Investigations of Oil Combustion in the Race Way of the Blast Furnace*  

By Mikio KONDO,** Toshihiro INATANI,** and Kyoji OKABE**

Synopsis

In order to clarify the phenomenological changes in the blast furnace accompanied with the injection of heavy oil through the tuyeres, the reaction gas in the race way was sampled by the use of a horizontal probe and analysed. In the case without oil injection, the CO₂ content gradually increased with decreasing content of oxygen along the inward direction, and the contents of CO and H₂ increased in the region passed through the maximum point of CO₂. As the injection rate of heavy oil increased, this trend was more intensified and it was accomplished in a shorter range. When the nozzle head of the oil burner was put back in the blow pipe, the decrease in the content of oxygen occurred even in the blow pipe. The decrease in the length of the raceway accompanied with the increase in the rate of oil injection was found also by the bar-test. The distributions of gases at the top of the shaft were measured by a probe horizontally installed at the stockline level and the efficiency of gas was calculated.

I. Introduction

A number of attempts have been made in order to reduce the coke consumption in the blast furnace operation, by using a large amount of the sinter and pellet of iron ores, high temperature blast, oxygen enrichment of the blast, fuel injection and other techniques. Since the cost of iron increased due to the insufficient supply of good coking coal, it was required to establish a new technique which was possible to make a further reduction of coke rate. The oil injection was considered as one of the best way satisfying the requirement from the economical reason that the price of oil was much cheaper than that of the metallurgical coke per calorific unit. By the injection of a large amount of heavy oil into the blast furnace, the coke rate was reduced to the level less than 400 kg/THM.

Under these conditions the ratio of ore to coke increases with increasing amount of heavy oil injected, and therefore the blast furnace operation is accompanied with several difficult problems, especially the gas permeability in the shaft. However, these difficult problems were solved by the application of suitable counter-measures, such as oxygen enrichment, high temperature blast, cutting off the moisture addition into the blast and increasing amount of sinter in the burden. By these methods, it became possible to inject a large amount of heavy oil for a long period of time.

The details of phenomenological changes in the blast furnace with heavy oil injection have not yet been clarified thoroughly. It would be rather said that the undissolved problems become increased, such as the formation of soot, the reduction of the oil replacement ratio, troubles taken place in the top gas cleaning process, and wall lining troubles. In order to obtain the fundamental data which are necessary for solving these problems, several experiments on the combustion of heavy oil in the race way were made and the reaction gas at that zone was analysed by taking the sample with a probe inserted horizontally.

Since the oil crisis happened in December 1973, it has been impossible to use heavy oil fully because of the economical deficit. However, a chance to know the phenomenological changes in the blast furnace and to apply the fine techniques necessary for smooth and steady operation has been given by several operations previously made with a large amount of oil injection.

II. Installation and Experimental Procedure

1. Gas Sampling Probe at the Tuyere Level

The over all length of the probe is 8 m and it consists of three coaxially arranged steel pipes as shown in Fig. 1. For preventing the burning out of the probe by excessive heating, it is cooled by circulating sea water, velocity of which is 5 m/sec in the channel between outer pipe and inner one, or between inner pipe and inner most one. The maximum temperature of cooling water at the outlet was 70°C during the experimental run. In Fig. 2 the installation for gas sampling is shown schematically. The probe is inserted into the race way through the tuyere stock (1) and the gas sealing devices (5, 6, 7 in Fig. 2), and is driven pneumatically.

During the gas sampling, the sampling position and the working condition of the probe were checked visually through a peep hole. Owing to the high gas pressure in the race way, the sampled gas blowing out of the innermost pipe of the probe was collected into a sampling glass flask. The molten slag and iron

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accompanying with the sampled gas often caused the stoppage of gas flow at the foremost end of the probe. The soot formed in the race was by the oil injection was also collected by the filters installed in the gas sampling system. The sampled gas was subjected for the analysis of O₂, CO, CO₂, H₂, N₂ and CH₄ by using Hempel method and gas-chromatography, but not for H₂O. The soot was also chemically analysed. The burning out of the probe has not been observed because the cooling system was strictly controlled.

