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Progression of Experimental Blast Furnace in Hasaki R&D Center

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Abstract

The experimental blast furnace in Hasaki R&D Center (Kamisu City in Ibaraki Prefecture), constructed as a melting furnace in 1982, carried out a total of 50 test operations over 27 years up to 2008. This article reviews the history of the technological development and knowledge obtained from the experimental blast furnace.

1. Introduction

Employing an experimental blast furnace is one of the R&D methods used to investigate ironmaking technology that is utilized at the early stage of the development of a new process technology, or at the stage where the solutions to problems arising from various conditions are required. However, such furnaces always suffer from the inevitable problems of their dissimilarity to a commercial blast furnace, or in other terms, discrepancies such as in the thermal level, reducing agent rate, in-furnace flow time, and in-furnace load. Such dissimilarity or discrepancies are inevitably caused by the relatively large thermal loss due to the small scale of the experimental blast furnace. Furthermore, relatively large-scale R&D resources are required, and therefore, not only the test cost, but also other issues including securing sufficient operator resources are common problems across countries and periods of time.

Figure 1 shows the transitions of the iron and crude steel production and experimental blast furnaces.[1–4] Systematic tests on an experimental blast furnace were conducted after 1916 in the US under the control of the US Bureau of Mines and later by a research association that consisted of US and Canadian steel companies, and in Europe, by the alliance of Belgium and France after 1957.[5] However, both in the US and Europe, the experimental projects became inactive in the latter half of the 1960s. Under such circumstances, the research based on an experimental blast furnace conducted by the Institute of Industrial Science (IIS), University of Tokyo, from 1955 to 1981 produced a lot of information on ironmaking technology in the early stage of the postwar production-growth period. Tate,[6] being aware of its problems, defined the abovementioned experimental blast furnace (hereinafter referred to as the “Tokyo University one-ton/day furnace”) as “the experimental furnace with which qualitative information pertaining to the state of the progress of various processes in a blast-furnace-type reactor is obtained, and appropriate problem presentation is provided thereby to the fundamental R&D on an experimental basis and/or to the survey on acommercial blast furnace basis”.

In Nippon Steel Corporation, after the prewar R&D based on the 1.2 m^3 experimental blast furnace in the Kamaishi Works (ex-Mitsui Mining Co., Ltd.),[7] a one-ton furnace (0.596 m^3) was constructed in Higashida in Yawata Works in 1934, and a three-ton furnace (4.6 m^3) was constructed in Tobata in 1944, both belonging then to corporate technology research and development laboratories. In these furnaces, a total of thirty-eight test operations over fifteen years were conducted. From the test operations, various information was obtained about the usability evaluation results of raw materials such as ore powder, reduced iron sand, and anthracite coal, and information pertaining to flux injection, low Si operation, mixed charging, and ferroalloy production.[8] Such information was transferred to the abovementioned Tokyo University one-ton/day furnace upon its construction. In addition, domestically, in the experimental blast furnace of the ex-Nippon Kokan K.K. (furnace volume 0.63 m^3, later expanded to 3.2 m^3) built in 1967, various R&D studies on the development of various new processes were conducted, and it was confirmed that the reduction of the reducing agent rate by 30 kg/t (5%) per 100 Nm^3/ton of the injected reductant gas, and lowering of the direct reduction ratio to about 10% are possible.[9–11]

The experimental blast furnace (12 t/d, last stage furnace volume 4.0 m^3) in the Hasaki R&D Center of the ex-Sumitomo Metal Industries, Ltd. (Kamisu City in Ibaraki Prefecture) was built as a melting

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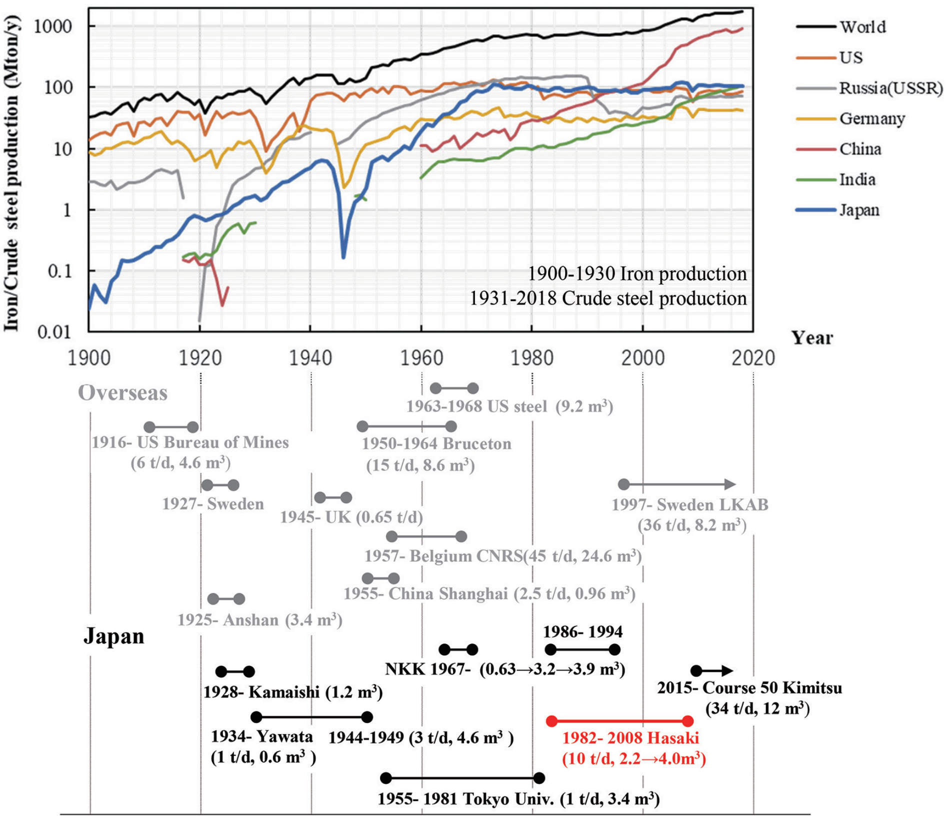

Fig. 1 Transitions of iron and crude steel production and experimental blast furnaces

furnace with a furnace volume of 1.3 m^3 in 1982 at the same time as the termination of the operation of Tokyo University's one-ton/day furnace. At this time when the domestic crude steel production exceeded 100 million tons a year, overtaking the US, the Japanese steel industry was suffering from the sharp rise of the crude oil price, and was forced to change its energy source. Then, the following R&D was conducted: development of coke rate reduction technology, the shift from heavy oil injection to pulverized coal injection, and development of new processes as substitutes for the blast furnace method. In the early period, the furnace was mainly used for studies on the maximum amount of pulverized coal injection, and the feasibility of producing ferroalloys with the blast furnace process to cope with the electric furnace process. By hot-connecting the melting furnace and the shaft-type reducing furnace (8 t/d, furnace volume 1.3 m^3) constructed adjacently in 1984, and by separating the function of iron ore reduction by a gas reductant and the function of melting the reduced iron, R&D was promoted for a new ironmaking process, the SC Process (Sumitomo/Shaft-Cupola), targeting the alleviation of raw material quality specifications, drastic energy saving, and cost reduction.[12] Furthermore, by using the melting furnace independently, test operations were conducted to develop new ironmaking process technologies such as oxygen blast furnace and scrap melting, and a total of thirty-six test operations using the furnace for melting were conducted until 1988.

After 1989, with the construction of a ceramic heat-exchange-type hot stove and with the alteration of lance-type blasting to tuyere-type blasting, the furnace was used as an experimental blast furnace (Sumitomo/Small Test Blast Furnace: STBF) for the development of the combined blasting of high-rate pulverized coal and powder ore (hereinafter referred to as ultra-combined blasting for furnace). After 1996, the furnace was equipped with measuring devices such as a sampling device and the like, and the furnace height was extended and an additional material hopper was installed on the furnace top. Thus, as a blast furnace simulator, the test operations continued for the evaluation of raw material quality, etc., and in 2008, after the completion of fourteen test operations as an experimental blast furnace, it terminated its service after a total of fifty test operations during the past twenty-seven years. Currently, there are only two experimental blast furnaces in operation: one from the COURSE50 Project in Japan,[4] and the other in LKAB (Luossavaara-Kiirunavaara Aktiebolag), a mining company in Sweden.

In this article, the history of the experimental blast furnace of the Nippon Steel Hasaki R&D Center (hereinafter referred to as Hasaki) from 1982 to 2008 (**Table 1**), and the information obtained therefrom are reviewed.

