1. Introduction

Because the fine coke discharge of the blast furnace deadman depends on its capability to pass molten iron and molten slag, primary attention has been placed on adverse effects of expanding the hearth diameter, and there is an opinion that the minimum hearth diameter should be achieved in order to secure the tuyere diameter and fuel combustion capabilities.\(^1\)

While the blast-furnace stable operation is regarded as the lifeline, abnormal furnace operating conditions will exert still more detrimental effects on the subsequent process than ever under the present circumstances in which blast-furnace integration takes place. The techniques to prevent blast furnace abnormal conditions and take appropriate measures against them has been discussed. In particular, it has been pointed out that pulverized coal (hereinafter called “PC”) injection operation tends to increase operation troubles, a greater number of troubles occurred in the transition period from all-coke operation to PC injection operation, and furthermore, increased size of blast furnaces and high-productivity operation partly contribute to increased troubles of recent years, to which our attention is particularly attracted.

Consequently, greater importance has been attached to the control of burden distribution and burden descent condition or profile and distribution conditions of the melting zone and raceway in increased blast-furnace size and high productivity operation. Therefore, in this report, we would like to analyze the raceway depth from the reflection intensity of microwaves (hereinafter called the “m-wave”) allowed to impinge through tuyeres and report the relevancy between PC injection and blast-furnace raceway profile to contribute to still further improvement in the blast-furnace operating technology.

2. Problems of Raceway Control at the Lower Part of Furnace

Because the raceway which serves as the initial point of gas flow in the furnace is a non-potential flow field and measurement during operation is restricted, there still remain many points which have not yet been elucidated from the viewpoints not only from liquid distribution but also from gas distribution at the lower part of the furnace.\(^2\)

Figure 1 shows the estimated temperature distribution in the radial direction of deadman coke by tuyere coke sampling during shutdown at the PC rate of 180 kg/thm level. When the tuyere wind velocity is 230 m/s, the high-temperature region reaches up to 2.2 m from the tuyere nose but when the tuyere wind velocity lowers to 210 m/s under reduced production, the high-temperature region is reduced to 1.0 m from the tuyere nose and furnace conditions were degraded. In particular, when PC is injected, the coke flow-in rate into the raceway decreases and unstable raceway formation is feared.

Hitherto, in the transition process to low production, Nishi et al.\(^3\) reported that the raceway is contracted by fine coke generation associated with coke fracture when the tuyere diameter is reduced to secure the raceway depth and increase the tuyere draft energy because the residence time of coke in the blast furnace is increased and coke becomes

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Analyses on Blast Furnace Raceway Formation by Micro Wave Reflection Gunned through Tuyere

Yoshiyuki MATSUI, Yasuhiro YAMAGUCHI, Muneyoshi SAWAYAMA, Shinji KITANO,\(^1\) Nobuyuki NAGAI\(^2\) and Takashi IMAI\(^1\)

R & D Lab., Kobe Steel, Ltd., 2222-1, Ikeda, Onoe-cho, Kakogawa, Hyogo 675-0023 Japan.
1) Kakogawa Works, Kobe Steel, Ltd., 1, Kakogawa-cho, Kakogawa, Hyogo 675-0137 Japan.
2) Electrical, Instrument and Computer Division, Shinko EN & M Co., Ltd., 1, Kanazawa-cho, Kakogawa, Hyogo 675-0137 Japan.

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The blast furnace raceway formation under the intensive coal injection by measurement of micro wave reflection gunned through a tuyere is discussed. As the flow rate of coke as the momentum of coke into raceway decreases by combustion of coal injected into tuyeres, the depth of raceway defined as the maximum position of micro wave reflection is easy to contract. It is expected that this new technology could detect the raceway collapse phenomena in short time and that the stability of raceway in coal injection is different from that in all coke operation. Finally the paper ends by summarizing the effect of raceway formation on unsteady phenomena forcing functional disorder on blast furnace performance of burden distribution for high productivity performance.