Figure 3 shows the position of tuyeres whereat the measurement was performed. The oil injected is directly supplied from the central pumping installation with a pressure of 10 kg/cm² and is sprayed through the injection nozzle inserted into the blow pipe.

2. Probe Horizontally Inserted in the Throat

In the throat of No. 2 blast furnace (inner volume 1395 m³ and hearth diameter 8.4 m) a probe having the overall length of 8 m and the outer diameter of 6.05 cm which is inserted horizontally is installed as shown in Fig. 4, for the sampling of gas from every radial position. It consists of two steel pipes with a water cooling system and is driven by an electric-motor.

**III. Experimental Results and Discussions**

1. Experiments for the Sampling of Gas in the Race Way

There is a number of experimental results reported on the distributions of gas contents in the race way for the case of natural gas injection, but only a few for the case of oil injection. Therefore, the mechanism of oil combustion in the race way under the coexistence of circulating cokes has not been clarified yet. The following three have therefore been mainly studied in the current investigation.

1) The distribution changes of gas contents in the race way with oil injection.
2) The influences of oil rate on the conditions of combustion.
3) The exclusive combustion of oil in a tuyere without the coexistence of circulating cokes.

Table 1 shows the operational conditions at the tuyere where the gas samplings were made. The run No. 1 was made at No. 1 blast furnace and the runs Nos. 2, 3 and 4 at No. 2 blast furnace of Chiba Works. The runs Nos. 1 and 2 are the cases which are changing the oil rate, the run No. 3 the case in which the position of nozzle for oil injection is changed and the run No. 4 the case that the probe was inserted into the axial direction of the atomized oil stream. The distributions of gas contents in the race way for the runs Nos. 1, 2 and 4 are shown in Figs. 5, 6 and 7, respectively.

2. Distribution of Gas Content in the Race Way

1. Influence of the Oil Rate on the Distribution of Gas Content

In order to clarify the influence of the oil rate on the distribution of gas content, it is necessary to examine the change of O₂ content in both cases with and without oil injection. The principal roles of O₂ in the blast wind are as follows:

1) The combustion of oil and coke

![Fig. 2. A schematic figure of horizontal probe at the tuyere level.](image)

![Fig. 3. Tuyere location for gas sampling.](image)

![Fig. 4. A schematic figure of horizontal probe at the throat.](image)

![Fig. 5. Distributions of gas compositions to the direction of blast flow for the run No. 1.](image)
Table 1. Experimental conditions at the tuyere where gas samplings were made

<table>
<thead>
<tr>
<th>Run number</th>
<th>Injection rate of heavy oil (l/hr)</th>
<th>Blast volume* (Nm³/min)</th>
<th>Oxygen enrichment (%)</th>
<th>Blast temperature (°C)</th>
<th>Blast humidity (g/Nm³)</th>
<th>Oil/oxygen ratio (l/Nm³)</th>
<th>Position of nozzle tip** (mm)</th>
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</thead>
<tbody>
<tr>
<td>1-1</td>
<td>0</td>
<td>93.8</td>
<td>4.26</td>
<td>1020</td>
<td>12</td>
<td>0</td>
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<td>460</td>
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<td>1020</td>
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<tr>
<td>2-1</td>
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<tr>
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<td>1090</td>
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<tr>
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<td>0.515</td>
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<td>1080</td>
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<td>0.473</td>
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<td>1080</td>
<td>18</td>
<td>0.481</td>
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<td>-3</td>
<td>780</td>
<td>111.1</td>
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<td>120.6</td>
<td>3.49</td>
<td>1100</td>
<td>20</td>
<td>0.506</td>
<td>-250</td>
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<tr>
<td>-3</td>
<td>900</td>
<td>120.6</td>
<td>3.49</td>
<td>1100</td>
<td>20</td>
<td>0.511</td>
<td>-250</td>
</tr>
</tbody>
</table>

* Calculated on the assumption that the total blast volume is equally distributed to all tuyeres.
** Distance from the tuyere nose. Positive sign shows the inward direction.

