Japanese iron and steelmaking industry has to reduce CO₂ emission by 11.5% in 2010 relative to the level of emissions in 1990. Stable blast furnace operation is required to reduce energy consumption and CO₂ emission in iron and steelmaking industry. For the stable blast furnace operation, precise controlled drainage is one of the important factors. However, there are many unrevealed phenomena in the hearth to perform the stable operation. Therefore, in this work, the effect of iron and slag dripping pattern, FeO concentration in the dripping slag on the iron and slag surfaces, thermal properties of refractory and brick on drainage temperature, temperature distribution in the hearth, temporal variation of iron and slag drainage rates and interfaces shapes were investigated by using three-dimensional mathematical model.

The results indicate that more than 2 mass% FeO in dripping slag will cause deterioration of slag drainage ability due to high slag viscosity around tapholes. Continuous monitoring of FeO concentration in the tapping slag is effective to prevent deterioration of slag drainage ability. The trends of the other side of tapping taphole temperature were varied dramatically according with FeO concentration in the dripping slag. Even in the case of 0 mass% FeO in the dripping slag, there is a solidified slag near the hearth wall except around the tapholes. A peripheral distribution pattern will result in a stable drainage. Slag, which dripped on near the other side of the tapping taphole, stays around the taphole, and does not drain from the tapping taphole located opposite side.

KEY WORDS: iron and slag flow; residual slag volume; numerical simulation; VOF method; blast furnace hearth; ironmaking; FeO concentration; hearth temperature.

1. Introduction

Japanese iron and steelmaking industry has to reduce CO₂ emission by 11.5% in 2010 relative to the level of emissions in 1990. Stable blast furnace operation is required to reduce energy consumption and CO₂ emission in iron and steelmaking industry. For the stable blast furnace operation, precise controlled drainage is one of the important factors.1–4)

Many researchers attempted to solve the issues by using experimental and mathematical models.1–11) However, there are many problems to understand drainage behavior in a blast furnace hearth because several important hearth values such as coke diameter, void fraction, temperature of iron and slag in the hearth, and levels of iron and slag cannot be measured during a tap. Because of these issues, there are many unrevealed phenomena in the blast furnace hearth.

In a previous paper,11) we developed a three-dimensional mathematical model, which can predict gas–slag and slag–iron interfaces shapes, total drainage rate, iron and slag drainage rates during a tap affected by various hearth conditions. The effect of various in-furnace conditions on drainage rates, gas–slag and slag–iron interfaces shapes and maximum gas–slag interfaces height were examined in another previous paper.12)

Takeda et al. measured FeO concentration in dripping slag in/around raceway with a sideways tuyere probe, and reported that FeO concentration in the slag in the raceway was about 15%, and that around raceway was about 0.3% which was nearly equal to that in tapping slag.13) Average FeO concentration in dripping slag is probably about 0.3%, because slag mainly drips around the raceway due to its low density. However, huge amount of unreacted iron ore and highly FeO contained slag will drip around raceway at low reducing agent rate operation due to a decrease of indirect reduction ability. On the other hand, Sugiyama et al. estimated slag viscosity and temperature distributions in a lower part of blast furnace from dissection analysis results, and suggested that slag mainly dripped in a peripheral region in the blast furnace hearth.14) Drainage behaviour of iron and slag in blast furnace hearth must be strongly related to FeO concentration in slag and slag dripping pattern, because direct reduction of wustite by carbon is huge endothermic reaction.

