. The outlet is a pressure boundary, and the pressure is 1 atmospheric, the outlet temperature is 1420\(^\circ\)C. The wall-boundary is non-slip boundary condition. The side wall convection coefficient of the hearth is 60W/(m\(^2\)K), and the bottom convection coefficient is 40W/(m\(^2\)K).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Volume utilization coefficient, \( \text{tm}^3\text{d}^{-1} \) & Inlet velocity, \( \text{ms}^{-1} \) \\
\hline
2.4 & 0.00024047 \\
2.6 & 0.00026051 \\
2.8 & 0.00028055 \\
3.0 & 0.00030059 \\
3.2 & 0.00032063 \\
3.4 & 0.00034066 \\
\hline
\end{tabular}
\end{table}

4. The numerical simulation model
The mesh element size is 0.15m for the total hearth model, the mesh at tap-hole is locally refined, and the mesh size is 0.02m. Usually, the 1150\(^\circ\)C isotherm of the axial section of the hearth is taken as the erosion boundary of the lining. If the erosion line of 1150\(^\circ\)C does not enter the inner of carbon brick, the slagging occurs at this position. Because the lining thickness of the model at -45\(^\circ\) axial section is minimal, there will be a certain thickness of slag skin attached to the lining surface under the condition of the external cooling condition. The thicker the slag skin thickness, the smaller the erosion radius of the position, and the safer the hearth. The erosion radius is taken as an indicator of the erosion degree.
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The velocity of iron-slag at -45° azimuth is smaller than that of other places because of mushroom erosion. But the erosion at this position is more dangerous, the velocity of iron-slag is taken as another indicator of the erosion degree. The calculation results of FLUENT extract the erosion radius at a 1.8m attitude of -45° axis section and iron-slag velocity at the evaluation point (-3.5m, 1.8m, 3.5m).

Figure 4 shows the relationship between the erosion radius of the mushroom-shaped erosion position and the velocity of iron-slag with the serial number of wind gap. Blocking 0# wind gap represents the situation of supplying air usually. It can be seen that the erosion radius of the hot lining surface is the smallest at the 1.8m elevation of the -45 degree axis section when the 7# wind gap is blocked. And the velocity of hot metal at the evaluation point is the smallest when the 6# wind gap is blocked. The velocity of iron-slag for plugging 7#, 8# and 9# wind gap is not much different than that of 6# wind gap. By comparison, plugging 7# wind gap is the best choice when plugging single outlet.

Figure 5 shows the relationship between the erosion radius of the mushroom-shaped erosion position and the velocity of iron-slag with the minimum residual thickness of the lining. The larger the residual thickness of lining is, the smaller the erosion radius is, and the higher the flow velocity of iron-slag is. Because adding titanium ore is directly repairing the lining from the root and slagging is helpful to protect the hearth lining, but adding titanium ore will strengthen the scour of the lining.

Figure 6 shows the relationship between the erosion radius of the mushroom-shaped erosion position and the velocity of iron-slag with the volume utilization coefficient. It can be seen that both erosion radius and iron-slag velocity decrease with the decrease of volume utilization coefficient. With the reduction of smelting strength, the volume utilization coefficient decreases by 0.2 and the erosion radius decrease by about 50-80 mm. Since after the production control, all kinds of indices will be reduced, the production control is an effective measure to protect the lining.

5. Conclusions

Through the 1-D theoretical prediction, a calculation method for determining the safe thickness of lining based on strength theory is deduced. The theoretical prediction has practical significance, since its results indicate whether the respective interventions are required or not.

In this paper, the hearth tapping process under the three interventions is studied. The study on the measures of blocking wind gap has explored the sequence number of the best blocking wind gap. The intervention measure of adding titanium ore was realized by changing the hearth model. The study on the intervention measures of controlling the production capacity revealed that the smaller the production capacity, the lower the erosion rate.

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