2) The oxidation of CO and H₂ in the bosh gas*
3) The re-oxidation of iron melts.²

The results obtained in the run No. 2-1 without oil injection shown in Fig. 6(a) indicate that the O₂ content decreases as it is getting towards the furnace center. On the contrary, the CO₂ content increases until the time wherein CO and H₂ begin to form at the position of +0.4 m.**

The gain in the CO₂ content is nearly equal to the loss in the O₂ content and the direct oxidation of C in coke is taken place apparently*** as follows:

\[ C + O₂ = CO₂ \] (1)

However, the total O₂ content of the combustion product defined as \( (O₂-CO₂-CO)\% \) is less than the O₂ content of the blast. This fact indicates that the re-oxidation of iron melts is taken place.

Furthermore, the CO₂ content shows the maximum value at the position where the O₂ content decreases to zero, and the following solution loss reactions begin:

\[ C + CO₂ = 2CO \] (2)
\[ C + H₂O = CO + H₂ \] (3)

The authors have already reported the several

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* It is well known that a compressible turbulent jet drags the atmospheric gas into the jet region.⁸
** The position of tuyere nose is mentioned as ± 0 m and the inside of that position is given by the sign of +.
*** Even when CO in the bosh gas reacts with O₂ in the blast, \( (O₂-CO₂-CO)\% \) of the combustion product does not change and shows the same value as that for the reaction with C in coke. It is impossible to determine how much O₂ is consumed for the oxidation of bosh gas.
cases\(^2\) that the CO and H\(_2\) contents rapidly increase simultaneously with decreasing CO\(_2\) content. However, at this experiment the O\(_2\) content does not reach to zero but increases at the region above +0.8 m by depressing CO and H\(_2\) generation. This phenomena are described afterwards.

In the case of oil rate 490 l/hr shown in Fig. 6(h) which is corresponding to the oil consumption 60 l/THM, there is some differences in the distribution of gas content as compared with the case without oil injection. The main differences are as follows:

1) The O\(_2\) content decreases rapidly after entering into the race way.
2) The distribution patterns of CO\(_2\), CO and H\(_2\) contents shift their positions towards the tuyere.
3) The maximum value of CO\(_2\) content decreases.
4) The generation of CH\(_4\) proceeds together with the increase of CO and H\(_2\) contents.

With increasing oil rate, the distribution pattern of O\(_2\) content shifts its position toward the tuyere, indicating that the consumption of O\(_2\) begins at an earlier stage. Moreover, the generation of CO and H\(_2\) which begins to increase after reaching to the maximum point of CO\(_2\) in the case without oil injection, proceeds with the increasing CO\(_2\) content, simultaneously. However the generation of CO and H\(_2\) occurs by taking with the decrease of O\(_2\) content in the similar manner as in the case without oil injection. The rapid decrease of O\(_2\) at the inlet of race way is depending upon the oil combustion. It is the characteristic feature of oil injection governing the phenomena in the race way.

With increasing oil rate, the maximum value of CO\(_2\) content decreases, but the CO and H\(_2\) contents increase. The generation of CH\(_4\), which begins after that of H\(_2\), indicates that the thermal decomposition of heavy hydrocarbon is taken place at the position +0.2 to +0.8 m. The amount of CH\(_4\) generated is nearly proportional to the oil rate.

On the basis of the results of oil combustion in the race way, the combustion process of atomized oil droplets can be traced as follows.\(^1\) The oil droplets atomized at the outlet of injection nozzle in the tuyere are rapidly heated up to its vaporization temperature by the convection of hot blast and by the radiation from the inner part of the furnace. A mixture of oil vapor and air makes a combustible gas layer around the droplet, and the combustion of oil begins thereby the diffusion of O\(_2\).