Therefore, in this work, the effect of iron and slag dripping pattern on iron and slag surfaces, FeO concentration in the dripping slag, thermal properties of refractory and brick on drainage temperature, temperature distribution in the hearth, temporal variation of iron and slag drainage rates and interfaces shapes were investigated by using revised mathematical model.
2. Mathematical Modelling

2.1. Governing Equations

A three-dimensional mathematical model considers momentum, energy and mass conservations for a fluid (iron, slag) flow at unsteady state. In a coke bed, advection term, pressure gradient term and drag interaction term were considered. Liquid–solid drag force in the coke bed was evaluated by Kozeny–Carman’s expression\(^{15}\) (Eq. (3)).

\[
\nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{............................}(1)
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + (\mathbf{u} \cdot \nabla) (\rho \mathbf{u}) = - \nabla p + \nabla \{\mu \nabla (\epsilon \mathbf{u})\} + \mathbf{F} \quad \text{..........................}(2)
\]

\[
F = 180 \mu \left(1 - \frac{e}{e^*}\right) \frac{d^2 e^*}{e^*} \quad \text{..........................}(3)
\]

\[
\frac{\partial (\rho \epsilon C_p T)}{\partial t} + (\mathbf{u} \cdot \nabla) (\rho \epsilon C_p T) = \nabla (k \nabla T) + \sum_{i=1}^{n} (\dot{n}_i \Delta H_i) 
\quad \text{..........................}(4)
\]

\[
\frac{\partial (\epsilon C_i)}{\partial t} + (\mathbf{u} \cdot \nabla) (\epsilon C_i) = \nabla (\epsilon D_i \nabla C_i) + \dot{n}_i \quad \text{...............}(5)
\]

2.2. Representation of Interfaces

For the determination of fluid properties in each computational cell, it is necessary to compute the proportion of gas, iron and slag in each cell. Gas–slag and slag–iron interfaces should be identified exactly. The VOF method\(^{16,17}\) was applied for the calculation of interfaces (gas–slag and slag–iron). Properties of each cell were determined by the weighted average of the fluids (gas, slag, iron) existed in the cell.

2.3. Drainage Rate Estimation from a Taphole

Total drainage rate of iron and slag \(u\) is derived from Eqs. (6), (7).

\[
\bar{u} = \frac{\Delta P D}{2 f \rho L} \quad \text{..........................}(6)
\]

\[
f = \frac{0.0626}{\left[\log \left(\frac{e}{3.7D} + \frac{5.74}{Re_{c}^{0.8}}\right)\right]^{2}} \quad \text{..........................}(7)
\]

Under typical blast furnace conditions, taphole conditions suppose to dominate the drainage rate \(u\). Therefore, these parameters (taphole diameter \(D\), taphole length \(L\), and surface roughness of the taphole \(e\)) are obtained from a total drainage rate of an actual blast furnace, which strongly related to taphole conditions.\(^{12}\)

2.4. Direct Reduction of FeO

Regarding mass transport, direct reduction of wustite in molten slag by core coke was considered in this model.

\[
(\text{FeO}) + \text{C(Coke)} = \text{Fe} + \text{CO} \quad \text{..........................}(8)
\]

Reaction rate of the reaction was evaluated by Miyasaka’s equation\(^ {18}\) (Eq. (9)). Specific surface of coke was given by Eq. (11). Enthalpy change due to the reaction was given by Eq. (12).\(^ {19}\)

\[
h_{\text{FeO}} = k_{\text{FeO}} A (C_{\text{FeO}})^{0.55} \quad \text{..........................}(9)
\]

\[
k_{\text{FeO}} = 0.278 \exp(11.554 - 19980/T) \quad \text{..................}(10)
\]

\[
A = 6e/d_p \quad \text{..........................}(11)
\]

\[
\Delta H_{\text{FeO}} = 155060 + 4.19 \times (-2.85T + 8.5 \times 10^{-4}/T^2)
+ 2.66 \times 10^{-7}/T \quad \text{..........................}(12)
\]

2.5. Solidification of Iron and Slag

Solidification of iron and slag were considered in this model. Solidification rates of iron and slag were infinity. Enthalpy change due to solidification of iron (Latent heat) was 272.35 \(\times 10^{3}\) J/kg. Solidification temperature of iron was 1423 K. Solidification of slag was described by setting apparent viscosity according to slag temperature. Liquidus temperature of slag was 1500 K. Iron and slag properties were given by a function of their composition and temperature.\(^ {20}\) Apparent slag viscosity between liquidus and solidus temperatures was evaluated by Orimoto’s model.\(^ {21}\)

