1. Introduction

As the growth of crude steel production is saturated at home and integration of iron production to large-capacity blast furnaces is encouraged to secure primary iron sources, particular attention is attracted to the stability in high productivity operation. Today the abnormal blast-furnace operating condition exerts unprecedented enormous effects on the downstream processes. The preventive and problem-handling technologies have been discussed. In particular, it has been pointed out that “the blast furnace is operated while it is subject to a large number of operation and external factors including material conditions, blast conditions, furnace body conditions, and others. It cannot be impossible to think that all these factors act on the blast furnace operation free of any variations. As a result, it is a matter of course that the blast furnace gives rise to some kind of abnormal phenomena, and what is important is to quickly detect the sign of abnormality.” Particularly in this Report, the increased size of the blast furnace and high productivity operation are pointed out as the causes of increased troubles of recent years, which particularly attract our attention.

From the viewpoint of the increased size of the blast furnace and high productivity operation, still more stringent control must be practiced on slag and metal. The blast-furnace tap hole closing refractory (hereinafter called the mud material) is important for tapping operation of the blast furnace, and the mud material filling distance in the in-furnace depth direction (hereinafter called the tap hole depth) is one of the important operation control items to control the hearth-side wall thickness. The characteristics which the mud material is requested to possess have been changed from simple closing of a tap hole to stable operation, improvement of working environment, reduction of consumption rate by reduction of the number of melts per day, and protection of hearth-side wall refractory and extended life of the furnace body by extension of the tap hole depth. Consequently, in addition to securing of gas and liquid permeability of deadman coke by coke center charging, it is important to maintain the tap hole depth in order to prevent the circulating flow of slag and metal from the free space forming behavior. However, fluctuation factors of the tap hole depth have not exactly been elucidated. Therefore, in this study, the raceway depth is measured from the reflection intensity of microwave that is struck from the tuyere and effects of raceway depth and various factors on the tap hole depth is reported with a hope to contribute to further improvement of the blast furnace operating technique.

2. Raceway Control Technique for Tap Hole Depth Stabilization

On facing the high productivity and elongation of life time in blast furnace iron-making, it is essential to protect the peripheral iron flow formed by a free space in the hearth in addition to maintaining the gas and liquid permeability of deadman. Therefore, it is important to stabilize the length of mud (tapping hole length) which is plugged and formed by hole closing refractory (mud materials), but the phenomena of fluctuation of tapping hole length are not clarified. In this paper, variables affecting the tapping hole length including the raceway depth measured by micro wave reflection struck tuyere are discussed under dimension analysis. As the burden weight above the raceway are balanced to upwind gas, the load to the hearth under the raceway is less than that in the furnace center and a high void ratio area or free space is easy to be formed under the raceway. As the result, it is clarified and quantified that the tapping hole length is recovered from shortage of distance by decreasing raceway depth which promotes deadman to sink further into bottom or increase the void ratio of peripheral area in the hearth.

KEY WORDS: blast furnace; raceway; micro wave; tapping hole length; mud material rate; furnace life time; deadman.
Kobe No. 3 blast furnace (tertiary campaign, inner volume: 1845 m³, blown in on April 5, 1983) are shown in the upper column. In the middle column, [%Si], [%Ti] in the molten iron which affect the molten iron viscosity are shown, and in the lower column, the values of tuyere stock flow rate of the tuyere right above the tap hole and the estimated raceway depth later discussed, which are assumed to intervene in the tap hole depth control, are shown. In August and October 2003, the mud material consumption rate was increased as against the reduction of the tap hole depth, and the tap hole depth was recovered. On the other hand, in November, the mud material consumption rate was increased as against the reduction of the tap hole depth, but the recovery of the tap hole depth was delayed. Consequently, it is assumed that changes of the tap hole depth would be subject to in-furnace phenomena other than the mud material consumption rate.