The oil droplet entering into the race way, where hot cokes are circulating, has a chance of competitive collision with O\(_2\), which reacts exclusively with coke in the case without oil injection. There will be a large number of chances for the collision of oil droplet with O\(_2\) because of the premixing with the blast by the atomization of oil at the tip of the injection nozzle. The generation of oil vapour and the formation of combustible gas mixture proceeds extensively at the tip of the tuyere and the combustion begins violently by curving the temperature rise. The violent reaction accelerates the decomposition of heavy hydrocarbon, which generates CO, H\(_2\) and CH\(_4\), and also the coke like a solid material, "cenospheres".

In the case of the run No. 4-3, the gas sampler is fixed at the position of −0.3 m, where the maximum value of CH\(_4\) content is obtained, and the soot is sampled. Table 2 shows the chemical compositions of soot and initial heavy oil. The soot is sampled by two collectors arranged in a series, one of which is a bubbling water vessel and the other is a fine paper filter, symboled as Nos. 1 and 2 in Table 2, respectively. A clear difference cannot be identified between them. The C/H value of the soot is three times as much as that of the initial heavy oil.

When the ratio of oil rate to the blast volume increases without changing the other blast conditions, it becomes unfavourable for the complete combustion. Tanazawa and Nukiyama\(^2\) mentioned that the diameter of atomized oil droplet becomes larger as the ratio of oil rate to the blast volume increases. This phenomenon is also the cause of low combustibility.

2. The Radial Distribution of Gas Content on the Cross-sectional Area in the Tuyere

The injection nozzle is inserted through the blow pipe at an angle of 13° to the gas flow direction and is fixed in the position 2 to 3 cm apart from the center. According to the observation through a peep hole, an umbrella-like stream of atomized oil was formed at the tip of the nozzle. The dispersion of oil droplet is not complete, and the enlargement of droplet stream proceeds with its dispersion into the blast. The combustion rate of oil at the center with sufficient droplets differs from that at the periphery with sufficient O\(_2\). The relative position of the gas sampler and the injection nozzle in the tuyere has a great importance for the evaluation of the distribution of gas-content along the direction of gas flow. Figure 8 shows the conditions for every experiment.

For the run No. 2 the gas sampler is positioned far below the injection nozzle. This seems to result in a little decrease of the O\(_2\) content till the position of tuyere tip. For the run No. 4 the gas sampler is just positioned into the oil stream resulting that, as shown in Fig. 7(a) and (b), O\(_2\) vanishes at the position of

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>H</th>
<th>S</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soot</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>84.2</td>
<td>3.74</td>
<td>2.26</td>
<td>1.0</td>
</tr>
<tr>
<td>No. 2</td>
<td>84.7</td>
<td>3.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy oil</td>
<td>86.0</td>
<td>12.1</td>
<td>1.20</td>
<td></td>
</tr>
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</table>
injected oil rate $V_o$ (l/hr). Under the condition of $V_o = 460$ to 860 l/hr the ratio of $X_o/V_o$ becomes 0.25 to 0.4. Since the C content in oil droplets becomes higher during the oil evaporation, the calculated value of $X_o/V_o$ may be larger than the actual one.

2. The Influence of Nozzle Position

From the result mentioned above, it is obvious that a part of injected oil burns in the tuyere. Then, if the nozzle position is drawn back towards outside of the furnace, the volumetric rate of the burned oil can easily be increased. This fact has been ascertained by the result of the run No. 3. The total length of the injection tube is 1.95 m and its nozzle tip is located at the position of $-250$ mm in the tuyere. The additional two tubes, the one is $200$ mm shorter and the other $150$ mm longer than the standard, have been used in these experiments. The experiments were made under a constant ratio of oil rate to oxygen volume.

