HIGH-PRODUCTION BLAST FURNACE OPERATION WITH HIGH-RATE PULVERIZED COAL INJECTION AND ANALYSIS OF SAMPLES TAKEN FROM IT

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SUMMARY: The following findings were derived from the analysis of high-production blast furnace operation with a high pulverized coal injection rate:

(1) The improvement of sintered ore quality and the adoption of a new type of chute with good burden distribution control capability providing an ore inflow control charging pattern resulted in the formation of an inversely V-shaped cohesive zone with an intensified central gas flow even in operations with the ore-to-coke ratio above 5.0. These improvements stabilized the gas flow and significantly improved the gas permeability and the packed structure of the burden in the lower part of the blast furnace.

(2) Analysis of the state of metallic iron and slag composition in the samples collected from the tuyere during shutdown revealed that good reduction was achieved even in high-production operations with a high pulverized coal injection rate.

(3) To ensure stable blast-furnace operation over a long period of time, it is necessary to maintain good gas and fluid permeabilities in the packed burden bed in the lower part of the blast furnace in consideration of the effect of the ash from pulverized coal.

KEYWORDS: blast furnace, pulverized coal injection, high productivity

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1. Introduction

The properties of iron ores have great effects on the operating condition, particularly the reducibility and permeability of the furnace burden, of blast furnaces. Many technical developments have been made toward the improvement of furnace burden properties. They include sizing and mixing of ore lumps, as a starter, preparation of acid sinter by sintering ore fines, self-fluxing sinter by adding limestone to sinter feed, acid pellets and self-fluxing pellets. Among others, self-fluxing sinter can so effectively improve the reducibility and permeability of the furnace burden that it now accounts for 70 to 80 percent of the materials charged into blast furnaces in Japan.

As the importance of the properties of sintered ores gains increasing recognition, research and development to further improve their reducibility, reduction degradation, cold strength (shatter index and tumbler index) and other properties have been continued. For example, a technique was developed to control reducibility, reduction degradation and cold strength by adding to the sinter feed the fluxes (such as limestone, silica and serpentine). They used to be fed in lump form for achieving composition control of the final slag discharged through the tapholes of blast furnaces to facilitate the slagging of gangue materials during melting of the burden. This technique has resulted in producing sintered ores containing substantial amounts of SiO_2, MgO and CaO.

Studies of dissected blast furnaces revealed the presence of the cohesive zone in the temperature region of 1000 to 1400°C. Since the cohesive zone became known to have a great effect on the reducibility and permeability of the blast furnace burden, the properties of sintered ores, particularly their reducibility and permeability, in the high-temperature region above 1000°C has been attracting attention. Low- SiO_2 sintered ores have been manufactured on a commercial scale [1-3]. As blast furnace operations with much pulverized coal injection become popular and the importance of the reducibility of sintered ores and permeability in the high-temperature region gains increasing recognition, commercial production of sintered ores containing less than 5 percent SiO_2 is attempted [4,5].

Coke, which is another charging material to the blast furnace, also plays an important role in the operation of blast furnaces. Coke serves as a reducing agent, heat source and medium to facilitate the passage of gas and molten materials. Proper control of coke properties is vital to the assurance of stable furnace operation and supply of low cost pig iron. Many technologies have been developed to control and improve coke properties. Such technologies include coke quality prescribing, coal blending (for attaining the prescribed coke quality) and coke oven operating techniques. The quality improvement of blast furnace coke has gone through several phases, such as the adoption of the drum index (DI) to control coke strength at room temperatures, improvement of the DI to meet the increase in blast furnace capacity, adoption of the CSR (coke strength after reaction) index, performance of blast furnace operation tests to separate the effects of the DI and CSR, and improvement of the CSR. As the pulverized coal rate increased, the ratio of fines in lower part of a blast furnace increased and the permeability in a blast furnace was impaired, some attempts have been made to reduce the quantity of fine and improve permeability by improving the DI of coke.

While the properties of blast furnace burdens have been improved as described above, one of today's most important challenges is the stable furnace operation with a high-rate of pulverized coal. Furnace operation with high-rate pulverized coal injection aims at lowering the cost of pig iron by increasing the use of non-coking coal in the short term and prolongation of the life of coke ovens by reducing the blast-furnace coke rate in the long term.

Operation with high-rate pulverized coal injection has been achieved through the improvements in blast furnace burden (such as the improvement of coke DI and sinter reducibility by reducing the content of alumina in sintered ores) on several blast furnaces in Japan [6-9], as in 1993 on the No. 3 blast furnace at Kimitsu Works of Nippon Steel Corporation. To lower the cost of pig iron, however, it is necessary to achieve high-production blast furnace operation with high-rate pulverized coal injection and a low fuel rate without requiring costly quality improvement of raw materials and fuels.

