Dissection of Blast Furnaces and Their Internal State*

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Synopsis

For the purpose of investigating the internal state of a blast furnace in operation, Higashida No. 5 B.F. having the inner volume of 646 m³ was water-quenched while in a normal operating condition and dissected in 1968. This was the first attempt to dissect a commercial blast furnace in Japan.

Hirohata No. 1 B.F. with the inner volume of 1407 m³ which had been operated with considerably high productivity, was next dissected in 1970. Then, Kukioka No. 4 B.F. having the inner volume of 1279 m³ was dissected in 1971 to investigate the characteristics of a low coke ratio blast furnace.

Descriptions of the dissection procedure, general observations on the internal state of these blast furnaces, characteristics of each furnace, and relationships between the internal state and operating conditions are given in this report.

I. Introduction

Complex phenomena are often seen occurring in connection with the blast furnace operation. To establish the operating techniques which are effective in dealing with these phenomena, a better understanding of the internal state of blast furnaces is a prerequisite. Because of the considerable difficulty in realizing this, the phenomena have so far been dealt with mostly by relying on the assumptions. It was therefore considered that the most direct and effective method for enriching our knowledge on the internal state of blast furnace would be to quench it while in operation and carry out the internal examinations.

Water quenching and subsequent internal examinations of Higashida No. 5 B.F. having the inner volume of 646 m³, Hirohata No. 1 B.F. of 1407 m³, and Kukioka No. 4 B.F. of 1279 m³ were carried out, respectively, in 1968, 1970 and 1971. The results of the examinations, which significantly differ from those of V.M. Murav’ev, et al.,A distinctly showed that the internal states highly correspond to the operating conditions adopted and the phenomena observed during the operation just before quenching. In addition, numerous facts and valuable information unforeseen before the dissection of these blast furnaces were obtained, and have been positively reflected on the later blast furnace operations and design. On the other hand, accurate analyses concerning the reactions in the furnace seemed to be very difficult, especially in the dropping zone, because the burden might have molten down and been further reduced after shutting down the blast and also the reoxidation might have occurred in the course of quenching.

The present report contains, as a general introduction to a series of dissection reports, descriptions of the methods of quenching, furnace dissection and examinations, general observations on the internal state of the furnaces, and correlations between the operating conditions and the internal state, leaving to subsequent reports the detailed accounts of the lumpy zone, the softening–melting zone, and coke condition in the furnaces.

The terms shown below shall have the following meaning throughout this series of reports.

Lumpy zone: the zone where ores descend as lumps in the furnace
Softening–melting zone: the zone where ores soften and melt down; the layers of ores in this condition are called softening–melting layers
Dropping zone: the zone where molten metal and slag flow down through a bed made up solely of coke

II. History of Dissection of Blast Furnaces by Nippon Steel Corporation

The purpose of the dissection of Higashida No. 5 B.F. was, first of all, to know the internal state of an active blast furnace by water quenching it to fix the internal state for dissection. It was ascertained by this dissection that the burden in the furnace descends while maintaining clearly its multi-layer structure down to the lower part of the shaft where ores, still keeping its strata, soften and fuse into slabs, and that the total burden floats on the hot metal in the hearth. Furthermore, the changes in the physical characteristics of ores and coke and those in the compositions of hot metal and slag were, for the first time, understood in their entire distributions in the furnace, which had not been possible by the conventional local sampling through the furnace wall.

In contrast to Higashida No. 5 B.F., which was a small blast furnace producing foundry pig iron and the furnace condition of which shortly before the quenching had been unsatisfactory, Hirohata No. 1 B.F., which was a medium size blast furnace operated at a high top pressure and manufacturing steelmaking pig
iron, was chosen for the dissection to investigate the internal state of such a type of blast furnace. The investigation was conducted with the utmost care and precision as employed in archaeological site excavations, and all the samples thus collected were examined and studied by setting the entire ironmaking research force of the company. As a result, detailed knowledge on the internal state of the furnace including softening and melting of ores and dropping of hot metal and slag was obtained. The most remarkable discovery was the presence of uniform softening-melting layers extending in an inverted V-shape from the upper part of the furnace down closely to the tuyeres. The presence of these softening-melting layers can be considered as the indication of a favorable gas flow, contributing to the high productivity coefficient (average 1.94 t/m³·day per campaign) of this blast furnace.

