Mathematical Model for Transient Erosion Process of Blast Furnace Hearth

Kouji TAKATANI, Takanobu INADA and Kouzo TAKATA

Corporate Research & Development Laboratories, Sumitomo Metal Industries, Ltd., 16-1 Sunayama, Hasaki-machi, Kashimagun, Ibaraki-ken 314-0255 Japan. 1) Technology Division, Iron & Steel Making Technology Department, 3 Hikari, Kashiwa-shi, Ibaraki-ken 314-0014 Japan.

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A mathematical model that can estimate the transient erosion process of the blast furnace hearth has been developed. This mathematical model can treat the molten iron flow, heat transfer and the brick/refractory erosion at the hearth. To verify the availability of the mathematical model, comparisons of computational final erosion profile of the hearth were made with the investigation results of the dissection blast furnace and computational results gave good agreement with the measured one. The effects of the distribution profile of the dripping molten iron flow rate into the hearth, the coke free layer size, production rate of the molten iron, thermal conductivity of the carbon brick and the fluid flow resistance through the coke packed bed were examined by using this mathematical model.

KEY WORDS: mathematical model; blast furnace; hearth, erosion; fluid flow; heat transfer.

1. Introduction

Many works 1–9) have been done about the hearth phenomena of the blast furnace such that molten iron flow, 3–9) mass and heat transfer, 1,5,7–9) structure 2,4,5) of the coke packed bed/coke free layer and so on. Much efforts have been made in development of blast furnace operation, furnace design and furnace repair technology to realize a long campaign life of blast furnace. However, regarding the hearth brick/refractory, it is difficult to repair in operation, therefore, it is one of the critical factors of blast furnace life. Though a great deal of effort went into this field, the erosion mechanism has been not clear.

It is widely believed that molten iron flow affects the erosion of the hearth brick/refractory and coke free layer exists between the coke packed bed and the bottom brick at the hearth. In estimating the furnace hearth erosion, two main mechanisms, one is thermo-chemical solution, the other is thermo-mechanical damage, might be taken into account. In either case, it is very important to understand molten iron flow and heat transfer through the coke packed bed/coke free layer and the brick/refractory.

Many mathematical models 2–9) have given the basic understandings about the molten iron flow and the heat transfer in the blast furnace hearth. But, those mathematical models are not available for the design of the furnace structure. In order to design the hearth structure, transient erosion procedure must be analyzed.

The purpose of this study is to develop a mathematical model for the fully coupled analysis of the molten iron flow, the heat transfer and the hearth erosion and to understand the transient erosion procedure.

2. Mathematical Model

The system to be analyzed consists of coke packed bed area, coke free layer and hearth brick/refractory area, as shown in Fig. 1.

2.1. Governing Equations

In this system, material and momentum balances for molten iron, and energy balances for molten iron and the hearth brick/refractory, it is difficult to repair in operation, therefore, it is one of the critical factors of blast furnace life. Though a great deal of effort went into this field, the erosion mechanism has been not clear.

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![Diagram of hearth erosion model](image)
where
\[ F = \left( 150 \left( \frac{1-e}{\varepsilon d_p \phi} \right)^2 + 1.75 \left( \frac{1-e}{\varepsilon d_p \phi} \right) \right) \rho U \]

2.2. Boundary Conditions

Boundary conditions are given as follows.
1) Upper Boundary: Temperature and flow rate of molten iron are given and refractory region is adiabatic.
2) Tap hole: The draining rate of molten iron is given as an outlet boundary.
3) Side and bottom wall surface: Total heat transfer coefficient is given.
4) Between the brick/refractory and the coke packed bed: Heat transfer coefficient is given.
5) Coke packed bed region: is given from the results by stress analysis of internal furnace in the case of verification, and is given suitably in other case.

2.3. Erosion Criteria

Erosion criteria through thermo-chemical solution were placed at 1150°C for carbon brick, and at 1350°C for chamotte brick, on the basis of investigations of dissected blast furnace.