It is possible to infer the behaviors of mud material in the furnace to a certain extent from the phenomena observed in daily tapping operation, in-furnace observation during relining, sample analysis by core boring, and simulation furnace experiment. It is reported that in the in-furnace investigation at the time of relining of Kakogawa Works No. 2 (primary) and No. 1 (secondary) blast furnaces, the mud material accumulated in the periphery of tap hole has generally similar shapes. In addition, the mud material inserted in the furnace pushes aside coke in the furnace and forms a large rock bed. It is also reported that the accumulation is thin at the tap hole level and thick at the bottom, with the lower end section dropping to the initial hearth position, and in the space above from the tap hole level, to the peripheral portion of integrated mud material, lumpy (φ20–40 mm) mud material is accumulated in the form of stonewalls.

What is important to think of the behavior of the mud material in the furnace in order to maintain the tap hole depth is lumpy (φ20–40 mm) stonewall accumulation in the peripheral section of the mud material or disintegration of the surface layer inside, and these decrease the tap hole depth at the same mud material consumption rate. Because the density of the mud material is about 2,200 kg/m³, lighter than that of molten iron (6,600 kg/m³) and slag (2,600 kg/m³), the mud material floats up and does not form a robust mud material layer unless it is pressed into coke gaps in the furnace. This is assumed to the lumpy mud accumulation or disintegration phenomenon of the inside. On the other hand, since the density of coke which captures the mud material in the furnace is as light as 500 kg/m³, in the event that the load which allows coke to land on the lower part of furnace decreases, the coke void ratio at the mud front surface increases and the mud material is easy to float up, and the tap hole depth decreases. Because at the raceway section, the burden load is balanced with the ascending gas flow, under the raceway, the actual load is less than that at the furnace center section, and a high void ratio coke region or free space are likely to be formed. Consequently, it is assumed that fluctuation of the tap hole depth is caused by fluctuation of load which allows coke to land on the lower part of furnace, that is, fluctuation of raceway depth.

### 3. Measuring Method and Principle

#### 3.1. Raceway Depth Measuring Method and Principle

Figure 2 shows the microwave striking method from the blast-furnace tuyere. The microwave is transmitted from a waveguide tube and is struck through the tuyere peep sight from a cylindrical antenna installed to the head end of the waveguide tube. The antenna has a conical indented portion formed inside in order to efficiently shoot ahead the transmission wave, which is a microwave, and the antenna is disposed in such a manner to be adjacent to the tuyere peep sight disposed at the blowpipe base end side.
Figure 3 shows the measurement principle. Part of the microwave transmission wave generated is branched, transmitted to a mixer, and combined with the received wave from the raceway to generate a beat wave. The frequency of the beat wave has the frequency component that corresponds to the distance to the object, and the distance to the object can be measured by a frequency analysis.

Figure 4 shows the hearth structure of Kobe No. 3 blast furnace and microwave striking method5) from the blast furnace tuyere. In this study, by locating the raceway head-end position (hereinafter called the raceway depth) from the peak detection position of the microwave reflection intensity by frequency analysis, the distance from the furnace center to the raceway head-end position \( r_{RW} \) was calculated.

The tap hole depth \( L_{TH} \) can be found as the drill entry length which is found by the change of drill driving torque from the beginning of the opening to the end of the opening when the tap hole is opened by a tapping machine. From the tap hole angle, the in-furnace tap hole position is calculated, and the horizontal distance \( r_{TH} \) from the furnace center to the in-furnace tap hole position was calculated.

Figure 5 shows effects of tuyere stock flow rate on the raceway depth by fitting measured data. As the tuyere stock flow rate decreases, the raceway depth decreases. In addition, the same tuyere stock flow rate, the smaller the tuyere diameter, the more increased is the velocity in front of tuyere, and the raceway depth increases. In the same figure, the tap hole depth at which the raceway head end coincides with the tap hole head end was included. In the event that the tuyere stock flow rate is not less than 80 Nm\(^3\)/min, the raceway depth becomes not less than 0.8 m and when the tap hole depth is not more than 3.0 m, the tap hole head end is situated more on furnace wall side from the raceway head end.