Hiroyata No. 1 B.F., operated stably with high productivity as mentioned above, nevertheless had a comparatively high coke ratio. The operation of Kukioka No. 4 B.F., on the other hand, aimed at a low coke ratio with a large quantity heavy-oil injection, and the coke ratio attained was below 400 kg/t. Therefore, the purpose of the dissection of Kukioka No. 4 B.F. was to ascertain the internal state of the furnace which had been operated with such a low coke ratio. The investigation resulted in the discovery of softening-melting layers having different distributions as compared with those of Hiroyata No. 1 B.F., thus indicating that the distributions of the softening-melting layers change in relation to the operating condition and the operational phenomena, and showing a significant bearing on the blast furnace operation and design. In addition, because not only the salamander tapping but also the final tapping before quenching had been given up, full information concerning the details of the condition close to the tuyeres and that of the hearth was obtained.

III. Operation Shortly before Quenching

Because of the then high demand for hot metal at Hiroyata Works, high productivity operation was enforced to Hiroyata No. 1 B.F., and a record monthly average of 2.3 t/m³·day had been attained in September, 1969, 10 months before the quenching. This blast furnace which was to be replaced by No. 4 B.F. would be blown out after a campaign of only 4 years and 3 months. As No. 4 B.F. was smoothly started up after the blow-in, the blast for No. 1 B.F. had to be somewhat reduced in the month of its quenching (July, 1970), resulting in slightly lower productivity (average productivity in the month of quenching was 1.85 t/m³·day) than that at the time of full operation.

Kukioka No. 4 B.F., which had been in service for 9 years and 8 months since its blow-in in September, 1961, was superannuated one when quenched. Since February, 1971, it nevertheless had been operated at a low fuel ratio of 470 to 480 kg/t-p by means of large quantity heavy oil injection with highly oxygen enriched blast. The average coke ratio and the heavy oil ratio in the month of its quenching (May, 1971) were 394 kg/t-p and 83 kg/t-p, respectively, showing a good operating condition. Operational data and burdens of the two blast furnaces for 3 days preceding their quenching, which can be considered as most relevant to the investigation of their internal states, are given, respectively, in Tables 1 and 2.

Remarkable variances in the operating conditions between the two blast furnaces were found in the top pressure, oxygen enrichment, humidity (seasonal difference), ore/coke ratio, and heavy oil injection. The sinter plus pellet ratio among the data on the burdens was approximately 65% for Hiroyata No. 1 B.F. and approximately 80% for Kukioka No. 4 B.F. Since the sinter ratio was 70% and such slagging substances as limestone and olivine were not added for the latter, the burden condition may be regarded as better than that for the former.

IV. Method of Quenching and Dissection

Higashida No. 5 B.F., Hiroyata No. 1 B.F. and Kukioka No. 4 B.F. were charged with the normal burden up to the time of blast shut-down. After the blast shut-down and gas venting, quenching water was poured into the furnace from several places at the furnace top.

### Table 1. Operating results of Hiroyata No. 1 B.F. and Kukioka No. 4 B.F. during 3 days just before quenching

<table>
<thead>
<tr>
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<th>Kukioka No. 4 B.F. (t/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Volume</td>
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</tr>
<tr>
<td>P/V</td>
<td>Temp. Humid. (°C)</td>
<td>(g/m³)</td>
</tr>
<tr>
<td>O₂</td>
<td>Top press. (g/cm³)</td>
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<tr>
<td>July 20</td>
<td>2</td>
<td>085 2</td>
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<td>21</td>
<td>2</td>
<td>094 3</td>
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<td>22</td>
<td>2</td>
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### Table 2. Operating results of Hiroyata No. 1 B.F. and Kukioka No. 4 B.F. during 3 days just before quenching

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Research Article
The burden was scrapped up to about 1 to 1.5 m deep, leaving a cross part, as shown in Fig. 1, and the vertical sections of which were examined and measured in the two directions. After scraping out of the cross part, steel plates or straw mats were laid over the surface and the surrounding brickwork and scaffold attached to the wall were demolished and transported outside the furnace. The dissection was carried out by thus alternating scraping and brickwork demolishing.