2. Test Operations of the Experimental Furnace as Melting Furnace

2.1 Pulverized coal injection and combined injection, and ferroalloy production development period

After the oil crisis in the 1970s, as a substitute for the heavy oil injection that was started in the 1960s, the study on pulverized coal injection was started in the early 1980s. An actual size model of the lower part of the Kokura No.1 Blast Furnace with a 48 degree-fanned section (after the third repair and improvement, furnace volume 750 m^3) was constructed in the Amagasaki R&D Center in 1972 (transferred to Hasaki in 1978, furnace volume expanded to 44 m^3). Based on the information obtained from the actual size tuyere combustion experiment conducted on the model,[13] study on the maximum amount of pulverized coal injection using the melting

Table 1 Chronology of the experimental blast furnace

Campaign No.	Schedule	Operation subject	Equipment transition
SC 1st-5th	1982/3-11	Evaluation of coke properties and maximum amount of PCI	1982 Melting Furnace (MF) established (10 t/d, 2.2 m^3, 3 mH).
6-12th	1982/12-1983/10	Ferroalloy production	
13-15th	1984/4-1984/7	Development of SC method	1984 Shaft Furnace (SF) established (8 t/d, 1.3 m^3, 3 mH). Reduction ore hot conveyor, Hot cyclone, and Sampling sonde were installed.
16-17th	1984/9-1984/11	Ferroalloy production	
18-22th	1985/2-1985/10	Development of SC method	
23-32th	1985/12-1987/10	Development of oxygen blasting and ultra combined blasting for furnace	1987 Hot stove established.
33-36th	1988/3-1988/12	Development packed bed type scrap melting process	1988 Furnace height extension (SL: TY+3.0 mH→3.5 mH) 2nd tuyere installation in shaft (TY+0.6 m, 1.2 m)
STBF 1st-7th	1989/5-1991/4	Development of ultra combined blasting for furnace	1989 Tuyere/Browpipe and hot blast control valve system 1990 Furnace height extension (SL: TY+3.5 mH→5.0 mH, 3 m^3)
8th	1996/3/11-3/17	Large amount of PC injection and low slag rate tests	1995 Installation of measurement systems (dripping and cohesive zone samplers, liquid level detector, stock level detector)
9th	1997/4/14-4/18	HBI charging, reduced iron and ore powder injection tests	
10th	1997/10/27-10/31	Evaluation of effect slag rate and low slag sinter properties on permeability	
11th	2000/3/25-3/29	Evaluation of effect of high Al_2O_3 slag on the operation.	1999 Ground flare stack was installed.
12th	2001/1/29-2/2	Wasted plastic powder injection test	
13th	2003/11/7-11/13	Evaluation of sinter reducibility and coke reactivity	2003 Furnace height extension (SL: TY+5.0 mH→6.0 mH, 4.0 m^3) Vertical prove was installed.
14th	2008/11/16-11/21	Evaluation of effect of mixed charge on permeability	2007 Hopper for mixed charging was installed.

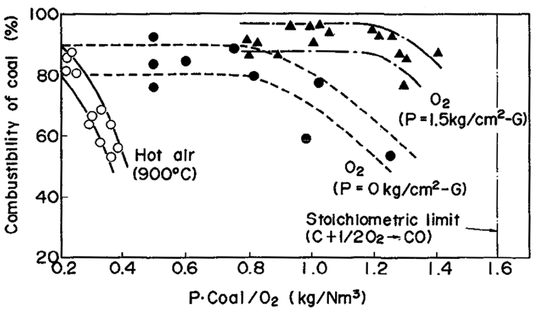

Fig. 2 Results of the coal combustion test

furnace was conducted.

As shown in **Fig. 2**, by oxygen-enriched ambient temperature air blasting, even under the condition of the high pulverized coal injection rate of pulverized coal/oxygen (PC/O_2) = 1.4 kg/Nm^3, a combustibility of coal as high as 87.5% could be maintained. Furthermore, study on the combined injection of pulverized coal with ore powder and flux materials was conducted. In the actual trial operation of the Wakayama No.4 Blast Furnace (after the third repair and improvement, furnace volume 2 700 m^3), reduction of [Si] of the molten pig iron (hereinafter referred to as hot metal) by 0.1% was confirmed per injection of ore powder of 30 kg/t.[14]

In addition, to solve the problem of the electricity cost of ferroalloys that used to be produced in the conventional electrical method, and to secure the competitiveness against the then imported low-priced ferroalloys, development of the production of ferroalloys in the blast furnace method was studied. The in-furnace high temperature refining region expanded by the high-amount pulverized coal injection was targeted, and was considered as appropriate for the production of ferromanganese and ferrochromium. Until 1984, nine test operations were conducted, and high carbon manganese of [Mn] = 75%, and high ferrochromium of [Cr] = 60% were produced.[15, 16]

2.2 New ironmaking technology (SC Process) development period

The SC Process that was developed independently in the 1980s by the ex-Sumitomo Metal[12] is a new ironmaking process to cope with the future scarcities of high-quality coal and high-quality iron ore, wherein the function of a blast furnace is divided into the functions of a melting furnace and a shaft reducing furnace to improve productivity (**Fig. 3**). **Figures 4** and **5** show the appearance of the melting furnace at the time of its construction in 1982, and its schematic diagram, respectively. The reduced iron reduced to the degree of 80–90% in the shaft furnace is carried to the melting furnace by the hot conveyer, and melted by coke. In the melting furnace, it was confirmed that, since the coke solution-loss reaction does not occur, the coke strength is sufficiently maintained even at the bottom of the furnace as shown in **Fig. 6**.[17]

2.3 Oxygen blast furnace, scrap melting development period

During the period from 1985 to 1987, test operations were conducted to confirm whether the oxygen blasting accompanying the injection of a large amount of pulverized coal is practically feasible as an ironmaking process.[18] As a result of the test operation, under

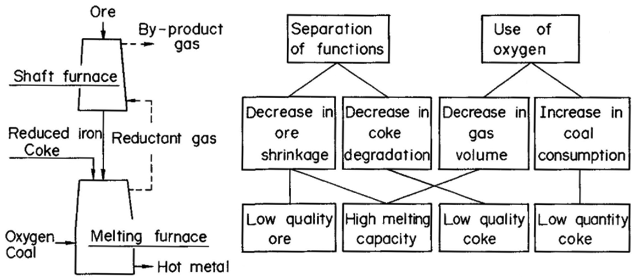

Fig. 3 Concept of the SC Process

Fig. 4 Appearance of the melting furnace (1982)

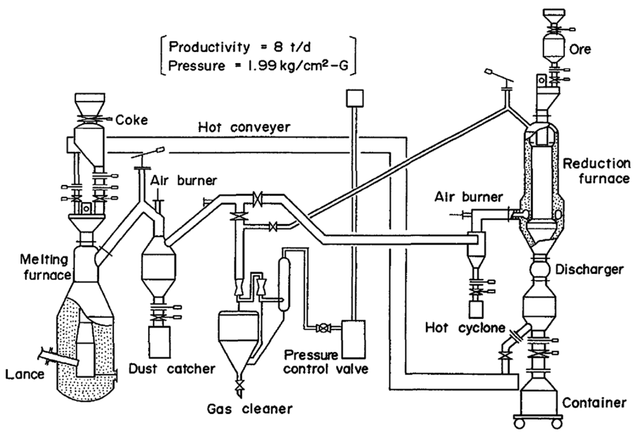

Fig. 5 Schematic diagram of the SC pilot plant

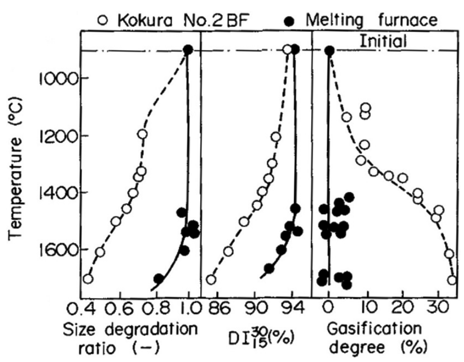

Fig. 6 Distributions of coke properties and gasification degree in melting furnace

the conditions of blasting the mixture of the ambient temperature oxygen and nitrogen with a mixing ratio of O_2 = 60% and of PC/O_2 = 1.2 kg/Nm^3, a pulverized coal rate of 407 kg/t, coke rate of 258 kg/t and productivity of 7.35 t/d/m^3 were achieved. **Figure 7** shows the result of the operation (plotted) and the result of the calculation by using one-dimensional blast furnace models (full line, broken line). Since the calculation result of this model agrees with the production operation result, through the simulation under the condition of PC/O_2 = 1.2 kg/Nm^3 assumed for a large commercial blast furnace (3 680 m^3), it was estimated that the operation result of a productivity of 3.30 t/d/m^3, pulverized coal rate of 375 kg/t, coke rate of 180 kg/t, and reducing agent rate of 555 kg/t is thermally achievable.