4. Measurement Results and Discussion

4.1. Evaluation of Effects of Various Factors on the Tap Hole Depth

When the load that allows coke to land on the lower part of furnace decreases at the in-furnace tap hole position as described above, the coke void ratio in front of the mud material increases and the mud material is easy to float up, and the tap hole depth decreases.2) This is because at the raceway section, the burden load balances with the ascending gas flow, the value of actual load below the raceway becomes less than that at the furnace center, and a high void ratio coke region or a free space is likely to be formed. Consequently, it is assumed that the tap hole depth may be varied according to the fluctuation of load that allows coke to land on the lower part of furnace, that is, changes of raceway depth.5) Furthermore, since the flow rate of the molten iron and slag that flow the boundary between the deadman coke layer and mud material accumulated layer increases dependently on the value of the void ratio of the deadman coke layer at the boundary, erosion of the mud material accumulated layer that is exposed to the molten iron and slag and wears is promoted. Consequently, the wear of the in-furnace accumulated mud material layer by formation of the free space is affected by the viscosity of molten iron.

Therefore, in this study, the effects of raceway head-end position \( r_{RW} \) on the tap hole head-end position \( r_{TH} \) were dimension-analyzed in conformity to the following equation to evaluate effects of various factors on the tap hole depth on the period of same estimated raceway depth:

\[
R_{TH} = C \cdot R_{RW}^a \cdot MR^{b} \cdot [\%Si]^c \cdot [\%Ti]^d \ 
\]

where,
- \( R_{TH} \): Dimensionless tap hole head-end position \( (=r_{TH}/r_{H}) \) on the basis of hearth radius \( r_{H} \);
- \( C \): Constant;
- \( R_{RW} \): Dimensionless raceway head-end position \( (=r_{RW}/r_{H}) \);
- \( MR \): Mud material consumption rate (kg/thm);
- \( [\%Si] \): \( [\%Si] \) in molten iron; and
- \( [\%Ti] \): \( [\%Ti] \) in molten iron.
4.2. Effects of Raceway Depth and Mud Material Volume on Tap Hole Depth

Figure 6 shows the relationship of the intensity index \( \alpha \) that indicates a degree of effects of raceway head-end position \( (R_{RW}) \) on tap hole head-end position \( (R_{TH}) \) to \( R_{TH}/R_{RW} \) \( (r_{TH}/r_{RW}) \). When \( R_{TH}/R_{RW} \) \( (r_{TH}/r_{RW}) \) becomes 0.95 or higher, \( \alpha \) becomes nearly zero. Therefore, even if the raceway depth is varied, the tap hole depth does not vary.

As against this, when \( R_{TH}/R_{RW} \) \( (r_{TH}/r_{RW}) \) is less than 0.95, \( \alpha \) becomes nearly zero, enabling the tap hole depth to vary by varying the raceway head-end position \( (R_{RW}) \). That is, because \( R_{RW} \) \( (r_{RW}) \) is increased, the raceway depth is increased, that is, \( R_{TH} \) can be decreased.

Figure 7 shows the relationship of intensity index \( \beta \) that indicates a degree of effects of mud material consumption rate \( (MR) \) on the tap hole head-end position \( (R_{TH}) \) to \( R_{TH}/R_{RW} \) \( (r_{TH}/r_{RW}) \). When \( R_{TH}/R_{RW} \) \( (r_{TH}/r_{RW}) \) becomes not less than 0.95, \( \beta \) becomes nearly zero, and even if the mud material consumption rate is varied, there is little effect on increase in the tap hole depth. As against this, when

\[
R_{TH}/R_{RW} \ (r_{TH}/r_{RW}) \text{ is less than 0.95, } \beta < 0 \text{ is constantly achieved, making it possible to vary the tap hole depth by varying the mud consumption rate (MR). That is, because } MR < 1.0 \text{ and } \beta < 0, \text{ increasing the mud material consumption rate increases the tap hole depth, that is, effects of decreasing } R_{TH} \text{ increase.}
\]

Consequently, when \( R_{TH}/R_{RW} \) becomes not less than 0.95, that is the tap hole depth \( (L_{TH}) \) excessively decreases, \( r_{RW} \) should be increased to allow \( r_{TH}/r_{RW} \) to become less than 0.95. That is, it is assumed effective to decrease the race-
way depth. In order to decrease the raceway depth, it is effective to increase the amount of tuyere injected auxiliary fuel such as pulverized coal, waste plastic, or others, or decrease the tuyere stock flow rate.