Ore and coke samples weighing 100 kg each were taken out of 9 points on each level (12 levels for Higashida No. 5 B.F., 15 levels for Hirohata No. 1 B.F., and 18 levels for Kukioka No. 4 B.F.). Sampling was made by carefully scraping, the surface of above-mentioned cross part, so that the samples could be taken out uniformly in the vertical direction.

Core samples were taken out by vertically driving the pipes of 30 or 40 cm in diameter and 1.2 to 2.6 m in length into the burden to examine the filling condition and the permeability of burden (23 for Hirohata No. 1 B.F. and 33 for Kukioka No. 4 B.F.).

In addition to the above-mentioned core samples taken out of the hearth, the samples of 1.8 m in width and 2 m in height, were taken out in order to observe the as-quenched structure of the burden. The burden close to the tuyeres was all taken out as distinct samples of 20 cm cubes and 40 cm cubes.

For Higashida No. 5 B.F. and Kukioka No. 4 B.F. of which no iron tapping was conducted prior to quenching, cylindrical samples of 70 mm in diameter and 2 to 3 m in length were taken out by boring both in the vertical and horizontal directions in order to investigate the conditions of the pig iron and slag in the furnace bottom (Kukioka No. 4 B.F.: 17 samples in the vertical direction, 3 in the horizontal direction, and 1 in the slant direction).

V. A General Description on the Internal State of the Furnaces

1. Descent of Burden

The condition of a descending burden differs in detail with the extent of erosion of the furnace wall and the condition of scaffold. In general, however, the following was found common to all the three furnaces. Until the ores melted down, the boundaries between the ore layers and the coke layers remained distinct so that the number of layers could be counted. As the burden descended farther in the furnace, however, the layers became thinner and flatter. Figure 2 shows, as an example, the state of descending burden in Kukioka No. 4 B.F.

Along the furnace wall of Kukioka No. 4 B.F., a mixed layer of ore and coke was found, which had the thickness of 30 to 50 cm at the furnace top but increased in thickness, while it descended, up to 2 m at certain locations in the bosh. A model test was conducted by using a 2-dimensional furnace model of 1/20 scale to investigate the cause of this phenomenon. As a result, it was found that such a mixed layer is formed, as shown in Photo. 1, when the armour plates have fallen off from the furnace throat. It was considered that the softening-melting layers were distributed in the W-shape configuration, because this mixed layer had good permeability as will be explained later in this report.

In the lumpy zone, the size degradation of sinter by the reduction-induced disintegration was severe and lump ores were also disintegrated extensively, while pellets showed little size degradation though their strength decreased markedly in the upper part of the shaft. In comparison of Hirohata No. 1 B.F. with Kukioka No. 4 B.F., it is obvious that the change in the ore size in the radial direction of the furnace was large in the former and relatively small in the lat-
ter. (Refer to Fig. 5 of the 2nd report of this series.) This was due to the different temperature distribution and, consequently, the gas flow distribution in accordance with the configuration of the softening–melting zone in each furnace.

The reduction degree of ores in the lumpy zone was generally low even in consideration of the reoxidation by water quenching, but sharply rose at high temperature region near the softening–melting zone. Hence the distribution of reduction degree formed a configuration corresponding to that of the softening–melting zone. (Refer to Figs. 11 and 12 of the 2nd report of this series.)

2. Distribution of the Softening–Melting Layers

The burden in the furnace undergoes the following series of processes: reduction, softening, melting and dropping into the hearth as pig iron and slag. The ore layers which are in the temperature range between the start of softening and melting down form the softening–melting layers. Accordingly, their structures change continuously from that where ores are lightly attached to each other to a semi-molten state where the metal and slag phases begin to separate from each other.

The discoveries that these softening–melting layers are uniformly distributed corresponding to the temperature distribution pattern in the furnace and that their distribution and their locations in the furnace differ with the operating condition of each blast furnace can be said without exaggeration to be the most outstanding results of this series of dissections. The distribution patterns of softening–melting layers in Higashida No. 5 B.F., Hirohata No. 1 B.F. and Kukioka No. 4 B.F. are shown in Fig. 3.

The precision and accuracy of the distribution of the softening–melting layers in Higashida No. 5 B.F. were far inferior to those of the other two blast furnaces, because the existence of such layers was newly discovered through this first dissection, and moreover, the furnace condition had been unstable with frequent breakages of its tuyeres since about a week before the quenching.