2.6. Conditions for Calculations

Conditions of an assumed blast furnace are: Inner volume of the blast furnace is 5000 m\(^3\), hearth diameter is 14 m, distance between bottom of the hearth and the taphole is 3.0 m, quantity of production is 10000 t/d, and slag ratio is 300 kg/tm. In the calculations, only taphole diameter was varied as drainage time, and taphole length and surface roughness of the taphole were fixed to 2.5 m and 1 mm, respectively. Initial taphole diameter was 3.0 mm, and expansion rate of the taphole was 1.736 \(\times 10^{-6}\) m/s. Gas-slag interface pressure was 4.5 \(\times 10^4\) Pa. Outflow pressure for a taphole was fixed to 1.0 \(\times 10^5\) Pa. Inflow pressure for the taphole was obtained from the fluid flow estimation model at each time.

Initial slag composition was 0.3 mass\% FeO, 34 mass\% SiO\(_2\), 15 mass\% Al\(_2\)O\(_3\), 42 mass\% CaO and 6.5 mass\% MgO. Iron and slag dripping temperature was 1823 K.

Interactive force and energy transfer between iron and slag in slag layer were not considered in this model. Slag surface was adiabatic. Coke temperature in the hearth was same as fluid temperature. Overall heat transfer coefficients for brick and refractory were given as specific values, and temperature in the brick and refractory were not solved. Cooling water temperature was 298 K.

Numbers of grid cells were 15 \(\times 22 \times 32\) \((z) \times 32(\theta)\), and time increment was set small enough values to satisfy numerical stability. Iron and slag were tapped from two tapholes located opposite angle alternately.

2.7. Calculation Procedure

Difference equations were derived from the governing equations based on the finite difference method. The difference equations were solved by the HSMAC method\(^{16,17}\) on
staggered grids of a three-dimensional cylindrical coordinate system. The VOFs were solved with the donor-accepter method. In this model, numerical analysis proceeds as follows.

1) Molten iron and slag dripped on the iron and slag surface, respectively.
2) Fluid properties in the tapping taphole determined by the weighted average of fluids properties existed in the nearest cell to the taphole. A total drainage rate was calculated by Eq. (6).
3) A fluid flow in the hearth was solved with the total drainage rate.
4) Gas–slag and slag–iron interfaces moved according with the fluid flow.
5) Inflow pressure for the taphole was obtained from the fluid flow.
6) Concentration of FeO in slag was calculated by Eq. (5).
7) Iron and slag temperatures in the hearth were calculated by Eq. (4), and solid fraction of iron was calculated according with the temperature.
8) Iron and slag drainage rates were calculated from their mass balances.
9) These steps were repeated until the gas–slag interface reaches the taphole.
10) When the gas–slag interface reached the taphole, the taphole was closed. If the fluid flow behavior and drainage rates pattern did not reach quasi-steady state, the other taphole was opened, and above procedure was repeated for the next tap. Calculations were performed up to 6th tap due to limited calculation resources.

3. Results and Discussion

Under various conditions, the effect of iron and slag dripping pattern (uniform dripping pattern, non-uniform dripping pattern: iron and slag drip on the region which is 0–2 m from the hearth wall), FeO concentration in the dripping slag (0, 2, 5, 10 mass%), thermal properties of refractory and brick (21.42, 15.0 W/m · K) on drainage temperature, temperature distribution in the hearth, temporal variation of iron and slag drainage rates and interfaces shapes were investigated by using the mathematical model. Common conditions are; Uniform packed bed with 30 mm of coke diameter and 0.3 of void fraction, 0 s of drainage interval.