2.4. Solution Procedure

The computational algorithm of Navier–Stokes’s equation was applied SOLA method and the all governing equations are digitized on the staggered grid and the third-upwind scheme was used for convective term, and second-order central scheme was used for diffusive term. The boundary fitted coordinate system was applied as shown in Fig. 2.

Numerical analysis proceeds in time marching method as follows.
1) Fluid flow analysis for molten iron.
2) Heat transfer analysis for a whole area including the brick/refractory.
3) Judgement of the erosion and replace the brick/refractory with molten iron according to the erosion criteria.
4) Repeat above procedure until the brick/refractory are not eroded any more.

Therefore, this analysis gives information about transient erosion process of the heath as well as final erosion profile, as will be discussed in the following section.

3. Verification

To verify the availability of the numerical simulation model, comparisons of computational final erosion profiles were made with dissection data. Computational condition is shown in Table 1 and Fig. 3, these conditions are chosen so that inner volume may be greatly different. In these cases,
uniform temperature and flow rate of molten iron distribution were given at an upper boundary condition and the coke packed region was given from the results by stress analysis.\(^{12}\)

Computational results are shown in Fig. 4, which are Kashima #3B.F. (1st campaign in Kashima Steel Works), Wakayama #3B.F. (3rd campaign in Wakayama Steel Works) and Kokura #2B.F. (1st campaign in Kokura Steel Works), respectively, and it took 30000 steps of time marching process to get the final erosion profile. Computational results give good agreement with the dissection data, so the availability was confirmed among furnaces of various inner volume and refractory layouts.

4. Results and Discussion

Under the typical blast furnace condition, the effects of the distribution profile of the dripping molten iron flow rate into the hearth, the coke free layer size, production rate of the molten iron, thermal conductivity of the carbon brick and the fluid flow resistance through the coke packed bed on the hearth erosion were examined by using this mathematical model including transient phenomena. Base conditions are shown in Fig. 5 and results are as follows.

4.1. Distribution Profile of the Dripping Molten Iron Flow Rate

To investigate the effect of the distribution profile of the dripping molten iron flow rate on the hearth erosion, a) uniform and b) un-uniform distribution profile computed by 3D-dynamic blast furnace model\(^{14}\) are adopted as upper boundary condition. The molten iron flow in the coke packed bed becomes uniform quickly because of the large flow resistance of the packed bed even if there is flow rate distribution at the entry. Therefore, as shown in Fig. 6, effect of the flow rate distribution is not remarkable. Furthermore, as shown in Table 2, it is understood that there is no difference comparing the thickness of the remaining brick at the positions A and B in Fig. 5. Therefore, un-uniform distribution of the molten iron flow rate at the upper boundary condition will be adopted for future computations.

4.2. Flow Rate

Computational results that were changed the flow rate are shown in Fig. 7 and the thickness of the remaining brick at the positions A and B in Fig. 5 is shown in Table 3. As the flow rate of molten iron increases more, the erosion of the brick/refractory increases more and the effect of the flow rate on the remaining brick thickness is more remarkable at the side wall than the bottom. It is easy understand that as the flow rate increases, the heat flux increases.

4.3. Coke Free Layer Size

Coke packed bed height was changed to examine the effect of the coke free layer size on the hearth erosion without changing the profile of coke packed bed. Computational results of flow field at final erosion stage (30 000 steps) and transient erosion process are shown in Figs. 8-1, 8-2. As shown in Figure, a) without coke free layer, hearth erosion is small, c) in the case of wide coke free layer, hearth erosion is small too, but b) in the case of the narrow coke free layer size, the hearth erosion is more remarkable at the bottom corner than other conditions, because the fluid velocity through the coke free layer is faster as shown in Fig. 8-1. It is very important to maintain the coke free layer size suit-
Fig. 6. Effect of flow rate distribution on final erosion profile.