In the case of Hirohata No. 1 B.F., the formation of softening–melting layers started at the position approximately 4 m below the stockline in the center of the furnace at the upper part of the shaft, and the 3rd layer and those existing below that showed a doughnut-like shape as their center parts had molten down. The center holes in the layers enlarged as they descended, while the softening–melting portion also extended radially and almost reached to the furnace wall in the bosh, and all the layers had molten down just above the tuyeres. The thickness of the softening–melting layers was 400 to 500 mm for upper ones and 70 to 100 mm for those near the lowest level. Since the ore layers thus molten down from their center parts as they descended, the melting zone was formed as a cone connecting the inside brims of the softening–melting layers, and was an inverted sharp V-shape as viewed
in the vertical cross-section of the furnace.

On the other hand in Kukioka No. 4 B.F., the formation of the softening–melting layers started at the position 12.5 m below the stockline in the center of the furnace at the lower part of the shaft, considerably lower than that in Hirohata No. 1 B.F. In addition, as mentioned previously, the mixed layer of ore and coke formed along the furnace wall developed into a softening–melting zone of unstratified structure below the lower part of the shaft, thus, as a whole, existing in the shape of the letter W. The smaller thickness of the softening–melting layers of Kukioka No. 4 B.F., as compared with that of the layers of Hirohata No. 1 B.F., was due to a smaller quantity of ore per charge of the former.

It was thus made clear that the softening–melting layers of blast furnaces are distributed either in an inverted V-shape pattern or in a W-shape pattern. The results of the investigation made by Murav’ev, et al.\(^3\) of USSR and those of the investigation on Kawasaki No. 4 B.F. of Nippon Kokan K.K.\(^5\) showed a V-shape distribution pattern of softening–melting layers. The relationship between the distribution of softening–melting layers and the blast furnace operation is an important subject to be studied in the future.

Although the details of the formation and melting down of softening–melting layers will be reported in the 3rd report\(^6\) of this series, the formation temperature was around 1,100°C and the melt-down temperature 1,400°C to 1,500°C. The metal at the time of melt-down contained little Si, about 1% or less C, and 0.1% or less S. The CaO/SiO\(_2\) ratio of melt-down slag was almost equal to the average value of ore materials except the slagging agents (limestone and olivine). The FeO value in slag was considerably higher in some parts inside the softening–melting layers, but reduced to several percents or less at the time of melt-down.

3. Furnace State Close to the Tuyeres

Sufficient investigation on the furnace state close to the tuyeres could not be conducted for Hirohata No. 1 B.F., because the salamander tapping was carried out before quenching. In the case of Kukioka No. 4 B.F., however, neither the salamander tapping from the furnace bottom nor the final tapping was performed in order to preserve the furnace state near the tuyeres.

The furnace state close to the tuyeres differed from tuyere to tuyere as shown in a vertical cross-section near a tuyere and in a horizontal cross-section at the tuyere level in Figs. 4 and 5, respectively. Generally speaking, the cavity at the top of the tuyere is surrounded by coarse coke and then small roundish coke. To the fore of and below the small roundish coke portion there is a dense portion composed of slag, pig iron drops and fine coke of -5 mm size produced possibly in the raceway. From this portion toward the centerline of the furnace, large lumpy coke increases and fine coke decreases gradually.

Judging from the results of the rod test conducted in the course of operation, the range including the portion of small roundish coke mentioned above, namely, the areas indicated as I, II and III in Fig. 4, can be considered as the raceway during the operation. It can also be considered that the coarse coke found in front of the tuyere falls into the raceway from an upper part when the blast is shut down and that the small roundish coke has been fluidized in the raceway. The above conclusions are in good agreement with the condition inside the raceway observed from tuyeres through an endoscope by Greuel, et al.\(^2\) Fur-
thence, the portion densely filled with fine coke, etc., was also observed in the coke combustion model test conducted by Hatano, et al., and that made by the authors. The extension of this portion is closely related to the quality of coke used, posing itself as an important factor greatly influencing the gas flow in the lower part of the furnace.

Taking a view of the horizontal cross-section of the furnace, the raceways are found to exist separately but the state between them varies—coarse coke is found to exist in some of them and dense portion in the others.

As for the changes of the coke properties in the furnace, details will be given in the 4th report of this series.