The No. 2 blast furnace at Muroran Works of Hokkai Iron and Coke Corporation (hereinafter referred to Muroran No. 2 blast furnace), which has been in operation for over ten years, has achieved high-production operation with high-rate pulverized coal injection and a low fuel rate by improving the quality of sintered ore and burden distribution control without decreasing the content of alumina in sintered ores. This paper deals with the main measures taken for the Muroran No. 2 blast furnace, results of operation, findings from the examination of samples taken from the furnace and tasks for the future.

2. Problems and Solutions for High-production Blast Furnace Operation with High-rate Pulverized coal Injection

Fig. 1 shows the problems and solutions with high-production blast furnace operation with high-rate pulverized coal injection. In the upper part of the blast furnace, the ore-to-coke rate, which is the ratio of ore to coke by weight, will become high and an increase in the gas flow rate will result in lower burden permeability. In the lower part of the blast furnace, increased burden descent speed, occurrence of local flooding, hang-down of the cohesive zone caused by a localized increase in the heat flow ratio, descent of incompletely reduced ore, scaffolding, and coke embrittlement through increased reaction between coke and melt will reduced the gas and fluid permeability of the burden.

To avoid these phenomena, an inversely V-shaped cohesive zone was formed to stabilize the gas flow and control the descent of unreduced iron ore. To improve the permeability in the upper part of the furnace, oxygen concentration in the blast was increased to prevent a drop in the heat flow ratio and a new type of chute [10] was adopted to increase the gas flow in the central part of the furnace. To improve the permeability in the lower part of the furnace, the properties and strength of sintered ore were improved by reducing the thickness of ore layers and the contents of SiO_2 and MgO [11,12].

The air ratio with a targeted pulverized coal injection rate at approximately 190 kg per ton was on the order of 0.8. As this air ratio was considered to present no problem [13], the conventional single lance was used for pulverized coal injection.

2.1. Improvement of Permeability in the Upper Part of the Blast Furnace

With a view to controlling the horizontal speed and stabilizing the trajectory of the burden, the Muroran No. 2 blast furnace adopted a new type of chute equipped with a trajectory control plate at its tip. As compared with the conventional chute, the new type of chute reduces the horizontal velocity component of the burden, thus allowing the burden to fall vertically with greater ease. This, in turn, produces a smooth flow of the burden toward the center of the furnace, which promotes segregation of the burden and allows larger materials to gather in the center of the furnace (Fig. 2). As the new type of chute controls the sideslip of the burden toward the furnace wall, the inclination angle of the burden inside from the charging point is substantially equal to the angle outside from the charging point and the angle of inclination varies less from charging point. The new type of chute has a greater ability than the conventional chute to control the burden profile, irrespective of the point of charging.

In the blast furnace operation with high -rate pulverized coal injection, the ore to coke ratio exceeds 5. With such a high ore to coke ratio, the ores flowing into the center of the furnace will reduce the gas flow in that region. To avoid this phenomenon, the new type of chute was used to promote the segregation of burden particles and control the inflow of ores to the center of the furnace by adjustment of the charging pattern.

For the prevention of the descent of incompletely reduced ores and scaffolding by the localized increase in the heat flow ratio, it is necessary to avoid a localized increase in the ore to coke ratio. It is particularly important to ensure that the ore to coke ratio does not become excessively high in the peripheral region including the neighborhood of the furnace wall. The burden charging pattern of the Muroran No. 2 blast furnace was adjusted so that the relative ore to coke ratio, which is the ratio of the ore-to-coke ratio in the peripheral region (sounding position) to that of the whole burden, becomes approximately 1.0 or less in the process in which the ore to coke ratio of the whole burden is increased by increasing the pulverized coal rate (Fig. 3).

2.2. Improvement of Permeability and Reducibility in the Lower Part of the Blast Furnace

It was confirmed by way of experiments [14,15] that increasing the thickness of ore layer impair the reducibility and permeability of the burden in the lower part of the blast furnace. Therefore, the coke base (CB which is the quantity of coke per charge) of the Muroran No. 2 blast furnace was reduced by keeping the ore base (OB which is the quantity of iron ore per charge) fixed (Fig. 4). However, the permeability resistance index (K value) in the upper part of the blast furnace rose when the mean thickness of lump coke in the belly region was reduced to 180 mm. Therefore the mean thickness was increased to 190 mm, with the result that the K value in the upper part of the furnace dropped from 1.8 to 1.6 (Fig. 4). This suggests that, to maintain adequate permeability, the mean thickness of lump coke layers in the belly of the furnace must be approximately 190 mm or above.