When the amount of tuyere injected auxiliary fuel is increased, the coke combustion ratio decreases and the combustion ratio of room-temperature auxiliary fuel increases; therefore, the flame temperature lowers and the actual gas flow rate decreases, and as a result, the raceway depth decreases. To reduce the tuyere stock flow rate, a method to replace the tuyere with that of small inside diameter can be adopted. Reducing the inside diameter of the tuyere increases the gas velocity in front of the tuyere in the furnace but increases pressure loss at the tuyere and reduces the air volume inside the tuyere stock, and as a result, the raceway depth decreases. By the way, when the tap hole depth excessively decreases, it is possible to block the tuyere and decrease the raceway depth completely to zero.

When $R_{TH}/R_{SW}$ becomes less than 0.95, that is, when the tap hole depth ($L_{TH}$) is included in a appropriate range, $\alpha>0$ is constantly achieved, where the tap hole depth is ready to be changed by changing the raceway depth. Consequently, while keeping the raceway depth constant, the mud material filling rate to compensate for the eroded volume of the mud material accumulated layer thickness should be maintained, and the tap hole depth should be kept constant. By this, while the mud material consumption rate is suppressed to avoid an excessive increase of operation cost, the tap hole depth can be more definitely stabilized and the furnace life can be extended.

Figure 8 shows the relationship between the mud material consumption rate (MR) and the tap hole length ($L_{TH}$) by fitting calculated data. In this event, the tap hole depth means the relative tap hole depth of 1.0 with that at the mud material consumption rate of 0.5 kg/thm set as the reference and the relation of the mud material consumption rate to the relative tap hole depth is shown. Even if the mud material consumption rate is in the same range, it can be assumed that if $r_{TH}/r_{SW}$ is 0.92, the tap hole depth $L_{TH}$ can be increased 23% as compared to the case when $r_{TH}/r_{SW}$ is 0.98 by increasing same mud material consumption.

Based on the foregoing, by reducing the raceway depth with respect to the tap hole depth, the tap hole depth can be increased. This is assumed to be attributed to the following: the buoyant force by the in-furnace ascending gas flow is reduced and the deadman coke layer lands on to the hearth, the void ratio of deadman coke layer at the boundary between the deadman coke layer and the mud material accumulated layer lowers, and the flow rate of molten iron and slag that flow the boundary portion decreases, and the wear rate of the mud material accumulated layer decreases, and the molten iron circulating flow is suppressed by the landing of the deadman coke layer to the hearth.

4.3. Effects of Molten Iron Component on the Tap Hole Depth

Figure 9 shows the relationship between intensity indices $\gamma$, $\delta$, which denote the degrees of effects of [%Si] and [%Ti] in molten iron on the tap hole depth ($R_{TH}$), and $R_{TH}/R_{SW}$ ($=r_{TH}/r_{SW}$). With respect to $R_{TH}/R_{SW}$, $\gamma$ forms a curve that is protruded upwards and indicates the maximum value when $R_{TH}/R_{SW}$ is in the vicinity of 0.95, where $\gamma<0$. On the other hand, $\delta$ forms a curve that is protruded downwards with respect to $R_{TH}/R_{SW}$, and indicates the minimum value when $R_{TH}/R_{SW}$ is in the vicinity of 0.95, and in such event $\delta>0$.

When $R_{TH}/R_{SW}$ is not more than 0.95 or not less than 0.95, $\gamma$ and $\delta$ successively approximate to nearly zero, and even if [%Si] and [%Ti] in molten iron varies, the tap hole depth does not vary. As against this, when $R_{TH}/R_{SW}$ is in the vicinity of 0.95, $\gamma<0$ and $\delta>0$ are always achieved, and the tap hole depth varies as [%Si] and [%Ti] in molten iron vary.

When $R_{TH}/R_{SW}$ is 0.95, [%Si] in molten iron $<1.0$, $\gamma<0$, and [%Ti] $<1.0$ and $\delta>0$, and therefore by the increase of [%Si] in molten iron or decrease of [%Ti], the tap hole depth is extended, that is, $R_{TH}$ is reduced.

Based on this, it is assumed that when $R_{TH}/R_{SW}$ is 0.95, the void ratio of the deadman coke layer at the boundary between the deadman coke layer and the mud material accumulated layer lowers and the flow rate of molten iron and slag that flow at this boundary decreases, and the tap hole depth is likely to be susceptible to the molten iron viscosity.