Figure 10 shows the measured results of $O_2$ and $CO_2$ contents. These are not affected by the radial distribution of oil droplets in the tuyere mentioned above, because the gas sampler was inserted into the region of rare oil droplets. The distribution pattern of gas content is drawn back in accordance with the nozzle position. The $O_2$ contents at the tuyere tip are $17.5, 22.0,$ and $22.5\%$ for each nozzle position, respectively. These results are considered to indicate that the residence time of the oil droplets becomes longer and that the progress of dispersion into the blast is greater in this region, if the nozzle position is drawn back. The displacement distance of the distribution patterns of $O_2$ and $CO_2$ is shorter than that of the nozzle position.


Bardin et al.\(^{(18)}\) pointed out that two peaks of $CO_2$ content were detected in the distribution curves of gas compositions in the race way under the conditions of

$-0.1$ m and $CO_2$ and even $CH_4$ generate in the tuyere. In this case the gas content distribution, which is developed until $+0.8$ m for the run No. 2 seems to be condensed in the tuyere. The $CO$, $H_2$ and $CH_4$ contents decrease once at the inlet of the race way, but increase again. This phenomenon suggests that a radial mixing in the gas stream is taken place at the inlet of the race way, which should be investigated in the future.

3. Oil Combustion in the Tuyere

1. The Influence of Injected Oil Rate

The nozzle position for the run No. 1 is settled between the positions for the run Nos. 2 and 4, and the $O_2$ content at the tuyere tip is considered to be close to the mean value over the entire cross sectional area as shown in Fig. 5. With increasing oil rate, the $O_2$ content at the tuyere tip decreases gradually. The combustion rate can be calculated on the basis of the oxygen balance between the nozzle tip and the tuyere tip. In this region, where coke is not coexisting, only the injected oil burns. Here, it is assumed that only two reactions described by Eqs. (4) and (5) take place, and the $O_2$ consumption is proportional to the C and H contents in heavy oil according to these equations.

$$C(oil) + O_2 = CO_2 \quad \cdots \cdots (4)$$
$$H_2(oil) + \frac{1}{2} O_2 = H_2O \quad \cdots \cdots (5)$$

On the basis of the oxygen balance, the volumetric fraction of $O_2$ in the dry gas at the tip of the tuyere $X'_o(\sim)$ can be expressed by Eq. (6) containing the volumetric rate of burned oil $X_o(l/hr)$.

$$X'_o = \frac{60V_o(0.21 + X'_o) - 22.4 \cdot \rho_o \cdot X_o \cdot (C_o/12 + H_o/4)}{60V_o - 5.6 \cdot \rho_o \cdot X_o \cdot H_o} \quad \cdots \cdots (6)$$

where, $\rho_o$: specific weight of oil (kg/l)

$C_o, H_o$: mass fraction of C and H in oil, respectively (\sim)

$V_o$: dry blast volume for one tuyere including enriched $O_2$ (Nm$^3$/min)

$X_o$: oxygen enrichment ($\%O_2/100$)

The value of $X_o$ can be calculated if $X'_o$ is measured. Figure 9 shows the dependences of $X_o$ and $X'_o$ on the

**Fig. 9.** Dependence of the burning rate inside the tuyere $X_o$ and the oxygen content in sampled gas at the tuyere nose $X'_o$ on the injection rate $V_o$

**Fig. 10.** Relation between the positions of nozzle-tip and the distributions of gas compositions
combustion with coke circulation. On the other hand, Gotlib\textsuperscript{4} reported that only one maximum of CO\textsubscript{2} content was observed in their experiments made with No. 3 blast furnace at Zavalozistaly. It is considered, however, that these two different results do not represent the corresponding condition, but an indetical condition in the race way.\textsuperscript{30} This can be explained by assuming that the flow of blast bends upwards in the race way, as illustrated schematically in Fig. 11. When the flow of blast bends upwards in the race way and the gas sampling is made along the line OA in Fig. 11, this line passed through the reducing zone (hatched) and the oxidizing zone (not hatched) twice for each, resulting in the representation of two CO\textsubscript{2} peaks and one O\textsubscript{2} peak. This gas distribution pattern is named as B-type, while that showing a maximum content as A-type in the case of the gas sampling along the line OB in Fig. 11, this line passed through the reducing zone and the oxidizing zone twice for each, resulting in the representation of two CO\textsubscript{2} peaks and one O\textsubscript{2} peak.