KEY WORDS: blast furnace; raceway; micro wave; coal injection; coke; unsteady phenomena.
fragile. On the other hand, in the transition process to high production, Tamura et al.\textsuperscript{4)} reported that coke degradation rate in the raceway and accumulation rate of fine coke at the deadman surface increase when the raceway depth becomes 1.3 m or more. As against these, Nogami et al.\textsuperscript{5)} handle both solid and gas as a continuum and carry forward the raceway analysis with the raceway boundary assumed as the section where the gas velocity reaches the fluidization start velocity. However, Miura\textsuperscript{6)} cited in “Defects and Expectation in Coke Research” that the absence of knowledge in the coke collapse theory which can be utilized in high-speed particle collision and collapse is a feature to be investigated in the raceway region for fine coke discharge by the mechanism of surface breakage or volume fracture rather than abrasion.

With respect to the measurement of raceway depth in actual furnaces, measurement by Shimizu et al.\textsuperscript{7)} by inserting a 19-mm-$\phi$-diameter metal rod or measurement by Tamura et al.\textsuperscript{4)} by the use of a raceway depth indicator equipped with a loadcell are reported, but there is a problem of measurement accuracy under the disturbance by contraction of cross sectional area of wind and PC injection. In addition, Hatano et al.\textsuperscript{8)} collected coke in front of tuyere, applied a relational expression of raceway factor and penetration factor at an experimental furnace, and estimated the raceway depth, but this is not suited for tracing the dynamic behavior of raceway. For non-contact measurement, reflected wave detection using laser output by Duval et al.\textsuperscript{9)} or Formoso et al.\textsuperscript{10)} is reported, but since they need high-output laser, there remains a problem from the viewpoint of versatility. Therefore the measurement of micro wave reflection gunned through a tuyere with easy versatility as follows is developed.

3. Measurement Method and Principle

3.1. Raceway Depth Measurement Method and Principle

Figure 2 shows a $\mu$-wave\textsuperscript{11)} impinging method from a blast-furnace tuyere. The $\mu$-wave is transmitted from a waveguide tube and allowed to impinge from a columnar antenna installed at the head end of the waveguide tube through a tuyere peeping window. The antenna has a conical recessed section formed inside in order to efficiently fire the transmitted $\mu$-wave to ahead, and is disposed in such a manner to be adjacent to the tuyere peeping window on the base end side of a blowpipe.

Figure 3 shows a measurement principle. Part of the transmitted $\mu$-wave \(\oplus\) generated is branched \(\otimes\) and transmitted to a mixer \(\ominus\), where the $\mu$-wave is combined with the transmitted wave \(\ominus\) from the raceway to generate a beat wave. The beat wave frequency has frequency components equivalent to the distance to the object, and the distance to the object can be measured by frequency analysis \(\ddagger\).

Now, at the transmission section \(\oplus\), the $\mu$-wave generated is frequency-modulated to form a transmitted wave, and this transmitted wave is fired to the deepest part of the raceway from the antenna \(\otimes\) through the blowpipe and tuyere. When the $\mu$-wave is generated at a $\mu$-wave generator comprising gun diodes and other semiconductor elements, this $\mu$-wave is frequency-modulated to become a saw-tooth wave. Frequency modulation is a technique to control the frequency to make predetermined changes in proportion to time. The frequency-modulated $\mu$-wave becomes a frequency-modulated continuous wave (FM-CW). This FM-CW is guided to the antenna via the waveguide tube as a transmitted wave, from where it is fired to the deepest part of the raceway. Part of the transmitted wave is sent to the beat wave generator \(\ddagger\) by a circulator (directional coupler) to form a beat wave. The fired transmitted wave is divided into the deepest part reflected wave generated by reflecting at the deepest part of the raceway and the non-deepest part reflected wave generated by reflecting at places other than the deepest part, and is received by a receiving section, that is, antenna \(\ominus\), and transmitted to the circulator \(\otimes\) by the waveguide tube. Each reflected wave (received wave) which

![Fig. 1. Effect of tuyere velocity on deadman coke activation.](image)