In 1988, under the condition of the blasting of oxygen-enriched ambient temperature air under the normal furnace top pressure, and by using coke and pulverized coal, a test operation was conducted for melting 100% steel scrap. As opposed to the ordinary cupola process that uses the low-reactivity, high-quality, large-size lump coke exclusively, since the coke generally used for the blast furnace is used in this operation, in the furnace, the coke for blast furnace use is combusted evenly. Consequently, the coke becomes highly reducible as compared with the weak reducibility in the case of the cupola, and desulphurization and carburization are promoted thereby. As a result, as shown in **Table 2**, the reducing agent rate became 275–290 kg/t, and further improved to 240 kg/t due to the addition of air through the second tuyere installed in the shaft section.[19] The productivity remained at 15 t/d/m^3 due to the equipment restriction. However, it was estimated that, on the condition of a bosh gas velocity of 0.5 Nm/s, a productivity of 30 t/d/m^3 is possible, and furthermore, that the reducing agent rate can be reduced to 150 kg/t under the condition of a gasification degree of 50%.[20] Further, in the extended type of the packed-bed-type scrap melting process using a converter[21] where iron ore was added, heat efficiency as high as that of the all-scrap melting process was confirmed.[22]

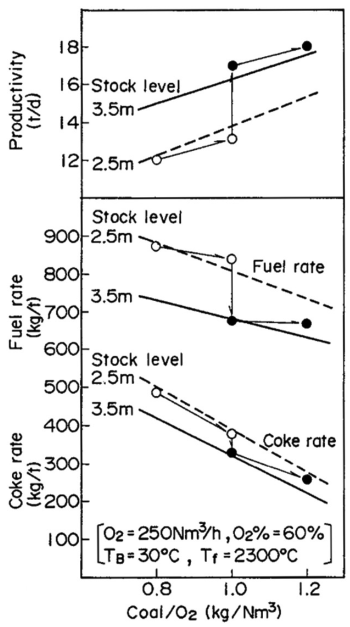

Fig. 7 Comparison of operation results of oxygen injection and calculation results

Table 2 Results on all scrap operations of the experiment blast furnace

Indices / Case No.		1	2	3
Bosh gas volume	(Nm^3/h)	800	714	614
Flame temperature	(°C)	2500	2700	2700
Productivity	($t/d{\cdot}m^3$)	11.7	14.7	14.7
Coke rate	(kg/t)	275	150	125
Coal rate	(kg/t)	0	140	115
Fuel rate	(kg/t)	275	290	240
Oxygen rate	(Nm^3/t)	104	147	122
Additional air	(Nm^3/t)	0	0	74
By product gas	(Mcal/t)	981	1255	881
Hot metal temperature	(°C)	1508	1486	1480
C	(%)	4.70	4.63	4.35
Si	(%)	0.29	0.35	0.21
S	(%)	0.032	0.041	0.036
Slag CaO/SiO_2	(-)	1.33	1.15	1.13
MgO	(-)	15.8	22.2	22.1
(%S)/[%S]	(-)	58.3	72.8	35.1

3. Test Operation as Experimental Blast Furnace

3.1 Outline of equipment

With the alteration of the lance-type blasting system to the tuyere/blowpipe-type system and the installation of a hot stove conducted in 1987–1989, the experimental furnace was modified from an SC-type melting furnace to a small experimental blast furnace (STBF) that resembled a commercial blast furnace. After 1989, a total of fourteen blast-furnace-type test operations were conducted, incorporating the evaluations obtained from the actual blast furnace operation. During this period, the furnace height was extended three times, the stock level of the burden was heightened from 3.0 m to 6.0 m, and the inner volume was expanded from 1.3 m^3 to 4.0 m^3. After 1995, measurement systems and charging hoppers were additionally installed. The appearance of the experimental blast furnace in 2008 is shown in **Fig. 8**, and the equipment flow and the schematic diagram of the experimental blast furnace are shown in **Figs. 9** and **10**, respectively.

The hot stove is of the direct heat exchanging type, consisting of a two-stage heat exchanger of a metallic type and ceramic type (employment of SiC heat transmission tube), and the blast temperature at the exit of the hot stove is about 1050°C. However, the blast temperature into the furnace is about 800°C due to the temperature drop before the blast reaches the tuyere tip. The hot stove system has a maximum air blast rate of 900 Nm^3/h with two 500 Nm^3/h air compressors, and supply capacities of 400 Nm^3/h of oxygen, 600 Nm^3/h of nitrogen, and 30 Nm^3/h of LPG. The furnace has three tuyeres (35 mm in diameter) and the blast volume at each tuyere is controlled by the hot blast air control valve installed at each branch pipe based on the blast volume measured by the flowmeter equipped to each branch pipe. There is one tap hole, and a tap hole opening machine and a mud gun. The hot metal and the molten slag are tapped to a rectangular ladle with a capacity of about one ton for about five minutes with a tap to tap time of about two hours. The injection systems are as follows: pulverized coal (300 kg/h), ore powder (150 kg/h) and the flux materials powder (30 kg/h). The system is designed so that each powder is injected into the furnace via a distributing equipment using a carrier gas of nitrogen through the injection lance installed below the tuyere. Atop the furnace, one hopper for coke

Fig. 8 Appearance of the experimental blast furnace (2008)

(capacity 800 kg) and two hoppers for the iron source materials of ore family such as sintered ore, pellet and lump ore (capacity of 700 kg each) are installed. By a cut gate valve, the volume of a charge of a coke bed is divided into five or six units, and each unit is charged intermittently (inching charging). The ore family iron source material in the hopper is charged uniformly in the radial direction by a table feeder. The gas cleaning system consists of a dust catcher and a venturi scrubber, and the furnace top gas is combusted and discharged by the flare stack after the water sealing equipment.

The furnace is equipped with one sampling device for the cohesive zone and three sampling devices for the dripping zone (upper, middle, lower). These sampling devices analyze the in-furnace gas compositions and measure temperatures during operation, and additionally, are able to take samples of the in-furnace material during operation by exchanging the probe of the device. **Figure 11** (a) shows an example of sampling the in-furnace material with the sampling device. With the front end tip of the cohesive zone sampler, and with the dripping zone samplers, samples of the cohesive material could be frequently taken. Occasionally, the insertion of the probe into the bottom part of the furnace had to be abandoned due to the high resistance force to thrusting.

The liquid level detector dips the probe directly into the liquid of the molten slag and the hot metal produced and stays at the hearth bottom during the operation, and enables the detection of the surface levels of the molten slag and the molten slag/hot metal boundary (Fig. 11 (b)). The stock level detector detects the level of the burden surface and measures its descending rate. The rigid vertical-type probe follows the descent of the burden, and the vertical distributions of the in-furnace temperature and the gas compositions are obtained.

Figure 12 shows the results of the measurement by the liquid level detector and the stock level detector. The in-furnace vertical stresses of the experimental blast furnace are about 5–10 kPa or about 7 kPa on average, and estimated to be about 7% of a commercial blast furnace (about 100 kPa) even in the neighborhood of the cohesive zone (Fig. 12 (a)). From the mechanical balance between the vertical stresses and the buoyancy from the hot metal and the molten slag phase, the floating state of the deadman coke in the experimental blast furnace can be estimated. Figure 12 (b) shows the transition of the burden stock level during tapping, and the liquid levels identified by the amount of drainage of the hot metal and the liquid level detector. It is considered that the packed coke bed sinks