With respect to the molten iron viscosity, it is assumed that both [%Si] and [%Ti] increase the molten iron viscosity, but in the effects on the tap hole depth described above, [%Si] and [%Ti] in molten iron work conversely. This is assumed to result from coupling reactions between [Si] and [Ti] in the reduction of TiO2 by Si in the furnace.

Figure 10 shows the effects of [%Ti] on the viscosity of carbon-saturated molten iron in the nitrogen atmosphere by Onoe et al. At all temperatures, a sudden increase in viscosity is indicated at a certain [%Ti] or higher, and the
[%Ti] that causes the sudden increase in viscosity tends to move to the higher [%Ti] side as the [%Ti] temperature increases. The [%Ti] level in the present study ranges from 0.10 to about 0.20% as shown in Fig. 1, which corresponds to the level of [%Ti] at which the viscosity at 1 400°C suddenly rises. Consequently, it is suggested that the temperature of molten iron and slag that flow at the boundary between the deadman coke layer and mud material accumulated layer which affects the extension of the tap hole depth would be lower than the temperature of molten iron which is subject to the hearth cooling and discharged to the furnace outside.

5. Conclusion

In order to achieve high productivity and extended life in blast-furnace operation, it is important to stabilize the mud material filling distance (tap hole depth) filled and formed by the tap hole closing refractory (mud material) to prevent the molten iron circulating flow by forming a free space in addition to securing gas and liquid permeability of deadman coke. In the present study, the raceway depth was measured from the reflection intensity of microwave that was struck from the tuyere, and effects of various factors on the tap hole depth were evaluated by dimension-analyzing the effects of raceway head-end position on the tap hole head-end position, and the results of the work carried out allow us to draw the following conclusions.

(1) In the positional relationship between the raceway head-end position \( R_{\text{RW}} \) and the tap hole head-end position \( R_{\text{TH}} \), when \( R_{\text{TH}}/R_{\text{RW}} = r_{\text{TH}}/r_{\text{RW}} \) is less than 0.95, the raceway depth is extended. That is, it becomes possible to extend the tap hole depth by decreasing \( R_{\text{RW}} \).

(2) In the relationship between the mud material consumption rate (MR) and the tap hole head-end position \( R_{\text{TH}} \), when \( R_{\text{TH}}/R_{\text{RW}} = r_{\text{TH}}/r_{\text{RW}} \) is less than 0.95, the tap hole depth can be extended by increasing the mud material consumption rate. That is, the effects for reducing \( R_{\text{TH}} \) increase.

(3) Consequently, in the event that the tap hole depth \( L_{\text{TH}} \) excessively decreases and \( R_{\text{TH}}/R_{\text{RW}} \) becomes not less than 0.95, it is effective to reduce the raceway depth so that \( r_{\text{TH}}/r_{\text{RW}} \) becomes less than 0.95.

(4) In the relationship between the mud material consumption rate (MR) and the tap hole depth \( L_{\text{TH}} \), even if the mud material consumption rate is within the same range, but in the event that \( R_{\text{TH}}/R_{\text{RW}} \) is less than 0.95, it can be expected that the tap hole depth increases.

(5) In the relationship of [%Si] and [%Ti] in molten iron to the tap hole head-end position \( R_{\text{TH}} \). [%Si] in molten iron rises where \( R_{\text{TH}}/R_{\text{RW}} = r_{\text{TH}}/r_{\text{RW}} \) is in the vicinity of 0.95, or the tap hole depth is increased by the decrease of [%Ti]. With respect to the viscosity of molten iron, it is assumed that both [%Si] and [%Ti] would increase the molten iron viscosity but [%Si] and [%Ti] in molten iron work reversely with respect to the effects of the tap hole depth, and this is assumed to be the result of coupling reactions between [Si] and [Ti] in the furnace.

In the future, in the event that further low reducing agent ratio operation is intended, securing of deadman permeability and fluidity against an increase of deadman fine ratio becomes increasingly important. It is necessary to deepen dynamic understanding concerning the flow of molten iron and slag at the boundary between deadman coke layer and hearth solidified layer by verification using the actual furnace and the control is required.

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