![Fig. 2. Micro wave technique to determine the raceway depth.](image)
pass the circulator is guided to the beat wave generator ④, where the transmitted wave and received wave are overlapped and a beat wave is generated. The beat wave is generated as a result of interference when two waves of slightly different frequencies overlap and is the “beat wave” called in the sound wave world, and the frequency is the difference of frequency between the received wave and the transmitted wave. When the frequency of this beat wave is made clear, it becomes possible to compute the distance to the object which reflected the transmitted wave fired from the antenna by the use of the frequency. The beat wave passes a band-eliminator later discussed, and is Fourier-transformed by the use of an FFT algorithm, etc. at the Fourier-transforming section, and the frequency spectra are found. Then, based on, for example, the peak value of this frequency spectrum distribution, the distance to the deepest part of the raceway is found by the following equation:

\[ l = \frac{c \times t}{2} = \frac{c \times T \times fb}{2 \times F} \]

where,

- \( l \): Raceway depth (distance between the tuyere and the deepest part of raceway)
- \( t \): Time required for \( \mu \)-wave to make a round trip
- \( T \): Frequency (frequency sweep time)
- \( fb \): Beat wave frequency
- \( F \): Frequency modulation width
- \( c \): Light velocity.

The frequency spectrum of beat wave is frequency-distance converted based on the above equation, and the frequency spectrum is converted to the distance spectrum with the distance to the reflected object taken as abscissa. By smoothing this distance spectrum, noise on the data is removed. And then, the peak spectrum value is computed from the distance spectrum distribution.

### 3.2. Raceway Depth Measuring Technique Under Intensive Coal Injection

Examples of reflection of transmitted wave at places other than the deepest part of raceway include reflections from inner wall surface of blowpipe, opening on the blowpipe side of the lower bend, opening on the blowpipe side of PC lance, and others. Consequently, even if the frequency spectrum is used as it is and the distance from the peak value is found, the raceway depth cannot be found.

**Table 1. Application of micro wave on detection of raceway boundary in blast furnace**

<table>
<thead>
<tr>
<th>Problems</th>
<th>Countermeasures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Efficiency of micro wave reflection</td>
<td>1. Gunned from cone antenna directly</td>
</tr>
<tr>
<td>2. S/N ratio under fume from coal combustion</td>
<td>2. Band eliminator</td>
</tr>
<tr>
<td>3. Multi reflections between blow pipe and tuyere nose</td>
<td>3. Selection of reflection wave based on circling direction in spiral vector composed by electro-magnetic field</td>
</tr>
<tr>
<td>5. Heat resistance</td>
<td>5. Conducting cable from signal analyzer</td>
</tr>
</tbody>
</table>

**Figure 3. Principle to determine distance by micro wave reflection.**
pipe prepared in the radio wave absorbing zone, the relative reflection intensity from the coke layers arranged to the head end section was measured with the coke layer void ratio and the number of layers varied. The coke layers were disposed at the position 4 300 mm from the antenna, and even in the coke single layer with a void fraction of 0.8, the position can be located, but in the coke single layer with a void fraction of 0.5, which corresponds to the raceway surface layer section, the locating position is 4 330 mm, where the position 30 mm inside from the coke layer surface can be located but the relative reflection intensity is markedly high. On the other hand, when the coke layer with a void fraction of 0.8 were piled in three layers, the locating position was expanded to 4 300 to 4 380 mm, while the relative reflection intensity is lower than that of the coke single layer with a void fraction of 0.5. The frequency of the beat wave generated by combining with the received wave from the actual furnace raceway has the frequency component that corresponds to the distance to the object. Because this beat wave is Fourier-transformed and rotates through the raceway inside in order to find the raceway depth based on the peak value of the frequency spectral distribution found, it is possible to accurately locate the stationary raceway boundary position as the raceway depth.

Figure 5 shows the relationship between the relative reflection intensity and coke layer measurement distance in the experiment outside the blast furnace. Through the blowpipe prepared in the radio wave absorbing zone, the relative reflection intensity was measured while varying the position of coke single layer with a void fraction of 0.5 arranged at the head end portion. Irrespective of the disposal position of the coke layer, the position generally 30 mm inside from the coke layer surface was detected and it was able to be confirmed that the position can be followed.