From the investigations on the distribution of gas content in the race way with natural gas injection, Volkov et al.\textsuperscript{5} and Gorskichov et al.\textsuperscript{6} found that there are three peaks for CO, H\textsubscript{2}, and O\textsubscript{2}. The existence of these peaks was described to be owing to the insufficient mixing of the injected natural gas with the blast.

One of the characteristic features for the gas content in the race way found by the authors and others is the coexistence of the combustible elements H\textsubscript{2} and CO, and O\textsubscript{2} in the blast blown in. On the basis of the chemical equilibrium, the generation of H\textsubscript{2} and CO occurs actually in the region of low O\textsubscript{2} content under the conditions of high temperature and sufficient mixing of the gas species. The lack of uniformity in the gas content is, perhaps, due to the use of a water-cooled gas sampler, which enable to stop the burning of combustible gas mixture.

5. \textit{The Radial Distribution of Gas Content at the Throat of Furnace Top}

A radial gas sampler is installed just above the stock level of No. 2 blast furnace. The gas samplings were made during the operational runs of which the oil rate was gradually increased.

Table 3 shows the experimental conditions adopted in the current work. During this experimental run, the stock level was kept at the position 1.5 m below the standard level and the charging sequence was C\textsubscript{4}H\textsubscript{10}O\textsubscript{4}. Only the ratio of ore to coke is changed considerably with increasing oil rate. Radestock\textsuperscript{40} studied the gas flow through the column of burdens in the blast furnace. It can be estimated from his calculated results that the gas flow pattern does not change by the location in the upper part of the shaft and the distribution of gas content depends strongly on the charging conditions. Therefore, the influences of oil rate on the distribution of gas content is equivalent to that of the ratio of ore to coke, which is one of the changing conditions, in the case of a constant rate of iron production.

Figures 12 and 13 show the radial distributions of gas content and of the calculated amount of CO utilization. With increasing ratio of ore to coke, the utilization of CO at the central part of the furnace rises clearly. This agrees qualitatively with the experimental results\textsuperscript{57} for the relation between the charging conditions and the radial distribution features of burdens, that is, the increasing ratio of ore to coke results in the increasing of gas flow resistance especially at the central part of the furnace because the charged ores are well rolled over the stock surface.

In connection with the effect of coke base, the coke weight for each charge, Okabe reported that the greater the coke base is, the more uniform the radial distribution features of burdens and of gas flow become.\textsuperscript{58}

When the volume of injected oil increased from

![Fig. 11. Schematic figures of the gas flow and the distributions of gas compositions in the race way](image)

### Table 3. Operational conditions during the sampling of top gas

<table>
<thead>
<tr>
<th>No.</th>
<th>Blast volume (Nm$^3$/min)</th>
<th>Blast pressure (Kg/cm$^2$)</th>
<th>Top pressure (Kg/cm$^2$)</th>
<th>Oil injection rate (l/hr)</th>
<th>Enriched oxygen (Nm$^3$/hr)</th>
<th>Composition of top gas (%)</th>
<th>Ore/Coke</th>
<th>Coke base (t/ch.)</th>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>2540</td>
<td>220</td>
<td>0.75</td>
<td>9800</td>
<td>5000</td>
<td>26.0</td>
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<td>10100</td>
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<td>0.75</td>
<td>13800</td>
<td>6500</td>
<td>23.0</td>
<td>22.0</td>
<td>4.9</td>
</tr>
<tr>
<td>V</td>
<td>2360</td>
<td>202</td>
<td>0.75</td>
<td>15600</td>
<td>7000</td>
<td>22.8</td>
<td>21.3</td>
<td>5.1</td>
</tr>
<tr>
<td>VI</td>
<td>2360</td>
<td>214</td>
<td>0.75</td>
<td>16000</td>
<td>8000</td>
<td>23.7</td>
<td>21.8</td>
<td>5.4</td>
</tr>
</tbody>
</table>