In a blast furnace operated with a high production rate and a high pulverized coal injection rate, as shown in Fig. 1, an increase in the burden descent rate, a delay in reduction and the hang-down of the base of the cohesive zone are likely to occur in the lower part of the blast furnace. These phenomena, in conjunction with the instability of gas flow and burden descent in the upper part of the furnace, will promote the descent of incompletely reduced ores to the lower part. The descent of such ores will impair the flow of gas and melt in the lower part of the blast furnace and lower the temperature in the deadman. Therefore, the high temperature properties of sintered ores were improved by reducing the contents of SiO_2 and MgO [11,12] and their cold strength by reducing the content of MgO while maintaining the percentage of alumina in a fixed range of 1.85 to 1.90 percent [12].

More specifically, the contents of SiO_2 and MgO in sintered ores were lowered by decreasing the quantity of dunite addition (SiO_2 = 42.1 % and MgO = 47.8 %) from 0.7 % to 0 % and the quantity of nickel slag from 1.4 % to 1.0% in the middle of August. As a result of this, the contents of SiO_2 and MgO decreased from 5.5 % to 5.1 % and from 1.2 % to 1.0 %, respectively. Compared with the base period of early January, the reduction index (RI) and cold strength (TI) increased by 0.6 to 2.2 points and 0.4 to 1.1 points, respectively, and the gas permeability in the high temperature region was improved. The improvement in cold strength despite the decreased SiO_2 content may probably be attributable to the lowering of the melting point and the increase in the quantity of melt induced by the decrease in the content of MgO. Although the reduced contents of SiO_2 and MgO raised the reduction degradation index (RDI) of sintered ores from 33 % to approximately 40 %, the gas flow in the shaft section of the blast furnace remained unchanged. The target values of both DI and CSR of coke were not changed. With lump dunite charged from the furnace top for adjustment of slag composition (alumina and magnesia), the slag volume was approximately 310 kg per ton.

3. Operation Results and In-furnace Evaluation

Table 1 shows the operating data for the Muroran No. 2 blast furnace during its typical operation periods. The pulverized coal rate was started to be increased in April when the lowering of SiO_2 and MgO contents in sintered ores was started. The pulverized coal rate averaged at a little less than 170 kg per ton through May. The rate rose to 176 kg per ton in late November and a little under 190 kg per ton in early December and averaged at 182 kg per ton throughout December.

The productivity leveled off at approximately 2.2 tons per day per cubic meter of the furnace capacity except the shutdown. The oxygen enrichment of the blast was kept to a minimum that will permit maintaining the combustibility of pulverized coal and the lower-limit frame temperature of 2100°C essential for the assuring of good heat transfer to the lower part of the furnace. Under the influence of the lowering fuel rate, the air ratio dropped to the order of 0.80 in early December.

Fig. 5 shows the data collected from the upper part of the shaft by the sensing probe before and after the application of sintered ore quality improvement in April and charging pattern adjustment, with a view to controlling the inflow of ores, in late June. Because of the above measures, the probe detected a drop in the utilization rate of gas and an increase in temperature in the center region, which indicated the intensification of the central gas flow, in late November. The intensified central gas flow, substantial increase in the gas utilization rate and temperature drop in the middle region suggested that an inversely V-shaped cohesive zone has been formed. A presumption of the in-furnace condition based on a two-dimensional overall furnace model indicates that the inversely V-shaped cohesive zone is narrow in width, as shown in Fig. 6. It is presumed that the formation of this narrow inversely V-shaped cohesive zone stabilized the flow of gas, reduced the descent of incompletely reduced iron ores, and decreased solution loss carbon (SLC), as shown in Table 1.

Fig. 7 shows the relationship between the ore-to-coke ratio and the permeability resistance index (K value). The K value with the same ore to coke ratio dropped significantly in both lower and upper parts of the blast furnace. First, replacement of the conventional chute with the new type of chute lowered the K value. Lowering of the contents of SiO_2 and MgO and the control of ore inflow lowered the K value further. The three improvements mentioned above lowered the K value more greatly in the lower part of the blast furnace than in the upper part. In the upper part of the blast furnace, the formation of the inversely V-shaped cohesive zone had a great effect on the stabilization of the gas flow. In the lower part of the blast furnace, lowering the SiO_2 and MgO contents in sintered ores improved the strength and other properties of the burden at high temperatures. In addition, the decreased descent of incompletely reduced iron ores improved the packed bed structure in the surface of the deadman (the region between 1.5 and 3 m away from the nose of the tuyeres) by reducing the ratio of fine under 3 mm and metal-slag holdup.

4. Analysis Results of Tuyere Samples

In blast furnace operations with such a high production rate and high pulverized coal injection rate as will raise the ore to coke ratio to above 5, inhibition of smooth reduction and generation and buildup of fine particles are likely to occur. To determine their relationship, samples collected from the blast furnace at the tuyere level during a shutdown (hereinafter refer to tuyere sample) were subjected to close inspection for the fine ratio and holdup.