3.1. Temporal Variation of Drainage Temperature

Temporal variation of drainage temperature in the 6th tap is shown in Fig. 1. Calculation conditions are 0 mass% FeO in the dripping slag, non-uniform dripping pattern, 21.43 W/m² · K in overall heat transfer coefficient for hearth wall (21.43 W/m · K in thermal conductivity, 1.0 m in wall thickness), 7.14 W/m² · K in overall heat transfer coefficient for hearth bottom (21.43 W/m · K in thermal conductivity, 3.0 m in bottom thickness). Temporal variation of drainage temperature measured by “Fiber In Metallic tube for Pig Iron Temperature” (FIMPIT) method is shown in Fig. 2. Both results show common trend that drainage temperature indicates the lowest temperature at the beginning of the tap, and increases rapidly, then decreases toward the end of the tap.

The drainage temperature drops at the beginning of the tap ((A) in Fig. 1) due to cold slag near the taphole. The temperature suddenly rises (B) because inner hot slag flows out due to the force balance caused by the inclination of the gas–slag interface. The temperature reaches the maximum temperature (C) and decreases gradually and keeps average temperature (D) because flow rate of cold iron below the taphole level increases gradually, and flow rate of slag decreases once then increases. The temperature decreases again (E) because flow rate of cold slag near the wall relatively increases. Then, the temperature reaches the second peak (F) because inner hot slag flows out again due to the inclination of the gas–slag interface toward the end of the tap. The temperature closes to the average (G) and reaches the bottom (H) because flow rate of cold iron below the taphole level increases again. The drainage temperature rises again (H) because two interfaces come closer to the taphole.

3.2. Effect of FeO Concentration in Dripping Slag

Figure 3 shows the effect of FeO concentration in the dripping slag on taphole temperatures with overall heat transfer coefficient of 21.42 W/m² · K for hearth wall and 7.14 W/m² · K for hearth bottom. The temporal variation of drainage temperature almost reaches quasi-steady state in
the 5th tap with 0 mass% FeO in the dripping slag, and the average drainage temperature is about 1773 K. The temporal variation of drainage temperature reaches quasi-steady state in the 6th tap with 2 mass% FeO. However, the calculation was aborted in the 5th tap with 5 mass% of FeO due to high slag viscosity.

The trends of the tapping taphole temperatures were not so much changed even FeO concentration in the dripping slag increased. However, the trends of the other side of tapping taphole temperature were varied dramatically according with FeO concentration in the dripping slag. When FeO concentration in the dripping slag is 0 mass%, the temperature rises gradually until the end of the tap. Increasing FeO concentration in the dripping slag decreases the temperature, especially latter half of the taps. Therefore, hearth conditions can be estimated by monitoring the temperature of the other side of the tapping taphole.

Figure 4 shows the effect of FeO concentration in the dripping slag on taphole temperatures with total heat transfer coefficients of 15.0 W/m²·K for hearth wall and 5.0 W/m²·K for hearth bottom. The overall heat transfer coefficients of refractory and brick in Fig. 4 are about 70% of those in Fig. 3. The temporal variation of drainage temperature almost reaches quasi-steady state in the 2nd tap with 2 mass% FeO and the average drainage temperature is about 1773 K. However, the temporal variation of drainage temperature does not reach quasi-steady state even in the 6th tap with 5 mass% FeO, and the calculation was aborted in the 5th tap with 10 mass% of FeO due to high slag viscosity. Basically, the trends of drainage temperatures are almost the same as in the cases shown in Fig. 3 even overall heat transfer coefficient for wall and bottom are changed. In Fig. 4(c), the drainage is continued for a while even the taphole temperature drops below the liquidus temperature. However, in Fig. 3(c), the drainage is aborted before the taphole temperature reaches the liquidus temperature, because solidification of slag just above the taphole level proceeds due to huge heat loss from the hearth wall. More than 2 mass% FeO concentration in dripping slag will cause deterioration of slag drainage ability due to high slag viscosity around tapholes.