Fig. 7. Effect of flow rate of molten iron on final erosion profile.

Table 2. Results of the remaining brick thickness.

| Flow rate distribution | Remaining brick thickness at position A (m) | Remaining brick thickness at position B (m) |
|------------------------|-------------------------------------------|-------------------------------------------|
| uniform                | 1.10                                      | 2.35                                      |
| un-uniform             | 1.10                                      | 2.35                                      |

Table 3. Results of the remaining brick thickness.

| Flow rate (ton/day) | Remaining brick thickness at position A (m) | Remaining brick thickness at position B (m) |
|---------------------|-------------------------------------------|-------------------------------------------|
|                     |                                           |                                           |
| 6600 × 0.75         | 1.28                                      | 2.64                                      |
| 6600                | 1.10                                      | 2.25                                      |
| 6600 × 1.25         | 0.91                                      | 2.35                                      |
4.4. Thermal Conductivity of Carbon Brick

Carbon brick of the hearth has the duty of refrigerating the chamotte brick, and the roll is very important to the protection of the chamotte brick. Simulation was conducted under the condition that carbon brick had two times thermal conductivity comparing the base condition. The hearth erosion decreases because the temperature of carbon brick itself and chamotte brick can be maintained low when the thermal conductivity of carbon brick increases as shown in Fig. 9 and Fig. 8-2-b.

4.5. Flow Resistance of Coke Packed Bed

It is assumed that the hearth erosion will be remarkable increasing the flow resistance of coke packed bed, because as the flow resistance of coke packed bed increases, the flow rate through the coke free layer increases. Actually, brick and refractory erosion decreases as shown in Fig. 10 and Fig. 8-2-b when the flow resistance of the coke packed bed is made to decrease by changing the bed void fraction in 0.5 from 0.2. At this time, transient erosion process is shown in figure, obviously the erosion rate is slower than the base condition (Fig. 8-2-b).
The followings are important in the actual blast furnace to suppress the hearth erosion on the above computational results.

1) To maintain the coke free layer size suitable
2) To keep the good permeability of the coke packed bed
3) Choice of the appropriate heat conductivity of the carbon brick corresponding to heat flux through the hearth.

5. Conclusion

A mathematical model that can estimate the transient erosion process of the blast furnace hearth has been developed. To verify the availability of the mathematical model, comparisons of computational final erosion profile of the hearth were made with the investigation results of the dissection blast furnace. The effects of the distribution profile of the dripping molten iron flow rate into the hearth, the coke free layer size, production rate of the molten iron, heat conductivity of the carbon brick and the fluid flow resistance through the coke packed bed on the hearth erosion were examined by using this mathematical model. Results are as follows.

1) The availability was confirmed comparing the computational results with the measured among furnaces of various inner volume and refractory layouts.
2) The effect of the flow rate distribution on the hearth erosion is not remarkable.
3) As the flow rate of molten iron increases more, the erosion of the hearth brick/refractory increases more.
4) Coke free layer size affects the hearth erosion remarkably, that is, the hearth erosion is small without coke free layer and with wide coke free layer, but the hearth erosion is more remarkable at the bottom corner in the case of the narrow coke free layer size, because the fluid velocity through the coke free layer becomes faster.
5) The hearth carbon brick has the duty of refrigerating...
chamotte brick, and the temperature of carbon brick itself and chamotte brick can be maintained low when the carbon brick has high thermal conductivity, therefore, the hearth erosion is suppressed.

6) As the hearth erosion increases, the flow resistance of the coke packed bed increases.

**Nomenclature**

\( C_p \): Heat capacity

\( d_p \): Diameter of coke packed bed

\( T \): Temperature

\( t \): Time

\( U \): Velocity vector

\( k \): Thermal conductivity

\( \varepsilon \): Void fraction of coke packed bed

\( \mu \): Viscosity of molten iron

\( \rho \): Density

\( \phi \): Shape factor of coke packed bed

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