* This test was carried out three hours after the repairs of rotating hopper from the trouble.
ults show that the segregation effect of ore at the end of radial distribution features. The experimental operation by means of avoiding the excess uniformity of the central part resulting from the increase of the ratio of coke to coke was suppressed to some extent and the central part worst and the radial distribution features of burdens change gradually with increasing oil rate, if there is no change in the other condition of the blast. In order to avoid that this unfavourable phenomenon is taken place, the blast volume is often reduced by enriching the blast with oxygen to the equivalent amounts. Therefore, the dimension of race way zone changes.

The length of race way zone has been measured by using the method of "bar-test" with which a steel rod of 19 mm diameter was inserted inwards through the tuyere cover of No. 2 blast furnace, as far as it reached to the wall of coke bed.

Empirical or theoretical equations have been proposed by several investigators\(^{19-27}\) for the expression of the penetration length of race way zone. Fialkov\(^{27}\) reported that the race way zone was considered to be a fairly complicated feedback system under the influences of many physical and chemical phenomena, and also mentioned that the final result such as the length of race way zone could not be precisely explained only by the input condition such as the kinetic energy of the blast. However, an empirical equation can be used for the analysis of the experimental results obtained, because in the case of oil injection the race way zone is considered to be the most complicated feedback system under the influence of burden distribution in the furnace. The same analytical method as used by Bardin\(^{21}\), Byalyi\(^{22}\), Wysocki\(^{23}\) and Kopyrin\(^{24}\) has been adopted in the current investigation on the basis of the kinetic energy of the blast.

The kinetic energy of the blast \(E_B\) (Kg·m/sec) is calculated by Eq. (7), in which the effect of enriched oxygen volume and blast moisture are taken into consideration.

\[
E_B = \frac{\left[4(0.21 + X_{O_2}) + 28\right]/22.3 + \varphi \cdot 10^{-3}}{9.8}
\]

\[
\left(\frac{V_B}{60}\right)^3 \cdot n^2 \left(\frac{D^2}{4}\right)^2 \cdot \left(1 + \frac{22.4 \varphi}{18000}\right) \frac{P_B}{T_B} \cdot \frac{T_B}{T_0} \quad \text{...(7)}
\]

where, \(\varphi\): blast moisture (g/Nm\(^3\))
\(n\): number of tuyeres
\(D\): tuyere diameter (m)
\(P_B\): blast pressure (atm)
\(P_0\): pressure under the standard state (1 atm)
\(T_B\): blast temperature (°K)
\(T_0\): temperature under the standard state (273 °K)

The length of race way zone \(L\) (m) is described by Eq. (8) containing two factors, \(E_B\) and \(V_o\) as a result of regression analysis.

\[
L = 0.88 + 0.92 \times 10^{-4}E_B - 0.37 \times 10^{-3}V_o \quad \text{...(8)}
\]

In this case the correlation coefficient between \(E_B\) and \(V_o\) has a small value. The value of \(L\) depends negatively on \(V_o\). The reason why such a result is obtained may be considered as follows. The blast flow in the race way zone bends upwards at the position closer to the tuyere, because the total volume of combustion products increases under the condition that the gas.

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**Fig. 12.** Radial distributions of gas compositions at the top of the shaft

**Fig. 13.** Radial distributions of \(CO_2/(CO + CO_2)\) at the top of the shaft

13.8 kl/hr to 15.6 kl/hr, the coke base was decreased from 8 to 7.5 t/charge, in order to stabilize the furnace operation by means of avoiding the excess uniformity of radial distribution features. The experimental results show that the segregation effect of ore at the central part resulting from the increase of the ratio of coke was suppressed to some extent and the utilization of CO in top gas was reduced as shown in Table 3.