4.1. Evaluation of the Packed Bed Structure from the Viewpoint of Incompletely Melted Burden Holdup

Fig. 8 shows how the tuyere samples were classified[16]. Samples under 3mm in size are called fine. The leftover obtained by removing lump coke from the samples over 3 mm in size was classified as the holdup. The holdup was divided into the granular holdup (metal and slag), indefinitely shaped holdup and incompletely melted holdup. The following discusses the state of reduction of the incompletely melted holdup that is closely related to the stability of the gas flow and the descent of the incompletely reduced ores and the fine that influences gas and fluid permeabilities.

Fig. 9 shows the cross sections of the incompletely melted holdups observed under the microscope at time 1 (PCR = 157 kg/t) and time 2 (PCR = 190 kg/t) before and after the improvement of sintered ore quality and the adoption of the ore inflow control charging pattern.

While all particles were well reduced and few iron oxides were found, the state of metallic iron varied among individual samples and particles. Therefore, the state of metallic iron was divided into four types as given in Fig. 10 and the state of reduction in the lower part of the blast furnace at the two points of time was evaluated. Fig. 10 shows the incompletely melted holdup sampled from a point 2.3 m away from the nose of the tuyeres and classified according to the state of metallic iron. At time 2 the blast furnace was operated with a higher pulverized coal rate (190 kg/t) and a higher ore to coke ratio (5.0) than at time 1. Even so, the percentage of type A with little coalescence in the solid-phase reduction state was much lower than in the sample collected at time 1 and that of type D with advanced coalescence and separation higher. This seems to indicate that adequately reduced sintered ore allowed assimilation and separation to proceed.

It is presumed that the favorable reduction in the lower part of the blast furnace resulted from the improvement of sintered ore quality (an increase in TI and RI) started in April and the intensification of the central gas flow by the adoption of the ore inflow control charging pattern in late June that led to permeability improvement and gas flow stabilization.

4.2. Evaluation of the Packed Bed Structure Based on the Fine Structure

Fig. 11 shows the radial distribution of the CaO to SiO_2 ratio (basicity) in the slags in the fine under 1 mm at the tuyere level in the blast furnace. The basicity in the slags in the fine under 1 mm was found to increase from the nose of tuyere to the center of the blast furnace. This indicates that the ash resulting from the combustion of coke and pulverized coal is prevented from moving toward the center of the furnace being trapped by the melt or coke and flowed up by the gas stream. The gradient of ascent of the basicity toward the center of the blast furnace was greater in operation with a high PCR (time 2) than in operation with a low PCR (time 1). This indicates that the ash of pulverized coal is less movable toward the furnace center but more movable upward than the ash of coke.

Fig. 12 shows the radial distribution of the basicity in the dripping slag at the tuyere level in the blast furnace. As in the fine under 1 mm, basicity in the dripping slag rose from the nose of the tuyeres toward the center of the blast furnace. The basicity in the neighborhood of the tuyeres at time 2 (PCR = 190 kg/t) was approximately 0.2 lower than that at time 1 (PCR = 157 kg/t). This indicates that the ash of pulverized coal influences the radial distribution of the composition of the dripping slag at the tuyere level in the blast furnace.

The difference in the radial distribution of the slag composition at the tuyere level in operations with different pulverized coal injection rates is due to the difference in the behavior of the ash of coke and that of pulverized coal. That is, the ash of pulverized coal is less movable in the direction of the radius and more movable upward than the ash of coke. By solution loss reactions, coke becomes smaller as it descends through the high-temperature region in the lower part of the blast furnace. The ash exposed during this shrinking process in which the burden descends by the hour comes in contact and assimilates with the dripping slag. In the still higher-temperature region near the raceway, the ash of coke volatilizes, ascends and reacts with the dripping slag. With the ash of coke, the percentage of ash that comes in contact and reacts with the dripping slag before reaching at the tuyere level is not small and the reaction region is great. By comparison, the ash of pulverized coal move upward in conjunction with gas by the second and then comes in contact and reacts with the dripping slag. Thus, the region of reaction between the ash of pulverized coal and dripping slag is smaller (mainly at the periphery zone) than that for the ash of coke. Therefore, it is presumed that the ash of pulverized coal has a greater influence on the radial distribution of the composition of the dripping slag.

In operations with high pulverized coal injection rate, the viscosity of the fine under 1 mm in the surface of the deadman may increase by the influence of the ash of pulverized coal containing more alumina and less lime. It is presumed that the high-viscosity fine under 1 mm and the dripping slag with a high basicity impairs the gas and fluid permeabilities at the surface of the deadman, increases the holdup of the dripping slag, and lowers the temperature of the deadman. To ensure long stable blast furnace operation with high pulverized coal injection rate, it is necessary to control the generation of coke fine and unburnt char and prevent the impairment of the gas and fluid permeabilities at the surface of the deadman caused by the ash of pulverized coal.