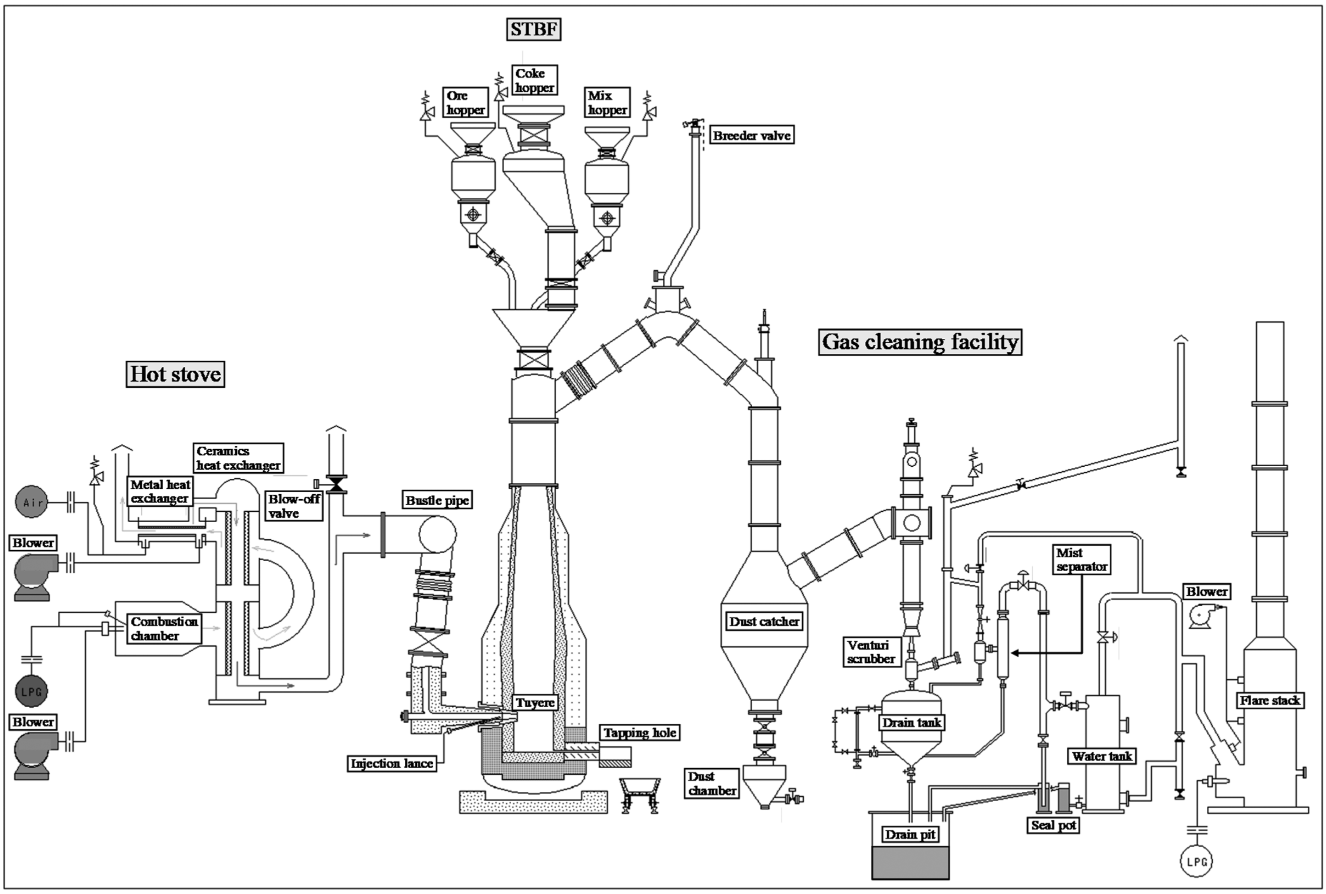

Fig. 9 Experimental blast furnace and peripheral facilities

Inner volume	(m³)	4
Hearth diameter	(m)	0.9
Stock level (max.)	(m)	5.0 (6.0)
Number of tap hole		1
Number of tuyere		3
Top pressure	(MPa)	0.15
Productivity	(t/d)	12

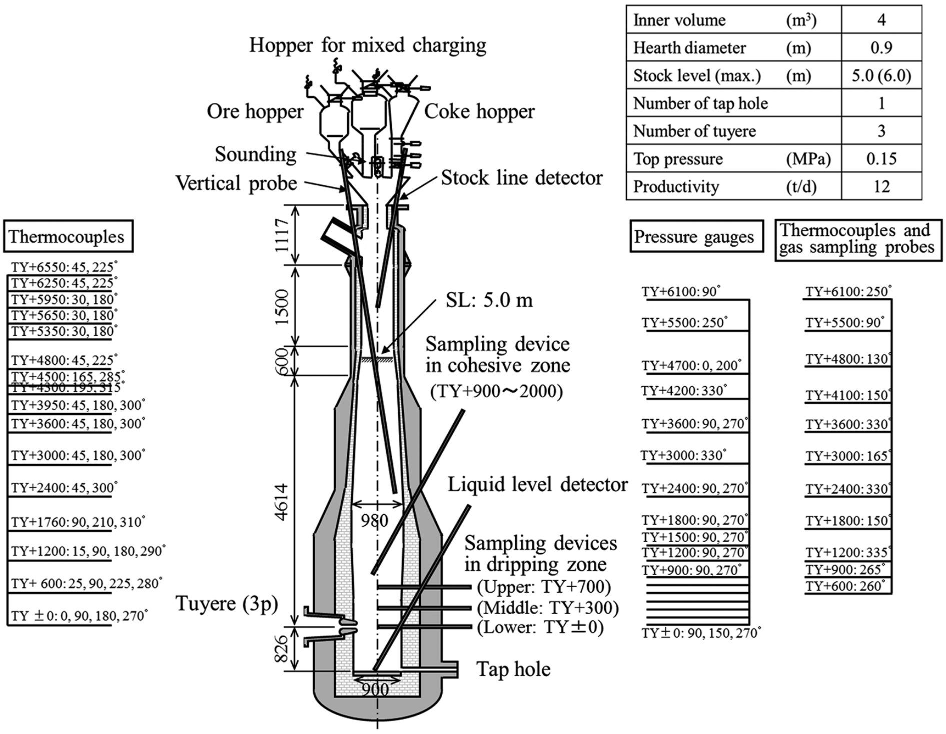

Fig. 10 Schematic diagram of the experimental blast furnace

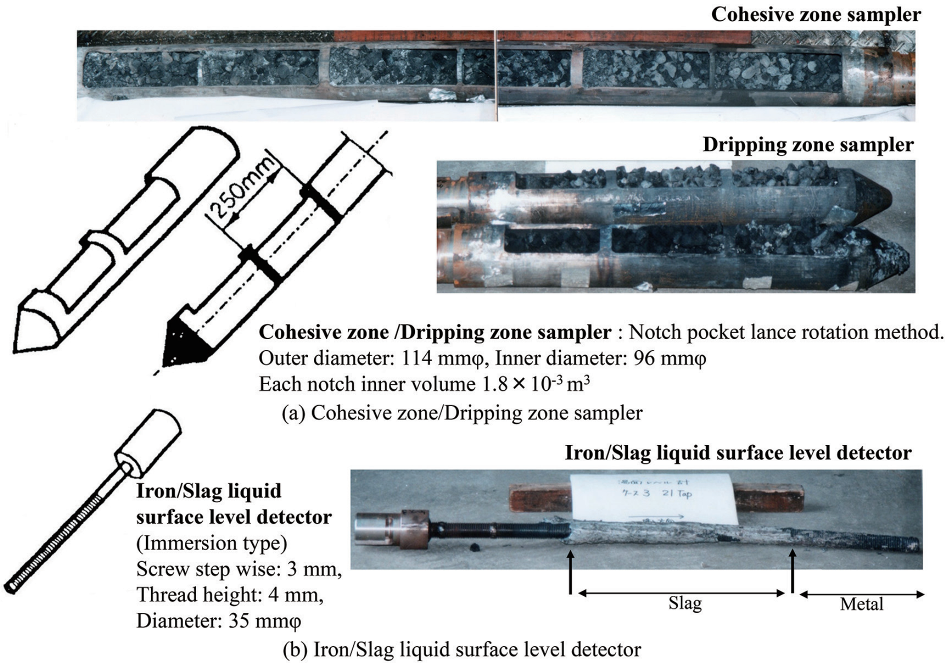

Fig. 11 State of collected samples by samplers and liquid level detector

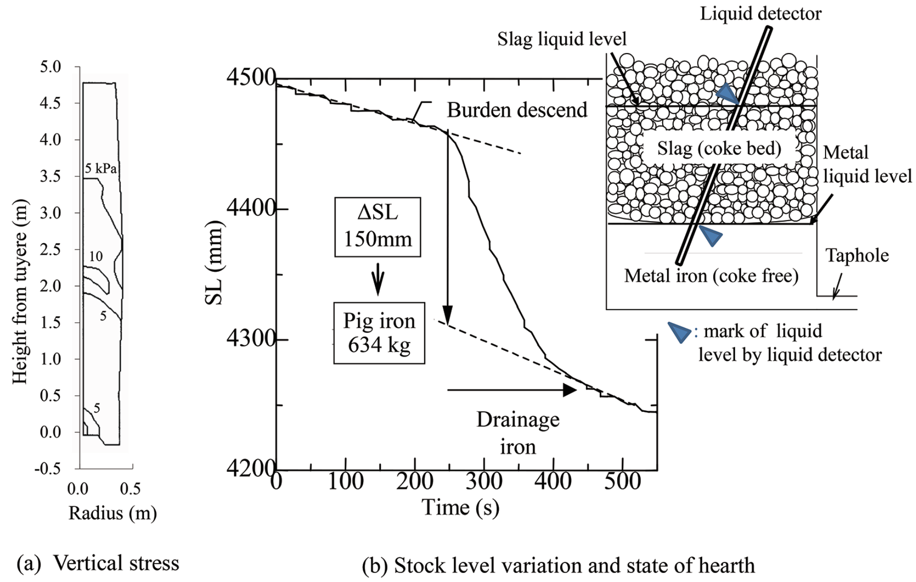

Fig. 12 Vertical stress, variation of stock level with drainage and state of hearth (eleventh test operation)

in the slag phase and floats on the hot metal phase, and it was confirmed that the state of the deadman coke agrees with the assumption of the abovementioned mechanical balance.