### 3.3. FeO Concentration in Drained Slag

Figure 5 shows temporal variations of FeO concentration in slag at the tapholes. FeO concentration in tapping slag indicates maximum value at the beginning and end of taps due to the short residence time caused by the inclination of two interfaces. In all cases, FeO concentration in slag at the other side of the tapping taphole is quite smaller than that at the tapping taphole because of a long residence time. Considering the fact that FeO concentration in a tapping slag of stable commercial blast furnaces is about 0.3 mass% and the results shown in Figs. 3–5, FeO concentration in dripping slag on the slag surface must be below 2 mass% for stable blast furnace operation. When FeO concentration in the dripping slag is more than 2 mass%, FeO concentra-
Fig. 4. Effect of FeO concentration in dripping slag on taphole temperatures. Total heat transfer coefficient of wall and bottom are 15.0 W/m²·K, 5.0 W/m²·K, respectively.

Fig. 5. Effect of FeO concentration in dripping slag on FeO concentration vicinity of tapholes. Total heat transfer coefficient of wall and bottom are 15.0 W/m²·K, 5.0 W/m²·K, respectively.
tion in the tapping slag at the beginning and the end of the tap exceeds 1.0 mass% (Fig. 5). Therefore, continuous monitoring of FeO concentration in the tapping slag is effective to prevent deterioration of slag drainage ability.

3.4. Effect of FeO Concentration on Interfaces Shapes and Drainage Rates

Figure 6 shows temporal variations of gas–slag and slag–iron interfaces shapes with various FeO concentration in the dripping slag. Total heat transfer coefficients for wall and bottom are 15.0 W/m²·K and 5.0 W/m²·K respectively. When FeO concentration in the dripping slag is 2.5 mass%, the maximum gas–slag interface height is about 2.0, 2.1 m respectively. There are no obvious differences on the interfaces shapes when FeO concentration in the dripping slag changes 2.0 to 5.0 mass%. However, when FeO concentration in the dripping slag is 10 mass%, the drainage is aborted because of high slag viscosity due to temperature drop caused by direct reduction of FeO.

Figure 7 shows temporal variations of total, iron and slag drainage rates.

Fig. 6. Effect of FeO concentration in dripping slag on gas–slag and slag–iron interfaces shapes. Total heat transfer coefficient of wall and bottom are 15.0 W/m²·K, 5.0 W/m²·K, respectively.

Fig. 7. Effect of FeO concentration in dripping slag on total, iron and slag drainage rates. Total heat transfer coefficient of wall and bottom are 15.0 W/m²·K, 5.0 W/m²·K, respectively.
Fig. 8. Effect of dripping pattern of iron and slag on temperature distribution and interfaces shapes.

Fig. 9. Temporal variation of temperature distribution and interfaces shapes.

Fig. 10. Effect of total heat transfer coefficient of hearth wall and bottom, and FeO concentration in dripping slag on temperature distribution in the hearth at the beginning of the tap.

Fig. 11. Effect of total heat transfer coefficient of hearth wall and bottom, and FeO concentration in dripping slag on temperature distribution in the hearth (below liquidus temperature of the slag) at the beginning of the tap.

Fig. 12. Effect of total heat transfer coefficient of hearth wall and bottom, and FeO concentration in dripping slag on FeO concentration in the hearth at the beginning of the tap.
slag drainage rates with various FeO concentrations in the dripping slag. The two intersections of iron and slag drainage rates move toward the end of the tap as increasing FeO concentration in the dripping slag. When FeO concentration is 10 mass%, the drainage is aborted in about 3800 s, and the drainage rates are vary unstable due to high slag viscosity around the taphole.