4. Measurement Results and Discussion
4.1. Effects of Tuyere Diameter and Draft Volume on Raceway Depth

Figure 6 shows effects of the tuyere diameter on the peak detection position (hereinafter called the “measured raceway depth”) of μ-wave reflection intensity in steady operation of Kakogawa No. 3 blast furnace from Oct. 31, 2002. In the figure, estimated values of Hatano et al. are shown, and estimated coke particle sizes estimated from Hatano’s equation based on measured raceway depth coincided irrespective of tuyere diameters. The smaller the tuyere diameter, the faster is the tuyere wind velocity, but the stock wind volume is small because the wind volume is distributed by differential pressure of each hot blast tuyere, and therefore, the raceway depth is shallow. This coincides with that Sasaki et al. demonstrates that the relationship between the raceway depth measured from the raceway shell, which is a dense layer with fine-grain coke and molten slag firmly clung in the dissection study of the Kokura No. 2 blast furnace and the tuyere diameter is the positive correlation.

4.2. Effects of PC Injection on Raceway Depth

Sasaki et al. quote that double to triple raceway shells formed in accord with the blast volume can be identified as carcass at the time of blowing down before shutdown in the dissection study of the Kokura No. 2 blast furnace. Figure 7 shows changes of measured raceway depth and estimated raceway depth by Hatano et al. with respect to the blast volume with μ-wave that impinges from the tuyere in the blast-furnace blowing down process. As the blast is blown down, the measured raceway depth decreases in the same manner as the estimated value, and it has been confirmed that the present measuring method can follow changes of raceway depth by blowing down. The period in which the estimated value indicates a specified value in the blowing-down process is attributed to an increased tuyere wind velocity due to the reduced pressure of draft pressure associated with the reduced furnace top pressure, and the present measurement can satisfactorily follow with respect to this, too. Furthermore, it is worth notice that the raceway...
depth is extended at a breath right after PC is cut off. This is assumed to be sudden recovery of blast energy by the rise of flame temperature because of PC cut-off.

Sugisaki et al.\(^{13}\) defines the ratio of the raceway area to the hearth cross-sectional area at the tuyere level shown in Fig. 8 as a raceway area ratio \(h_{\text{RW}}\) and finds that the reducing agents rate is low when \(h_{\text{RW}}/H_{11005}\) is 0.47 or 0.48 under heavy oil injection.

Figure 9 shows the relation between the ratio \(x_{\text{RW}}\) of measured raceway depth to estimated raceway depth of Hatano et al.\(^{8}\) (hereinafter called the “raceway depth ratio”) and ratio \(h_{\text{RW}}\) of raceway area to the hearth cross-sectional area (hereinafter called the “raceway area ratio”) when the \(\mu\)-wave is allowed to impinge from the tuyere in the blast-furnace blowing down process. For the raceway area ratio \(\eta\), the ratio of raceway area to the hearth cross-sectional area at the tuyere level is used as is the case of Sugisaki et al.\(^{13}\) As the raceway area ratio \(\eta\) decreases because of blowing down, the raceway depth ratio \(x\) lowers but the magnitude of lowering of \(x\) is greater in operation under PC injection than in all-coke operation. This suggests the three-dimensional profile change of raceway because of PC injection and furthermore instability to flow-in coke particle size.

5. Effects of Raceway Formation on In-furnace Solid Flow

In Kakogawa No. 2 blast furnace, making the best of burden distribution control by coke center charging and combustion technique using a double lance, the monthly coke ratio of 298 kg/hm (PC ratio: 123 kg/hm; heavy oil ratio: 62 kg/hm) below the 300 kg/thm mark was achieved for the first time in the world in April 1990 by PC-oil mixed injection.\(^{14}\) Figure 10 shows changes of relative burden descending speed for averaged speed at the throat section by the sounding type profile meter in the transition process to low coke ratio operation. As the PC injection rate increases, the in-flow coke rate to the raceway section decreases, and the descent speed around the throat lowers.