After the test operation, the furnace was cooled by nitrogen for two weeks, maintaining the designated stock level, and a dissection survey was conducted. From the top of the furnace, a sample was taken at each coke bed and ore bed at predetermined positions in the radial direction. **Figure 13** shows an example of the in-furnace bed structure. It was confirmed that the slag formed at above 1400°C in the middle of the cohesive zone has larger angles of contact with coke, and has not got wet as compared with the slag formed in the upper cohesive zone right before separation of the molten slag from the hot metal. However, it was confirmed that the molten slag having lower basicity in the dripping zone has good wettability with coke.

Figure 14 shows an example of the results of the in-furnace sample analysis by the dissection survey and the measurement during the operation. The carburization of the hot metal dripping from the upper part of the dripping zone progresses (Fig. 14(e)), and from right after the hot metal/molten slag separation, the slag starts to assimilate with ash and the basicity decreases. The slag FeO right before dripping is about 1.0%, which drops to the tapped molten slag level in the upper part of the dripping zone. From the data, the slag physical property can be estimated. In addition, since the analysis result of the in-furnace content obtained in the dissection survey and that of the sample taken by the sampling devices during operation agree with each other in general, the in-furnace state under any test conditions can be directly grasped by the sampling device and the dissection survey result.

The one test blast furnace operation continued for about five days, and was conducted by about fifteen shift operators on a three-shift basis. Each shift consisted of the following groups: the blasting group that controls the hot stove operation in the instrument pulpit, the charging group that conducts manual operation in the instrument pulpit, mounting work of the material hoppers with a hoist, and the blending work of raw materials, the powder injection group that controls the powder material transportation quantity such as pulverized coal powder and charging to powder material hoppers, the instrumentation group that handles various sampling devices, the tapping group that operates the compressed-air-driven tap hole opening machine, conducts tapping operation using the oxygen opening method and tap-hole-closing operation by a hydraulic mud gun and the handling of the molten slag/hot metal ladle, the utility group that controls the working conditions of equipment and controls the supply of utilities, and an overall operation control supervisor and assistant operation control supervisor.

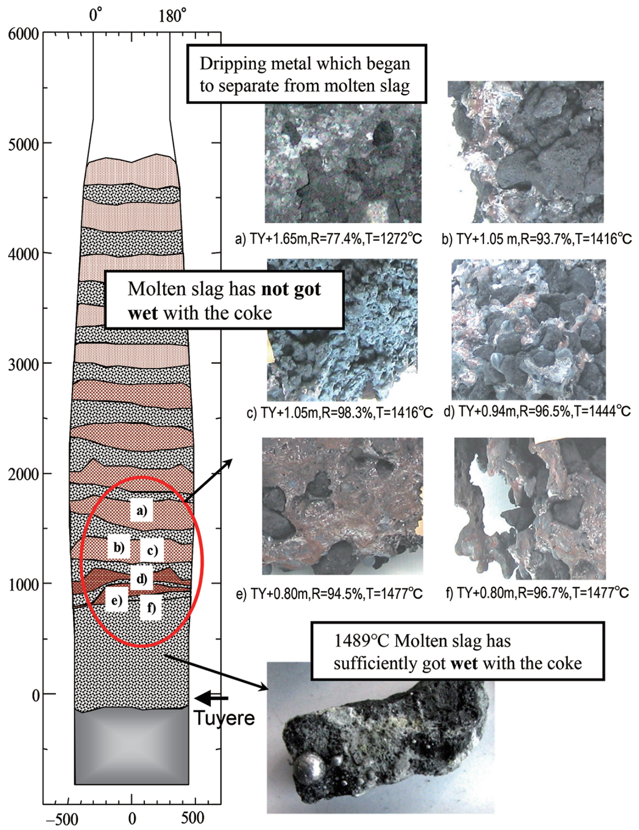

Fig. 13 Dissection of experimental blast furnace (thirteenth test operation)

3.2 Ultra-combined blasting development period

In the first to the seventh test operations during the period from 1989 to 1991, from the viewpoints of extending the coke oven furnace life, direct use of ore powder, the blast furnace productivity enhancement, and the hot metal composition control, the ultra-combined blasting technology in which large amounts of pulverized coal, ore powder, and slag formers are simultaneously injected in through the blast furnace tuyeres was developed.[23, 24] Its concept is shown in **Fig. 15**.

In 1988, a new coke packed-bed-type combustion furnace (1.5 m long × 1.0 m deep × 2.35 m high with one 65 mm in diameter tuyere) was built adjacent to the experimental blast furnace across the hot stove. After fully grasping the combustion state within the raceway and its periphery based on the detailed study using the furnace, a continuous six-day operation was conducted in the experimental blast furnace under the conditions of 300 kg/t + 100 kg/t and 200 kg/t + 200kg/t of the pulverized coal rate and ore powder rate. The reducing agent rate was maintained at 600 kg/t, and no slag FeO increase and no insufficiency in the reduction of the ore powder were recognized. In the total of eight tests using only one tuyere conducted during the same period at the Wakayama No.3 Blast Furnace (after the third repair and improvement, furnace volume 2150 m^3) and the Wakayama No.5 Blast Furnace (after the third repair

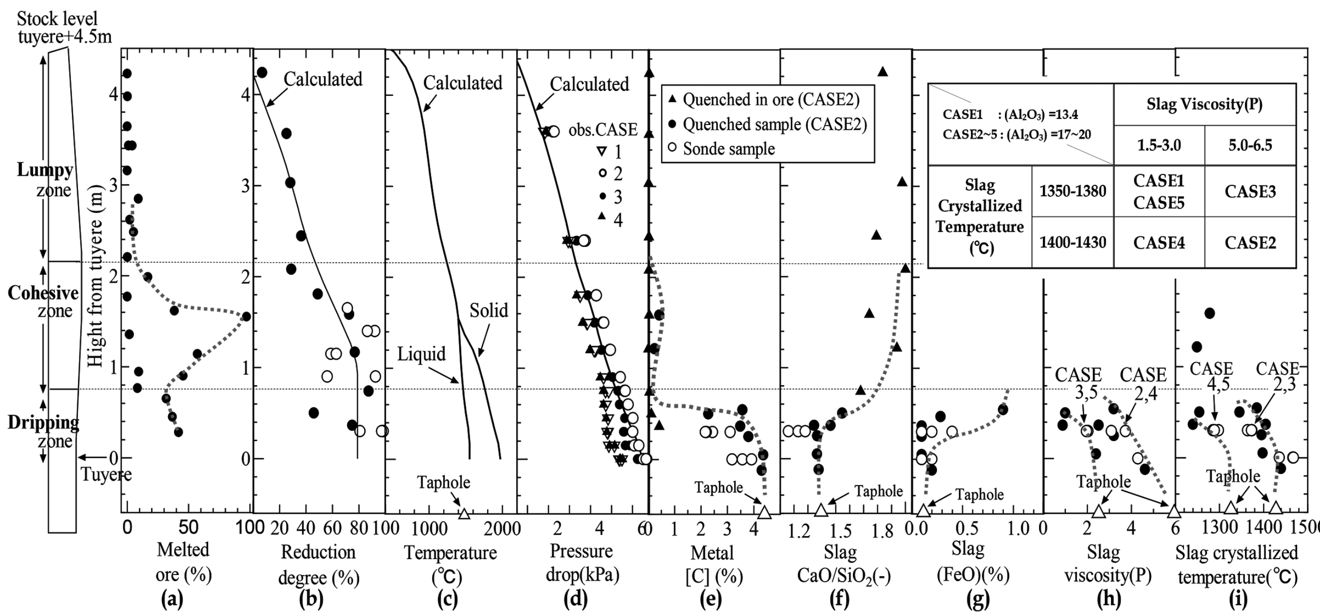

Fig. 14 Vertical distribution of sample analysis results by dissection and sampling sonde (eleventh test operation)

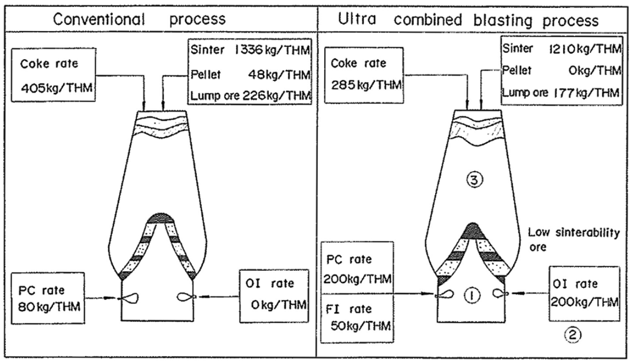

Fig. 15 Concept of ultra combined blasting for blast furnace

and improvement, furnace volume 2700 m^3), in the test under the condition of 200 kg/t+200 kg/t of the pulverized coal rate and ore powder rate, from the fiber scope observation,[24] melting of the ore powder was observed and it was confirmed that the ore powder injection was functioning sufficiently within the raceway. In addition, although the effect of decreasing [Si] by FeO was not as remarkable as that of a commercial blast furnace test,[14] hot metal chemical compositions almost equal to those of the commercial blast furnace were obtained. Additionally, to prevent the piping abrasion, a plug-type pneumatic conveyor powder transportation technology was established.