However, at the periphery part of the furnace no clear tendency can be identified. The \(H_2\) content increases with increasing oil rate over the entire area, but there is no change in the distribution pattern.

6. **The Length of Race Way Zone**

The gas permeability in the blast furnace becomes worse and the radial distribution features of burdens change gradually with increasing oil rate, if there is no change in the other condition of the blast. In order to avoid that this unfavourable phenomenon is taken place, the blast volume is often reduced by enriching the blast with oxygen to the equivalent amounts. Therefore, the dimension of race way zone changes.

The length of race way zone has been measured by using the method of "bar-test" with which a steel rod of 19 mm diameter was inserted inwards through the tuyere cover of No. 2 blast furnace, as far as it reached to the wall of coke bed.

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\[
E_B = \frac{\left[4(0.21 + X_{O_2}) + 28\right]/22.3 + \varphi \cdot 10^{-3}}{9.8}
\]

\[
\left(\frac{V_B}{60}\right)^3 \cdot n^2 \left(\frac{D^2}{4}\right)^2 \cdot \left(1 + \frac{22.4 \varphi}{18000}\right) \frac{P_B}{T_B} \cdot \frac{T_B}{T_0} \quad \text{...(7)}
\]

where, \(\varphi\): blast moisture (g/Nm\(^3\))
\(n\): number of tuyeres
\(D\): tuyere diameter (m)
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The length of race way zone \(L\) (m) is described by Eq. (8) containing two factors, \(E_B\) and \(V_o\) as a result of regression analysis.

\[
L = 0.88 + 0.92 \times 10^{-4}E_B - 0.37 \times 10^{-3}V_o \quad \text{...(8)}
\]

In this case the correlation coefficient between \(E_B\) and \(V_o\) has a small value. The value of \(L\) depends negatively on \(V_o\). The reason why such a result is obtained may be considered as follows. The blast flow in the race way zone bends upwards at the position closer to the tuyere, because the total volume of combustion products increases under the condition that the gas
permeability is reduced at the central part of the furnace and conversely raised at the periphery part, leading to the shrinkage of the race way zone. This is proved by the observation that the $O_2$ peak shifts towards the tuyere in the race way with increasing oil rate, as shown in Fig. 6.

The value calculated from Eq. (8) agrees with the measured value of $L$ within the limits of errors which is less than 0.1 m as shown in Fig. 14 and this equation is identical with those previously reported[21-24] if the third term in the right hand side of Eq. (8) is eliminated.

IV. Conclusion

The chemical reactions and the gas flow conditions in the blast furnace have changed with increasing oil rate. These changes have been investigated at the positions such as the race way zone, the gas inlet of blast furnace, and the throat, the gas outlet of furnace. The measurement has been made to know the distribution of gas content by using a sampling tube mounted at the tuyere level and at the throat of the furnace.

(1) At the race way the following are observed in the case of oil injection.

(i) The $O_2$ content decreases rapidly at the inlet of the race way.

(ii) The distribution patterns of $CO_2$, $CO$, and $H_2$ contents are changed to be drawn backwards.

(iii) The maximum value of $CO_2$ decreases.

(iv) The generation of $CH_4$ and soot proceeds together with increasing $CO$ and $H_2$ contents.

(2) The gas content is remarkably distributed in the sectional area of the tuyere tip which is perpendicular to the direction of gas flow. At the central part, where the density of oil droplet is high, the amount of $O_2$ consumed is more than that at the peripheral part.

(3) On the basis of the oxygen balance between the injection position and the tuyere tip, the combustion rate of heavy oil is calculated. If the injection position is replaced backward the combustible oil rate can be increased.

(4) From the results of “bar-test” over a long duration for the operating blast furnace, it is considered that Eq. (8) is the best equation representing the length of race way zone.

(5) Utilization of CO increases at the central part of the furnace shaft with increasing oil rate.

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