Yu et al.\(^{15}\) report that the raceway decreases when the peripheral section of the flow path of in-flow coke to the lower part of the furnace is blocked by the setting of quasi-cohesive zone in the solid-motion simulation in the raceway using the discrete element method. Considering that the computation conditions reflect the above-mentioned actual furnace phenomena in that the burden descent speed at the throat peripheral section decreases because the in-flow coke rate to the raceway section decreases as the PC injection rate increases, it may sound paradoxical, but it could be thought that the results of Yu et al.\(^{15}\) suggest that the actual furnace phenomena of the raceway depth which is shallow at the time of PC injection than that at the time of all-coke operation described in Sec. 4.2 would arise from the solid flow to the raceway.

For the phenomena at the throat section that correspond-
ed to the changes of radial descent speed distributions when the PC rate was increased, the phenomenon in that the gas temperature from the furnace center to the intermediate section lowered in the upper part of the shaft and the solution loss carbon rate rapidly increased was observed. **Figure 11** shows this center flow suppressing phenomenon. It is the feature of the throat gas temperature distribution that appears 6 to 10 h ahead of the changes of heart heat. This can be described that as the PC rate increases, the descent speed distribution at the peripheral region lowers and ore flowing into the furnace center is promoted as a result of increased O/C under pellet compounding. Consequently, in the high PC injection operation, the raceway formation and its stability are assumed to have effects even on the controllability of burden distribution.

Takahashi et al. finds out by cold experiments that slip occurs at the throat section when gas flow resistance of inflow particles to the raceway increases. It is assumed that this would suggest that changes in raceway resulting from coke degradation at the raceway section would change the solid flow of the whole blast-furnace system. With the foregoing description, it is surmised that in the blast-furnace method in which the singular packing structure is entrusted to coke in the lower part of furnace, coke is the key for raceway formation which serves as the initiation point of internal gas flow, and the unstable raceway would induce lowered gas permeability and abnormal burden descent particularly in the high PC injection operation and tends to result in functional disorder of the whole blast furnace system.

6. Conclusion

In the increased size of blast furnace and high-tapping operation, an extremely great importance has been attached to the control of burden distribution and burden descent condition or the profile and distribution condition of cohesive zone and raceway. In this report, the measurements technique of raceway depth was developed from the reflection intensity of μ-wave allowed to impinge from a tuyere and the results of the work carried out allow us to draw the following conclusions from the investigation on the relevancy between PC injection operation and the blast-furnace raceway profile.

1. It has become possible to measure the raceway depth with high accuracy by making the peak value of the frequency spectrum greatly prominent and by receiving no reflected waves that caused double reflection under intensive coal injection.

2. In the experiment outside the blast furnace, irrespective of the disposed position of the coke layer, the position generally 30 mm inside from the coke layer surface was detected as raceway boundary.

3. In the steady operation, the narrower the tuyere diameter, the faster is the tuyere wind velocity, but since the wind volume is distributed by differential pressure at each hot blast tuyere, the raceway depth is shallow as a result of small stock wind volume.

4. In the blowing down process, the degree of lowering the raceway depth is greater in PC injection that in all-coke operation. This suggests the three-dimensional profile changes of the raceway because of PC injection and furthermore instability to in-flow coke particle size.

5. Under intensive PC injection operation, the raceway formation and its stability exert effects even on the controllability of burden distribution.

In the future, still greater importance will be attached to securing of the deadman gas permeability and liquid permeability for the increased fine coke discharge at the deadman when still lower reducing agent ratio operation is intended. It is necessary to deepen the dynamic understanding of the flow-down of coke, furnace lower-part packing structure, to the lower part of furnace, coke particle size segregation, and its flow-in behavior into raceway and control all these factors. It is our sincere hope that successful results could be obtained in the research conducted jointly by universities and private sector corporations “Control of Blast Furnace Limit Phenomena intended for Minimum CO₂ Generation” that started in 2002.

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