After the extension of the furnace height in 1990, a stock level change test was conducted under identical operation specifications. As a result, by changing the stock level from 3.5 m to 5.0 m, decrease in unburnt char trapped in the furnace top was confirmed, and the furnace top temperature dropped by 100–150°C, the gas utilization efficiency increased by 5–6%, and the reducing agent rate decreased by about 100 kg/t. Further, according to the dissection survey, in the case of a stock level of 3.5 m, the cohesive layer was found in the upper part of the furnace. Therefore, a thermal reserve zone was not formed.

3.3 Blast furnace raw material evaluation technology development period

3.3.1 High pulverized coal rate, low slag rate test

In the eighth test operation conducted in March 1996, under the ordinary blast furnace raw material condition, namely a sintered ore ratio of 75% and a lump ore ratio of 25%, the change in the raw material properties in the furnace due to the difference between the high pulverized coal rate operation (PCR>200 kg/t, equal to or higher than the one in the commercial blast furnace operation) and the entire coke operation was studied. However, as stated earlier, as the blast air temperature of the experimental blast furnace is lower than that of the commercial blast furnace, to simulate the tuyere front combustion condition of the commercial blast furnace, the degree of oxygen enrichment was increased to fit the oxygen excess coefficient. As a result of the test operation, in the high pulverized coal rate operation, the soot generated at the furnace top increased, and an increase in the strength of the coke at the furnace bottom considered to be the effect of the unburnt char generated in the furnace was observed. In addition, it was confirmed that these phenomena become more remarkable in the low slag rate operation where the sintered ore ratio is lowered to 25%.

3.3.2 Evaluation of reduced iron

The ninth test operation was conducted in April 1997 to quantitatively grasp the effects of hot briquette iron (HBI) on the blast furnace productivity improvement and reduction of the reducing agent rate.[25] In the softening and melting test conducted prior to the experimental blast furnace operation,[26] the high permeability of HBI at high temperature was confirmed, and upon application of HBI to the blast furnace, not only improvements in the productivity and the reduction in the reducing agent rate, but also a great contribution to the improvement in permeability were expected.

In the test blast furnace operation, to supply HBI, two methods were used: charging lump HBI from the furnace top and the injection of the powder reduced iron (PRI) through the tuyeres. The test operations were conducted for six cases: the four cases of the HBI mixing ratio of 0, 25, 50 and 100%, one case of PRI (powder reduced iron) injection of 200 kg/t, and one case of powder ore injection (ore injection: OI) of 200 kg/t for comparison purposes. To compare and verify the improvements in permeability and productivity, all blasting conditions were fixed.

Throughout the test operation, the furnace condition remained stable. According to **Fig. 16** wherein the representative operation data are prepared, the 5.5% production rate improving effect and the 4.3% reducing agent reduction effect were obtained per HBI 100 kg/t, and above HBI 50%, a significant decrease in the resistance to the in-furnace permeability (permeability resistance) was confirmed. In the case of PRI, no changes were observed in the production rate and the reducing agent rate. However, in the case of OI, as the production rate deteriorated, accompanied by the worsening in the reducing agent rate, it was concluded that, for the improvement of blast furnace productivity using HBI, top furnace charging is more advantageous than the injection through tuyeres.

In addition, the effect of using HBI in the experimental blast furnace was analyzed from the viewpoint of kinetics by using the blast furnace mathematical models.[27] As shown in **Fig. 17**, the analysis clarified that the productivity improvement, the reduction of the reducing agent rate, and the decrease in gas utilization efficiency due to the increase in the HBI charge ratio are thoroughly elucidated. And additionally, based on the results of this test operation and the kinetics analysis, the effect of the employment of HBI in the commercial blast furnace was estimated. Later on, demonstration tests up to HBI 100 kg/t were conducted in the Wakayama No.5 Blast Furnace (after the third repair and improvement, furnace volume 2700 m^3), and the effects of the productivity improvement and the reducing agent rate reduction were confirmed as predicted by the theoretical analysis.[28]

3.3.3 Evaluation of low slag sintered ore

The tenth test operation was conducted in October 1997, six months after the ninth test operation. The test operation was conducted for quantitative analysis of the effects of the high temperature character, reducibility, and the slag rate of the low SiO_2 sintered ore on the blast furnace permeability.[29] **Table 3** shows the test conditions. The test operations were conducted for five cases of four different types of sintered ore and one case in which the material property and the blast furnace slag rate were changed by adjusting the amount of the flux materials. The blasting condition, charged O/C, and the target slag compositions are fixed.

As a result of the test, in **Fig. 18**, the effects of the blast furnace slag rate and the high temperature permeability resistance index of the sintered ore (KS)[26] measured by the softening and melting test on the blast furnace permeability resistance index (KR)[30] are shown. Focusing on Case 1 in Table 3 as the basis of the comparison, in Case 2, with the low SiO_2 of the sintered ore, KS decreases and the blast furnace slag rate decreases along with the decrease of SiO_2. In Case 3, the decrease in the blast furnace slag rate is covered

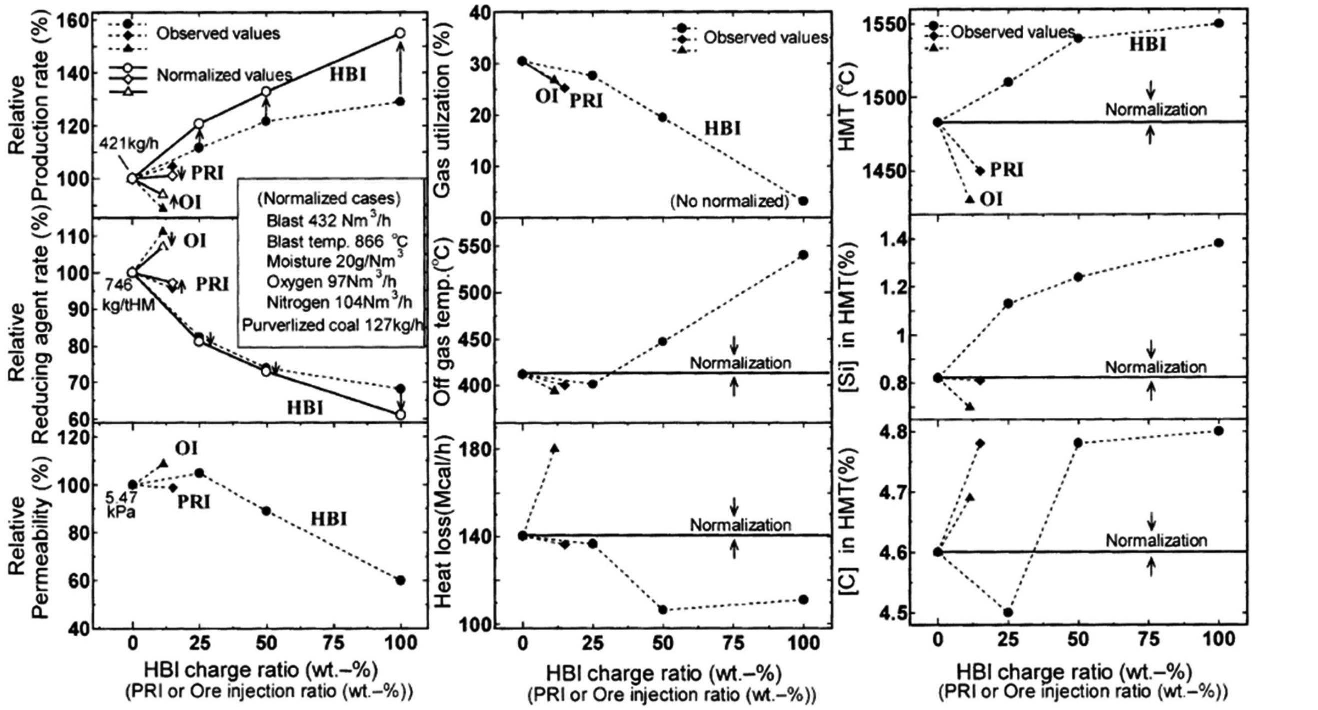

Fig. 16 Relative production rate, reducing agent rate and permeability through the reduced iron melting tests using experimental blast furnace

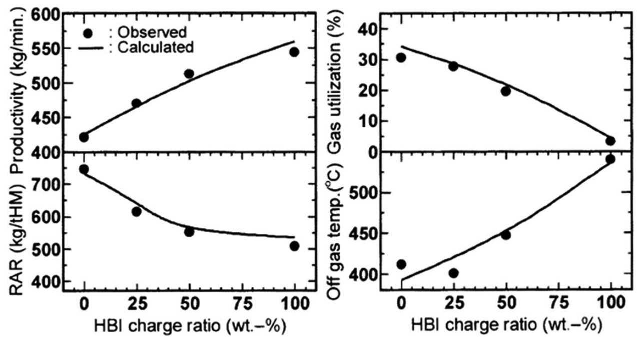

Fig. 17 Calculated results of experimental blast furnace operation

by the blast furnace flux materials. The figure shows that the effect of KS on the blast furnace permeability is significant, and the effect of the blast furnace slag rate is considerably small as compared with that of KS. Further, under these test conditions, there were no effects of RI and RDI of the sintered ore on the permeability.