5. Conclusions

The following findings were derived from the analysis of high-production blast furnace operation with a high pulverized coal injection rate:

(1) The improvement of sintered ore quality and the adoption of a new type of chute with good burden distribution control capability providing an ore inflow control charging pattern resulted in the formation of an inversely V-shaped cohesive zone with an intensified central gas flow even in operations with the ore-to-coke ratio above 5.0. These improvements stabilized the gas flow and significantly improved the gas permeability and the packed structure of the burden in the lower part of the blast furnace.

(2) Analysis of the state of metallic iron and slag composition in the tuyere samples revealed that good reduction was achieved even in high-production operations with a high pulverized coal injection rate.

(3) To ensure stable blast-furnace operation over a long period of time, it is necessary to maintain good gas and fluid permeabilities in the packed burden bed in the lower part of the blast furnace. To achieve this goal, it is necessary to not only control the generation of coke fine and unburnt char but also prevent the impairment of the gas and fluid permeability in the surface of the deadman caused by the ash of pulverized coal.

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Table.1 Operation results in Muroran No.2 BF(98 Jan.–Dec.).

	1998 ▽	▼				
	Jan.1–10	May	July21–31	Nov.21–30	Dec.1–10	Dec.
Productivity (t/d/m^3)	2.15	2.15	2.19	2.23	2.16	2.17
Fuel rate (kg/t)	522.2	511.9	505.9	496.8	509.6	511.8
PCR (kg/t)	144.8	169.8	164.1	176.2	189.3	182.3
O/C (–)	4.27	4.70	4.75	5.04	5.07	4.97
Vb (Nm^3/min)	3669	3745	3716	3610	3685	3514
OB (t/ch)	56.0	56.0	56.0	56.3	57.3	56.8
CB (t/ch)	13.1	11.9	11.8	11.2	11.2	11.4
O_2–enrichment (%)	2.44	2.47	2.92	2.55	2.03	2.37
Air ratio (–)	1.10	0.99	1.03	0.89	0.85	0.91
Tf (°C)	2176	2145	2135	2128	2095	2122
η co (%)	50.2	49.8	50.3	50.4	49.3	49.6
SLC (kg/t)	91.7	90.0	85.1	88.6	89.4	87.9
Total K–value $(G/cm^2)^2/(Nm^3/min)^{1.7}$	3.88	4.06	4.17	3.93	4.00	4.00
Slag volume (kg/t)	298	307	312	306	308	309
Slag Al_2O_3 (%)	15.14	15.57	15.31	15.77	15.83	15.88
Heat flux at hearth(kcal/h/m^2)	1222	935	1081	2809	2193	2120
Sinter SiO_2 (%)	5.52	5.24	5.30	5.11	5.11	5.10
Sinter MgO (%)	1.22	0.95	1.03	1.02	0.96	0.99
Sinter Al_2O_3 (%)	1.85	1.87	1.88	1.88	1.91	1.90
Sinter RI (%)	65.6	66.8	67.8	64.6	66.2	66.6
Sinter S–value (kgf·min/cm)	8.30	6.95	6.44	–	7.07	–
Sinter RDI (%)	33.7	37.5	39.1	40.0	40.1	38.8
Sinter TI (%)	73.9	75.0	73.8	74.3	74.3	74.7

▽ : Low–SiO_2 & MgO sinter, ▼ : Gas flow centralization based on charging pattern adjustment