4. Condition in the Hearth

For Higashida No. 5 B.F. and Kukioka No. 4 B.F., as mentioned before, core boring was performed both vertically and horizontally. Core samples of 70 mm diameter thus taken out were subjected to the investigation on the condition of the hearth.

Coke mass in the hearth invariably had a convex shape, and in the case of Higashida No. 5 B.F., it was altogether floating on the hot metal (Fig. 6 (a)). The coke of Kukioka No. 4 B.F., on the other hand, was found to be floating near the furnace wall but in contact with the brick of the furnace bottom in the center (Fig. 6 (b)). The condition of coke in the hearth, though it is dependent on various factors such as the depth of hearth, the ore/coke ratio of the burden, the magnitude of load on the hearth which may be influenced by the location and the pattern of the softening–melting layers, etc., requires further study, since it is related to stable iron tapping practice and erosion of hearth brick. Incidentally, the void ratio of coke immersed in the hot metal in the hearth was 47 to 55%.

Although the slag composition in the hearth did not show any large difference by locations, the contents of C, S, Si and Ti in the metal near the furnace bottom were significantly high. Particularly, in the area along the periphery of the furnace bottom TiN was found to be precipitated.

VI. Temperature Distribution

1. Methods of Investigating the Temperature Distribution Inside the Blast Furnace

The methods of investigating the temperature distribution inside Hirohata No. 1 B.F. and Kukioka No. 4 B.F. were the tempil pellet method and the coke graphitization measurement method. In addition to these two methods, a method of estimation by the agglomeration degree of the burden was adopted for the latter blast furnace to further support the overall estimation of the inside temperature distribution. Since each method was not sufficient enough to measure the exact temperature, the temperature distribution inside the blast furnace was estimated by putting together the results obtained by various methods.

1. Tempil Pellet Method

According to this method, 10 to 12 pellets of different substances which melt at specified temperatures (tempil pellets) were encased in a graphite capsule with a screw cap, as shown in Photo. 2, charged into a furnace from the furnace top at certain time intervals before the quenching, recovered from the furnace after dissection, and investigated. Tempil pellets of approximately 20 different melting points in the range of 200° to 1600°C were selected.

The greatest disadvantage of this method is that the temperatures of exact given locations are not always obtainable because the capsules are dumped into the furnace with the burden from the furnace top. In addition, the experimental errors due to the influence of atmosphere grow larger at high temperatures over 1400°C, and in the case that quenching water has entered into the capsules care has to be taken to distinguish the solution by water from the thermal melting of pellets.

2. Coke Graphitization Measurement Method

This method is based on the measurement of the graphitization degree of coke inside the furnace aimed at estimating the coke temperature, since the graphitization progresses as coke is heated and the graphitization degree is mainly influenced by temperature at which coke has been held. As a means of measuring the graphitization degree of coke, both the measurement of the half-band width of (002) plane interval peak by X-ray diffraction and that of electric conductivity were adopted. Under these methods, calibration curves had been prepared with the standard samples made by heat-treating the burden coke, and the measured values of coke inside the furnace were compared with the curves to obtain the coke temperatures. The calibration curves for Kukioka No. 4 B.F. are shown in Fig. 7.

Although it is possible by this method to know the coke temperature at a given location in the furnace, this method cannot theoretically be used for the esti-
3. The Sintering Temperature Distribution inside the Furnace

When the temperature distribution inside the furnace is known, the temperature at a desired location can be estimated by the test method shown in Fig. 8. The samples taken out of the furnace were subjected to the tumbler test to obtain the calibration curves, shown in Fig. 8. The samples were compared with those of the curve shown in Fig. 8 to estimate the temperatures. Because the exact simulation of the loading and reducing conditions inside the furnace is impossible, this method should be considered as the one giving a rough estimation.

2. Estimated Temperature Distributions for Kukioka No. 4 B.F.

The estimated temperature distribution inside Kukioka No. 4 B.F., derived from the generalization of all the measured values by the use of the methods so far described, and that inside Hirohata No. 1 B.F., obtained by the application of the temper-pellet method and the coke graphitization measurement method, are shown in Figs. 9 (a) and (b), respectively. In both cases the temperature distribution profile well matches the profile of softening-melting layers.