Based on the result of this test operation, to grasp the effect of KS on the permeability in the commercial blast furnace, the softening and melting test result was formulated and was incorporated into the blast furnace mathematical models, and the commercial blast furnace permeability based on this model[27] was evaluated. The calculation results agree very well with respect to not only the static pressure distribution on the experimental furnace wall when high/low SiO_2 sintered ore is used, but also, as **Fig. 19** shows, very well with respect to the actual KR values obtained from the Kokura No.2 Blast Furnace (after the second repair and improvement, furnace volume 1850 m^3) and the Kashima No.2 Blast Furnace (after the third repair and improvement, furnace volume 4800 m^3). In the case of the Kokura No.2 Blast Furnace, during the period of the subject operations, the blast furnace slag rate was almost constant. However, in the case of the Kashima No.2 Blast Furnace, the blast furnace slag rate changed with the change of KS. However, despite that, in both blast furnaces, since the behavior of the change of the values calculated by the model into which the KS evaluation model was incorporated without taking into consideration the influence of the blast furnace slag agrees with the behavior of the change of the actual values, it was concluded that, even in the commercial blast furnaces, similarly to the result of the test blast furnace operation, the effect of the blast furnace slag rate is small compared with that of KS.

Table 3 Experimental conditions

Case No.		1	2	3	4	5
Sinter	Sample	A	B	B	C	D
	SiO_2 (%)	5.01	3.89	3.89	4.63	4.60
	CaO (%)	9.99	9.09	9.09	9.44	9.86
	MgO (%)	1.09	1.11	1.11	1.19	0.94
	Al_2O_3 (%)	2.09	1.87	1.87	1.95	1.84
	FeO (%)	7.47	5.88	5.88	6.93	5.86
	RI (%)	64.6	68.0	68.0	68.1	66.9
	KS×10^5	1500	648	648	1085	1195
	RDI (%)	41.7	42.8	42.8	45.3	44.2
	TI (%)	76.9	81.3	81.3	75.1	67.2
Fluxes	(kg/t-HM)	33.5	13.3	74.1	5.5	19.3
Slag rate	(kg/t-HM)	302	258	302	271	271
Ore/Coke	(-)	3.64	3.58	3.60	3.59	3.61

3.3.4 Evaluation of high Al_2O_3 slag

The eleventh test operation was conducted in March 2000. The objectives of the test operation were to lower SiO_2 of the sintered ore aimed at blast furnace permeability improvement, and to clarify the in-furnace phenomena focusing on the permeability in the lower

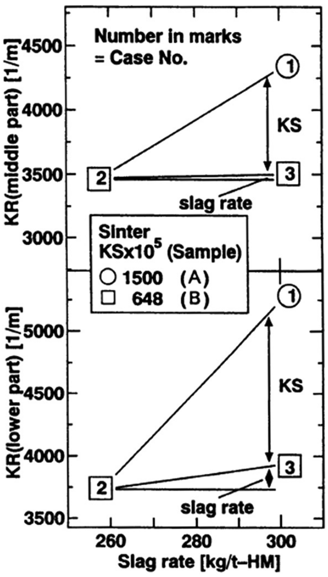

Fig. 18 Comparison of effect of KS on KR with that of slag rate

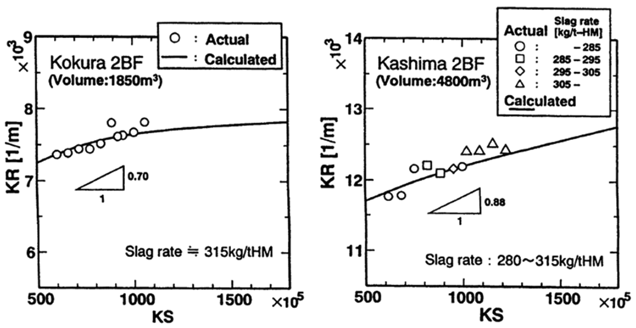

Fig. 19 Effect of KS on KR in the commercial blast furnace

part of the furnace and the slag drainage characteristics on the furnace working floor, to cope with the rise of the slag Al_2O_3 concentration coming from the blast furnace slag reducing movement promoted from the viewpoints of reducing the amount of slag disposal and the environmental protection.[31] The test operations were conducted, under the condition of fixed per tap slag output, for five cases wherein two types of sintered ore were used and the slag Al_2O_3, slag MgO, and the CaO/SiO_2 levels were differentiated by the addition of flux materials. **Table 4** shows the results.

Figure 20 shows the effect of the slag contents on the slag drainage rate on the 1500°C corrected base, eliminating the influence of temperature. Along with the rise of slag Al_2O_3, the slag viscosity rises and the slag drainage rate lowers, and as MgO rises, the slag viscosity lowers and the drainage rate rises. On the other hand, no effect of the slag crystallization temperature on the slag drainage rate was observed. Namely, the slag drainage phenomenon is a fluidity-dominant phenomenon, and since the high MgO slag content in the high Al_2O_3 content slag, despite raising the crystallization temperature, lowers the slag viscosity, high MgO was found to be effective in enhancing the slag drainage rate.

As **Fig. 21** shows, a positive correlation is recognized between the calculated static hold-up in the dripping zone and the permeability resistance index in the dripping zone (KR_L). The pressure drop in the dripping zone of the experimental blast furnace rises with the increase of the slag Al_2O_3, slag CaO/SiO_2, which is mainly attributed

Table 4 Results of experimental blast furnace operation

		Case 1	Case 2	Case 3	Case 4	Case 5
Pig output	(kg/tap)	784	695	734	873	666
Slag output	(kg/tap)	225	225	225	225	225
Melting time	(min)	97.7	96.6	96.8	100.5	112.5
RAR	(kg/pt)	742	783	823	773	848
Top gas temperature	(°C)	360	347	406	410	397
Top gas η_{CO}	(%)	40.5	40.5	37.1	40.5	41.9
KR	(1/m)	3080	3366	3323	3190	2815
Pig temperature	(°C)	1457	1446	1428	1418	1390
[C]	(%)	4.75	4.73	4.56	4.48	4.44
[Si]	(%)	0.77	0.7	1.35	0.63	0.72
[S]	(%)	0.025	0.023	0.056	0.05	0.057
Slag temperature	(°C)	1533	1541	1503	1500	1498
(Al_2O_3)	(%)	13.4	**18.6**	**20.4**	**19.2**	**16.5**
(MgO)	(%)	5.36	**8.5**	4.75	4.63	**10.6**
(CaO/SiO_2)	(%)	1.49	1.46	**1.21**	1.44	**1.18**
Viscosity	(poise)	2.35	2.5	5.93	6.03	1.45
Viscosity 1500°C	(poise)	3.07	3.51	6.04	5.64	1.43
Crystallization temp.	(°C)	1354	1430	1376	1404	1366
ΔTc	(°C)	179	111	127	96	132
Drainage rate	(kg/s)	4.93	5.17	3.24	3.15	5.99

ΔTc = Slag temperature − Slag crystallization temperature

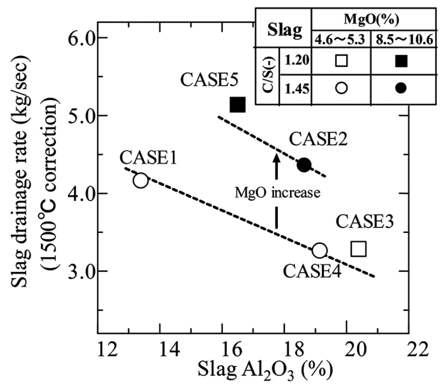

Fig. 20 Effect of the slag content on drainage rate

to the effect of the wettability via the slag static hold-up, and the effects of the slag viscosity and the crystallization temperature are small. Furthermore, as **Fig. 22** shows, the permeability resistance index of the cohesive zone (KR_M) is confirmed to depend on the sintered ore KS. Namely, even in the high Al_2O_3 sintered ore, the rise of the KS value is suppressed by increasing MgO, and the permeability of the cohesive zone is maintained thereby.