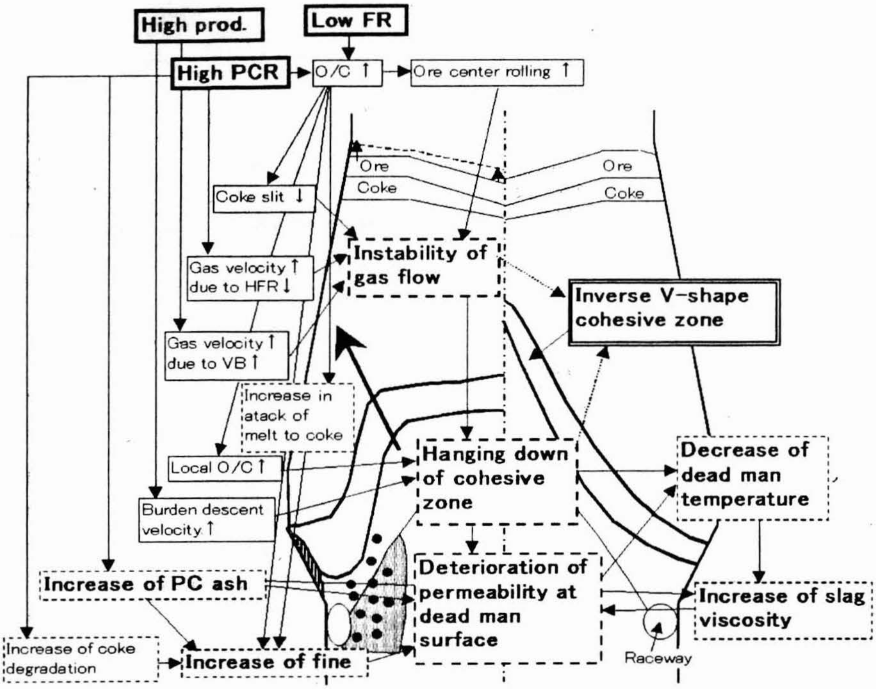


Fig.1 Problems under high PCR and high O/C operation.

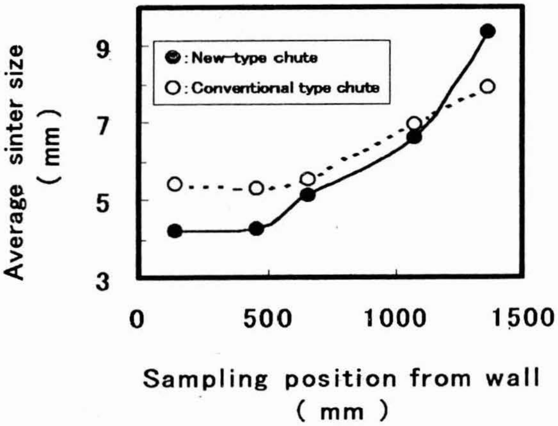


Fig.2 Particle size distribution of sinter in 1/3 scale charging model.

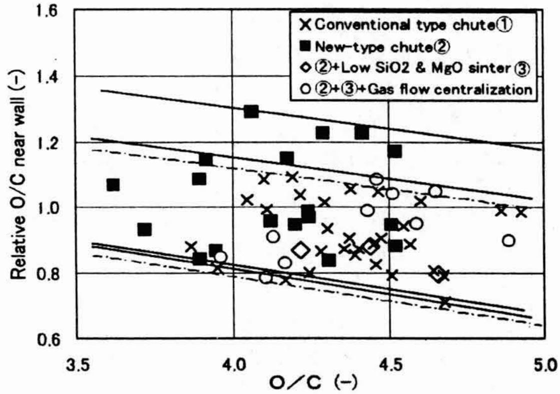


Fig.3 Relation between O/C and relative O/C near wall in Muroran No.2BF(94 Apr.–99 Apr., monthly data).

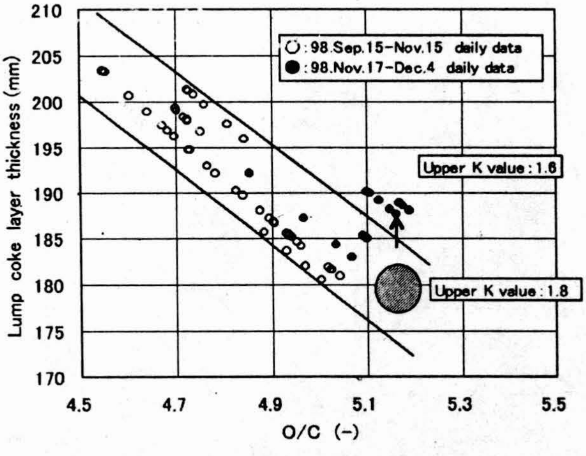
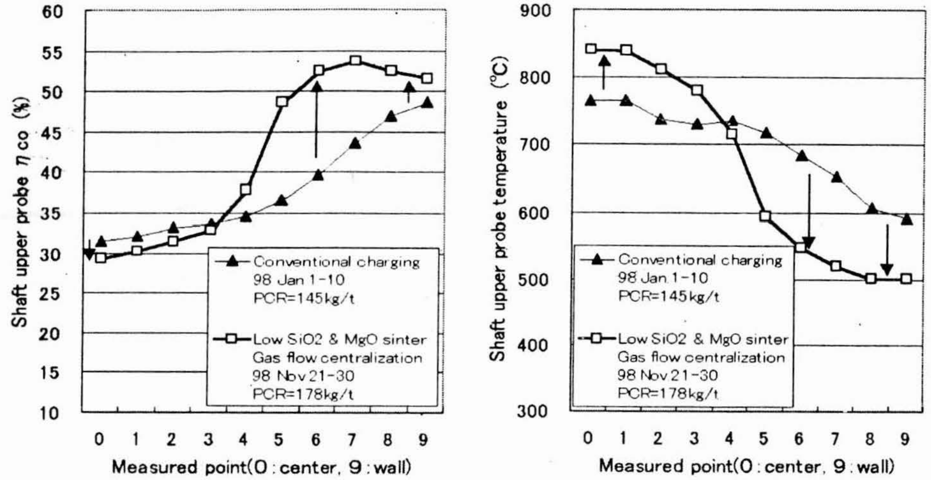
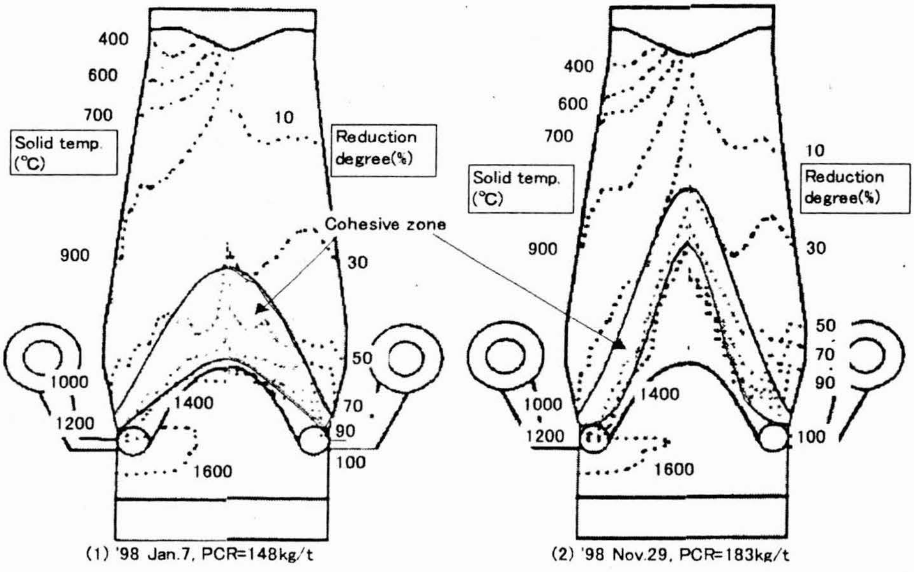