Although temperature rose sharply in the center zone of Hirohata No. 1 B.F. arriving rapidly at the softening-melting condition, the general trend common to both blast furnaces shows that temperature rises comparatively fast to about 700°C, then gradually to about 1100°C, and again rises sharply near the softening-melting layers.

It has been said concerning the temperature distribution in the vertical direction of a blast furnace that a uniform temperature zone called "thermal reserve zone" exists because of the offsetting actions between the exothermic reaction of the reduction from FeO to M-Fe and the endothermic reaction of carbon solution. As a result of testing with an experimental blast furnace having a small heat content ratio, a typical reserve zone was ascertained between 1000°C and 1100°C. In the cases of Hirohata No. 1 B.F. and Kukioka No. 4 B.F., the temperature gradient in the range of 700°C to 1100°C was small particularly in the peripheral zone of the former and in the intermediate zone of the latter. Since in these zones the reduction progresses slowly, it is doubtful that these zones are so-called thermal reserve zones produced by the offsetting functions of two reactions. Because these zones have a relatively low gas velocity in the lumpy zone, as will be described later in this report, and are the zones with a large heat content ratio, it will be more appropriate to regard them as it is showing the characteristics of a countercurrent heat-exchanging zone with a small temperature difference between gas and solid.

\[
* \text{heat content ratio} = \frac{\text{heat content of burden}}{\text{heat content of gas}}
\]
VII. Gas Flow Distribution

1. Estimation of the Gas Velocity Distribution Using Core Samples

The gas flow distribution inside the furnace can be imagined from the distribution of reduction degrees and that of such elements (S, alkali and Zn) which are carried away by gas, as will be described in detail in the 2nd report of this series, in addition to the distribution of the softening–melting layers and that of temperature, described in the preceding section. In order to endorse the estimation derived from these distributions, the gas velocity distribution in the vertical direction of the furnace was calculated using the permeability resistance coefficients (in the vertical direction) at various locations inside the furnace, together with the temperature distribution and the estimated gas composition.

The permeability resistance coefficients were obtained from the relationship between the pressure drop and the superficial velocity measured by flowing air through the core samples taken out at the time of dissection. The following relation was established between the pressure drop \((\Delta P/\Delta L)\) and the superficial velocity \((U_s)\) as long as the latter was 0.5 to 0.6 m/sec or higher, as in the case of an ordinary packed-bed,

\[
\Delta P/\Delta L = KU_s^{0.64}
\]

where, \(K\) is the permeability resistance coefficient determined by the physical properties of the fluid and the size and shape of the burden materials. From this relation the permeability resistance coefficient of each core sample was obtained. If the relation expressed by Eq. (1) is applicable to given locations inside the furnace, then the velocity at each location can be expressed by the following equation.

\[
U_{T,j} = [(\Delta P/\Delta L)_{T,j} \cdot (1/K_{ji})]^{0.64}
\]

Although \(K_{ji}\) actually changes with temperature, it is posited here as negligible. If the condition that \((\Delta P/\Delta L)_{T,j}\) is constant in the radial direction of the furnace can be established, the \((\Delta P/\Delta L)_{T_{ji}}\) can be obtained by the following equation (3), and the velocity, \(U_{T,j}\), at each location can be calculated using the above equation (2).

\[
(\Delta P/\Delta L)_{T,j} = (\bar{T}_j + 273) / 273 \cdot [1/(1 + P_j)] \cdot U_{i,j} \cdot Z_j - 1.64
\]

Further, this calculation is repeated until the following conditions are satisfied.

1. \(\bar{T}_j\) (by the formula for the heat balance in the upper part of the shaft) = \(\bar{T}_j\) (by the estimated value of temperature distribution inside the furnace)

2. \(Q_m = \Sigma (Z_{ji} \cdot U_{n,ji})\)

The distribution of gas velocity in the furnace obtained as a result of the above calculation is shown in Fig. 10. In the lower part of the shaft, the gas flow near the centerline of the furnace is fast, \(i.e.,\), 7 to 9 m/sec, but is slow, 2 to 4 m/sec, near the softening–melting layers. In the upper part of the shaft, the gas flow is generally slow because of low gas temperature, but becomes faster in the center part and the peripheral zone of the furnace than that in the intermediate zone. Hirohata No. 1 B.F., as compared with Kukioka No. 4 B.F., had a faster center flow while the other showed a faster peripheral flow. It can be said that these gas flow calculations give the relative gas flow distributions fairly well, though these calculations include some inevitable uncertainties relating to the determination of the permeability resistance coefficients, such as the burden contraction in the course of water quenching, absence of any melt...
in the dropping zone, impact of pipe driving, etc., and problems with the calculating method which takes into account only the vertical rising flow and neglects any cross flow of gas.