3.6. Effect of FeO Concentration on Temperature Distribution in the Hearth

Figure 10 shows the effect of FeO concentration and cooling conditions on temperature distributions in the hearth at the beginning of the 6th and 4th taps, and Fig. 11 shows temperature distributions below the temperature of 1653 K, which is liquidus temperature of the slag. Figure 12 shows the effect of FeO concentration and cooling conditions on FeO distribution in the hearth. Even in the case of 0 mass% FeO in the dripping slag, there is a solidified slag near the hearth wall except around the tapholes. The solidified slag around the taphole is generated and vanished according with the switch of the tapholes. Furthermore, the volume of the solidified slag layer is affected by FeO concentration in the dripping slag. Therefore, the solidified slag layer near the taphole will also cause different drainage behavior of the tapholes.

Increasing FeO concentration in the dripping slag causes decrease of hearth temperatures and increase of the slag volume below liquidus temperature near the hearth wall. Stronger cooling condition causes increase of the slag volume near the wall. Distribution of FeO concentration depends on residence time and slag flow in all cases. Increasing FeO concentration in the dripping slag results in high FeO concentration in the tapping slag and low temperature zone near the hearth wall. Therefore, under these conditions, FeO concentration in the dripping slag on gas–slag interface should be less than 2 mass% for a stable drainage.

4. Conclusion

The effect of iron and slag dripping pattern, FeO concentration in the dripping slag on the iron and slag surfaces, thermal properties of refractory and brick on drainage temperature, temperature distribution in the hearth, temporal variation of iron and slag drainage rates and interfaces shapes were investigated by using the mathematical model. The following results were obtained:

(1) More than 2 mass% FeO in dripping slag will cause deterioration of slag drainage ability due to high slag viscosity around tapholes. Continuous monitoring of FeO concentration in the tapping slag is effective to prevent deterioration of slag drainage ability.

(2) The trends of the tapping taphole temperatures were not so much changed even FeO concentration in the dripping slag increased. However, the trends of the other side of tapping taphole temperature were varied dramatically according with FeO concentration in the dripping slag. Therefore, hearth conditions can be estimated by monitoring the temperature of the other side of the tapping taphole.

(3) Even in the case of 0 mass% FeO in the dripping slag, there is a solidified slag near the hearth wall except around the tapholes. The volume of the solidified slag layer is affected by FeO concentration in the dripping slag.

(4) A peripheral distribution pattern will result in a stable drainage.

(5) Slag, which dripped on near the other side of the tapping taphole, stays around the taphole, and does not drain from the tapping taphole located opposite side. Therefore, it will cause different drainage behavior of the tapholes.

Nomenclature

- \( A \): Reaction area (m²)
- \( C_i \): Concentration for i species (mol/m³)
- \( C_p \): Specific heat (J/kg · K)
- \( D_i \): Diffusivity for i species (m²/s)
- \( D_t \): Taphole diameter (m)
- \( d_c \): Coke diameter (m)

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\( e \): Surface roughness of the taphole (m)
\( F \): Volumetric force (N/m\(^3\))
\( f \): Friction factor (–)
\( \Delta H \): Enthalpy change for i species (J/mol)
\( h_{\text{wall}} \): Overall heat transfer coefficient for the hearth wall (W/m\(^2\)·K)
\( h_{\text{bottom}} \): Overall heat transfer coefficient for the hearth bottom (W/m\(^2\)·K)
\( k \): Thermal conductivity (W/m·K)
\( k_i \): Reaction rate for i species (mol/s)
\( L \): Taphole length (m)
\( n_i \): Number of moles for i species (mol)
\( \Delta P \): Pressure difference between the inlet and outlet of the taphole (Pa)
\( p \): Pressure (Pa)
\( \text{Re} \): Reynolds number (–)
\( T \): Temperature (K)
\( t \): Time (s)
\( u \): Velocity of fluids (m/s)

Greek letters:
\( \varepsilon \): Void fraction (–)
\( \rho \): Density (kg/m\(^3\))
\( \mu \): Viscosity (Pa·s)

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