Fig.4 Relation between O/C, coke layer thickness at belly in Muroran No.2 BF.



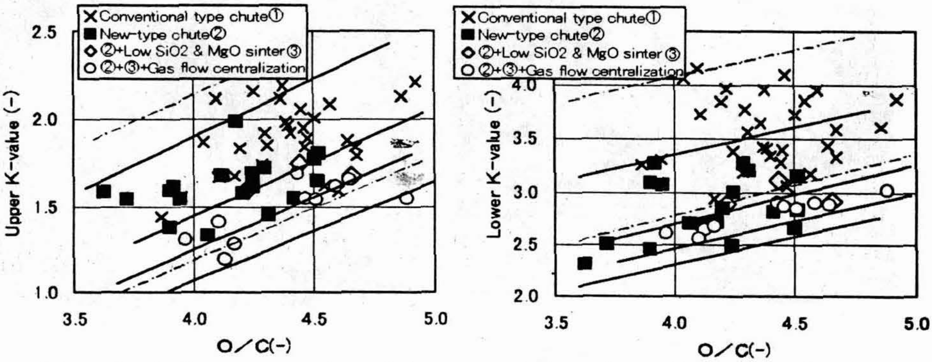
(1)Radial distribution of η co (2)Radial distribution of temperature

Fig.5 Relation between PCR and gas utilization (η co), temperature in Muroran No.2 BF.



(1) '98 Jan.7, PCR=148kg/t (2) '98 Nov.29, PCR=183kg/t

Fig.6 Estimation of cohesive zone by BRIGHT model.



(1)Upper K-value(between top and staveS1)

(2)Lower K-value(between staveS1and tuyere)

Fig.7 Relation between O/C and K-value in Muroran No.2 BF (94 Apr.-99 Apr., monthly data).