2. Gas Flow Distribution and Blast Furnace Operation

Figure 11 shows the furnace top gas temperature and the CO gas utilization rate, \( \tau_{CO} \), measured immediately before the quenching of both Hirohata No. 1 B.F. and Kukioka No. 4 B.F., as examples of operating data corresponding to the results of the dissection. The operating data of both blast furnaces well correspond to the estimated gas velocity distribution inside the furnace. Hirohata No. 1 B.F. was generally of the center flow type with a very high furnace top gas temperature at the center, but low in the intermediate zone and high again in the peripheral zone of the furnace. The furnace top gas distribution of Kukioka No. 4 B.F., on the other hand, shows a comparatively flat curve, indicating that the gas flow can be regarded as the peripheral flow type if the cross-sectional area ratio in the radial direction of the furnace is taken into consideration.

The operational factors which influence the furnace top gas distribution of both blast furnaces are: (1) charging sequence, (2) ore/coke ratio, and (3) coke base.

(1) Charging sequence: The charging sequence of CC ↓ CO ↓ OO ↓ was adopted for Hirohata No. 1 B.F. and that of CC ↓ OO ↓ for Kukioka No. 4 B.F. The mixed charging of CO ↓ for Hirohata No. 1 B.F. tended to get coke to flow into the center part and segregate coarse coke, and therefore the growth of center flow was promoted.

(2) Ore/coke ratio: The ore/coke ratio for Hirohata No. 1 B.F. was approximately 3.0 and that for Kukioka No. 4 B.F. was approximately 4.0. Generally, as the ore/coke ratio increases the ore layer becomes thick, and, at the same time, the ore/coke ratio in the center zone becomes larger than that in the peripheral zone, because the angle of repose of ore is less than that of coke. This is one of the factors responsible for promoting the peripheral gas flow of Kukioka No. 4 B.F.

(3) Coke base: The coke base was 12.5 t for Hirohata No. 1 B.F. and 7.2 t for Kukioka No. 4 B.F., making the average coke layer thickness larger for the former than the latter even if the greater inner volume of the former furnace is taken into consideration. As a general principle, if the coke base is increased, the ore/coke ratio tends to be equalized in the radial direction of the furnace. Hence, it is difficult to believe that the difference in the coke base between the two blast furnaces directly influenced their gas flow distributions.

Though the operational factors were taken into consideration, yet the presence of the mixed layer along the wall of Kukioka No. 4 B.F. seems to have had a greater additional effect.

VIII. Discussions

By way of summing up the results of the dissection so far described in the foregoing sections, the authors have come to the conclusion that the function of a blast furnace is distinctly separated into the upper and the lower sections by the softening-melting zone as the boundary. In the upper section there are the solid and the gas phases while in the lower section the three phases of solid, liquid and gas are coexisting, and the solid phase consists solely of coke. After the results of dissections, despite the ores in the center part of softening-melting layers have already molten down, yet no trace of sinking of the center is observed. This fact indicates that the packed state of coke in the dropping zone is comparatively loose and is therefore contributing to good gas and liquid permeabilities in this zone.

If the furnace is simulated using a model, the softening-melting layers would constitute gas distributing plates, and the gas generated in the raceway rises through the highly permeable coke bed of the dropping zone, and passes through the coke slits formed between the softening-melting layers into the lumpy zone. In the lumpy zone, the gas ascends with a velocity distribution influenced by the lateral permeability resistance distribution caused by the difference of the ore/coke ratio at the time of charging and the ore disintegration due to the reduction in the furnace. A large part of the total furnace pressure drop can be considered to take place when the gas passes through the softening-melting zone.

Therefore, in such a blast furnace as Hirohata No. 1 B.F. which had the softening-melting layers distributed widely in an inverted V-shape from the upper part of the shaft down to a level close to the tuyeres, the total area of coke slits is large, and hence it is advantageous from the viewpoint of permeability. With this shape of softening-melting layers, the \( \tau_{CO} \) in the center part of the furnace is low, and therefore a high productivity coefficient can be expected but the fuel ratio becomes somewhat high. In the case of Kukioka No. 4 B.F., the softening-melting layers were distributed in the lower part of the furnace, generally
improving the \( \gamma_{\text{SO}} \) and, in turn, lowering the fuel ratio. From the viewpoint of permeability, however, this furnace was slightly inferior.

Although in this description the softening–melting layer is regarded as a kind of louvre which does not let the gas permeate, the permeability actually increases continuously from zero at the inside semi-molten part to the peripheral lumpy zone. Consequently, if a burden of low softening temperature is used, the part with high permeability resistance widens, causing a large pressure drop.

From the viewpoint of heat, the high temperature gas generated in front of the tuyeres consumes quite a large amount of heat in melting the lowest softening–melting layers, and is distributed into coke slits while melting down the edges of subsequent softening–melting layers above it. Temperature fall, though relatively small in the dropping zone, is rapid in and around the softening–melting zone, showing that an active reaction of carbon solution is occurring in parallel with the reduction around this zone. Assuming that the sensible heat content of coke bed in the dropping zone indicates the thermal stores in blast furnace, the condition of Hirohata No. 1 B.F. which had considerably large volume of dropping zone was that of plentiful heat reserve, on the other hand, the low fuel ratio operation such as in Kukioka No. 4 B.F. was that with little heat reserve.

As for the reduction aspect, no definite statement can be made because of the problems inherent in dissection of a blast furnace such as the reoxidation at the time of water-quenching, progress of reduction after shunt-down of blast (e.g., Si reduction), reliability of melt sampling locations, etc. A generalization of the data available, however, shows that reduction of ores is comparatively slow in the upper and middle parts of the lumpy zone, but progresses rapidly near and in the softening–melting zone. The Si reduction does not occur down to the softening–melting zone but mostly finishes before melt reaches the tuyeres. Also, the desulfurization of hot metal seems to be almost completed before it reaches the tuyeres.

The importance of the softening–melting layers in the blast furnace operation has been clarified in the foregoing sections of this report. Although the main factors controlling the location and shape of the distribution of softening–melting layers are, of course, the ore/coke ratio and the furnace top distribution of the burden, the combustion condition in front of the tuyeres certainly plays an influential role. Namely, the depth and shape of raceway constitute the factors influencing the location and shape of the lower softening–melting layers. The optimum distribution of softening–melting layers will, of course, vary with the blast furnace operating policies adopted, and therefore the development of appropriate control techniques at the furnace top and tuyeres are earnestly awaited.

**IX. Summary**

Much information on the internal state of blast furnaces has been obtained as a result of these dissections of commercial blast furnaces. The dissections, however, were no more than static investigations, and the authors felt the need for different methods of investigating the dynamic reactions taking place in an operating blast furnaces. The greatest achievement of this series of dissections is the discovery of the uniform existence of the softening–melting layers, but the fact that they differ widely in the location and distribution under different operating conditions points out the enormous difficulty of blast furnace operation. Although remarkable progress has been made since the time when the blast furnace used to be regarded as a black box, the methods for detecting the internal state of the furnace which changes momentarily are not yet sufficient, and the operating techniques which can fully utilize such effective methods are yet to be developed. In this respect, the authors shall be happy if their reports on this series of dissections contribute to the development of ironmaking technology.

**Nomenclature**

\[ P: \text{ Static pressure [kg/m}^2\text{]} \]
\[ Z: \text{ Cross-sectional area of layer [m}^2\text{]} \]
\[ L: \text{ Thickness of layer [m]} \]
\[ T: \text{ Gas temperature [°C]} \]
\[ U: \text{ Superficial linear velocity of gas in a column [m/sec]} \]
\[ Q: \text{ Gas flow inside the furnace [Nm}^3\text{/sec]} \]
\[ K: \text{ Permeability resistance coefficient} \]

**Subscripts**

\[ i: \text{ Location in the radial direction of the furnace} \]
\[ j: \text{ Location in the vertical direction of the furnace} \]
\[ T: \text{ Value at temperature inside the furnace} \]
\[ o: \text{ Value under the standard condition} \]

**REFERENCES**