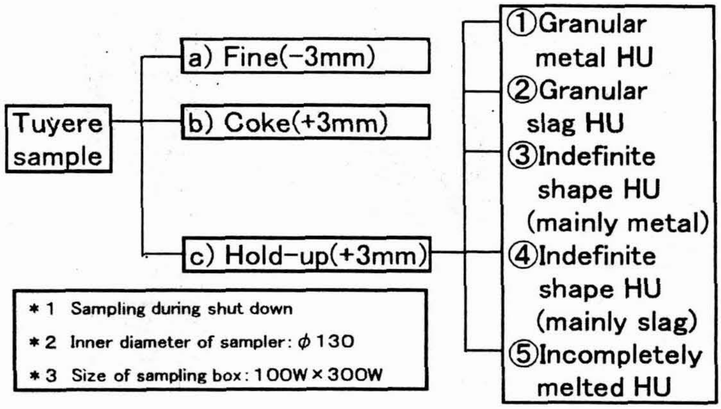
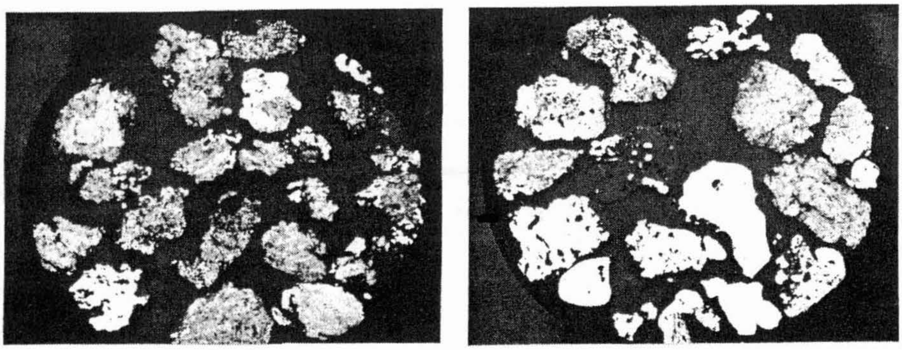


Fig.8 Classification of tuyere sample.



a) 【time 1】

1998 Feb.12(PCR=157kg/t)

b) 【time 2】

1998 Dec.14(PCR=190kg/t)

Fig.9 Microstructure of incompletely melted hold-up sampled at 2.3m from tuyere tip in Muroran No. 2BF.

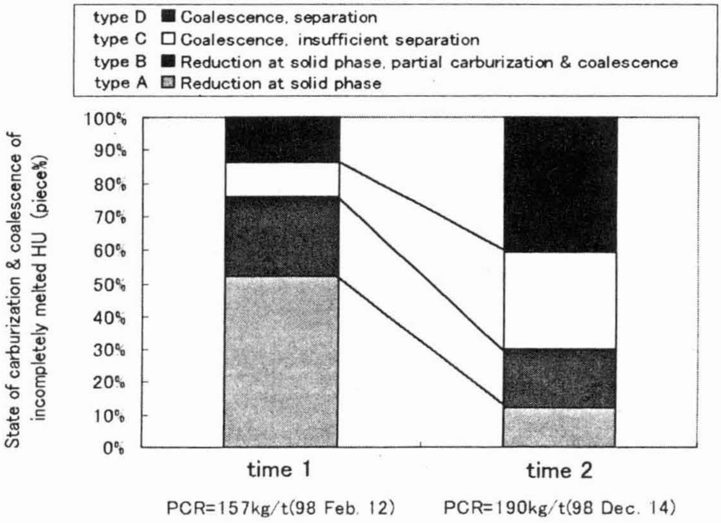
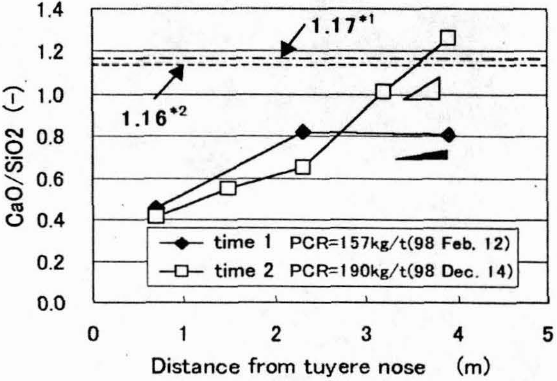
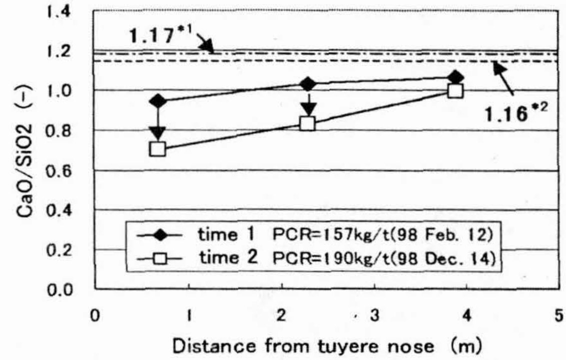


Fig.10 State of carburization and coalescence of incompletely melted hold-up sampled at 2.3m from tuyere tip in Muroran No.2BF.



*1: CaO/SiO2 in slag during final tap before blow-down at 157kg/t
*2: CaO/SiO2 in slag during final tap before blow-down at 190kg/t

Fig.11 Radial distribution at tuyere level of CaO/SiO_2 in fine(-1mm) in Muroran No.2 BF.



*1: CaO/SiO2 in slag during final tap before blow-down at 157kg/t
*2: CaO/SiO2 in slag during final tap before blow-down at 190kg/t

Fig.12 Radial distribution at tuyere level of CaO/SiO_2 in indefinite shape slag in Muroran No.2 BF.