3.3.5 Evaluation of material quality

In the twelfth test operation in January 2001, waste plastic powder was injected through the tuyere. However, since a sturdy hanging was built right after the start of the injection of the waste plastics, the test operation was terminated.

The thirteenth test operation was conducted in November 2003 with the objectives of evaluating the quality of the high-reducibility sintered ore and inspecting the effectiveness of the high-reactivity coke under the joint use state with the high-reducibility sintered ore.[32] In the experimental blast furnace, the reducing agent rate was 700–800 kg/t, higher than that of the commercial blast furnace due

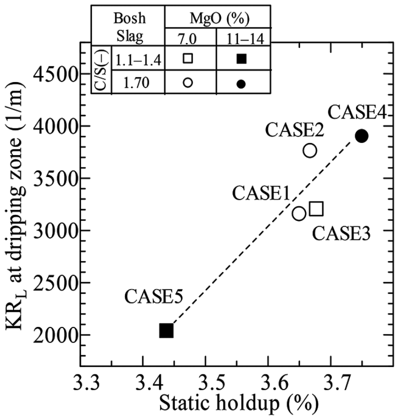

Fig. 21 Effect of calculated static hold-up on permeable resistance index of dripping zone KR_L of experimental blast furnace

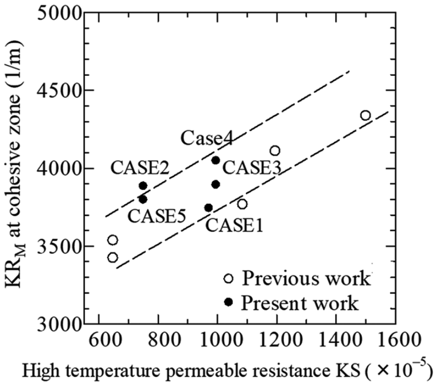

Fig. 22 Effect of sinter high temperature property KS on permeable resistance index of cohesive zone KR_M of experimental blast furnace

to: the large per ton hot metal heat diffusion from the furnace because of the restricted furnace volume, higher furnace top gas temperature because of the restricted furnace height and the restricted blast air temperature. Therefore, upon evaluating the sintered ore quality and the coke quality, various countermeasures were taken to conduct the operation under the in-furnace reducing condition as closely as possible to the actual blast furnace operation conditions.

As for the modifications of the equipment, aiming at heat loss improvement, the furnace height was extended, and the stock level was set at the height of 6.0 m from the tuyere level, heightened from the past 4.5 m level. By the extension of the furnace height, the furnace volume was expanded to 4.0 m^3 from the past 3.0 m^3. Furthermore, as new sensors to grasp the in-furnace state of the reaction further, a rigid-type vertical probe that follows the descent of the burden was installed, and the gas sampling devices that enable simultaneous gas-sampling in the height direction were installed on the furnace wall (Fig. 10). The modifications in the blasting condition are: increase of the bosh-gas volume anticipating improvement in the heat loss by the increased production, the rise of the temperature set in front of the tuyere anticipating increase in the hot gas flow rate, decrease in pulverized coal rate, and the dehumidified blasting by the application of nitrogen injection. Additionally, as a result of thinning the charged material layer aimed at improving the reactivity efficiency, and lowering the targeted hot metal temperature, an operation with a reducing agent rate of below 600 kg/t was achieved.

Table 5 Test cases of the experimental blast furnace

		Coke (CRI)	
		Coke A (25.6)	Coke B (42.2)
Sinter (RI)	Sinter A (65.3)	Case 1	-
	Sinter B (72.3)	Case 2	Case 3
	Sinter B-fine (86*)	Case 4	Case 5

*Apparent RI

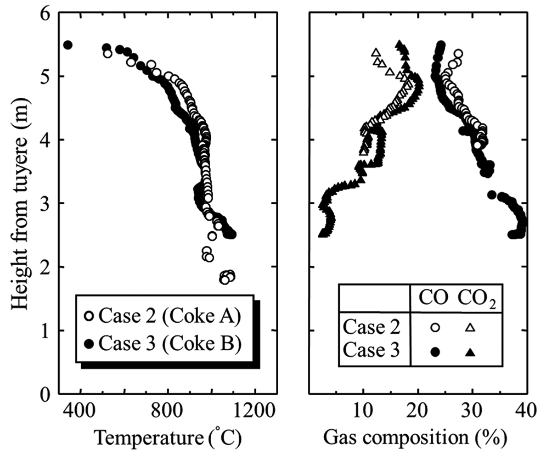

Fig. 23 Vertical distribution of temperature and gas composition

As shown in **Table 5**, the test operations were conducted for the four cases wherein the combination of each of the two types of coke and each of the two types of sintered ore arranged as below was changed. Two types of coke were produced by changing the coal blending ratio so that the coke reactivity index (CRI) of the coke is differentiated by 10%. The two types of sintered ore have different levels of reducibility index (JIS-RI). One case in which the apparent JIS-RI of the high-reducibility sintered ore is further improved by grain-refining was additionally arranged.

In the case where the coke reactivity is fixed and the sintered ore reducibility is changed, in addition to the rise of the hot metal forming rate, increase of the top gas utilization and improvement in the reducing agent rate by the enhanced JIS-RI, the improvement in permeability was confirmed. In the case where the sintered ore reducibility is fixed and the coke reactivity is changed, improvement in the top gas utilization efficiency and lowering of the top gas temperature by the use of high-reactivity coke were confirmed, while the amount of solution loss carbon decreased. As shown in **Fig. 23**, according to the measurement by the vertical probe at the same time, with the high-reactivity coke, the thermal reserve zone temperature dropped to 920°C from 980°C, and the improvement in reaction efficiency was confirmed. Simultaneously, to grasp the in-furnace phenomena when the high-reactivity coke is used, evaluation of the strength of the in-furnace coke sampled by the sampling device during operation was also conducted.

According to **Fig. 24**, when the high-reactivity coke was used (Case 3), the amount of solution loss carbon decreased as compared with Case 2, and as a result thereof, the degradation of coke was considered to be suppressed. However, when KR was maintained at the same level as that of Case 2, the improvement of the in-furnace permeability was not confirmed, which is considered to be attributed to the extremely small load in the experimental furnace as compared

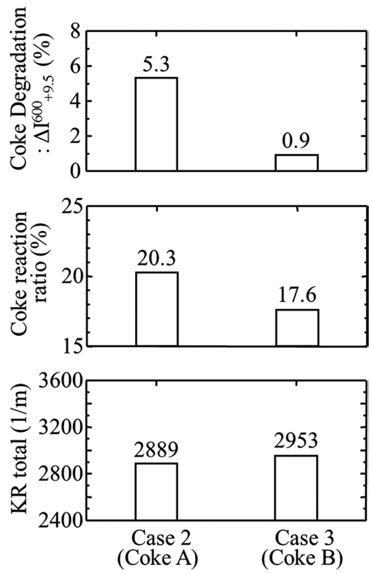

Fig. 24 Comparison of effect of CRI on coke degradation, reaction ratio and KR

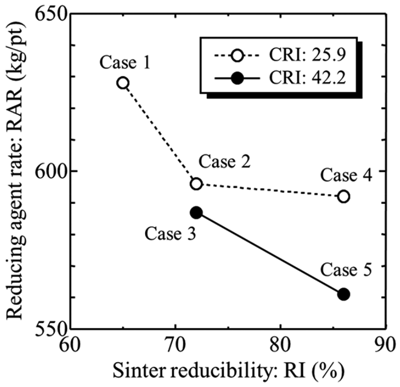

Fig. 25 Effect of JIS-RI and CRI on reducing agent rate

with that of a commercial blast furnace.

Figure 25 shows the effects of the sintered ore JIS-RI and the coke CRI on the reducing agent rate. With a fixed CRI, along with the rise of JIS-RI, the top gas utilization rises and the reducing agent rate is lowered. When JIS-RI is fixed, since the abovementioned trend is remarkable when the high-reactivity coke is used, it was confirmed that the operation-improving effect of the high-reactivity coke works effectively under the joint use with the high-reducibility sintered ore. Further, JIS-RI of the grain-refined high-reducibility sintered ore is equivalent to 86%. However, its effect on the gas utilization efficiency and the reducing agent rate was small. The rise of the top gas temperature is considered to offset the reducibility improving effect by grain-refining.

3.3.6 Evaluation of the effect of mixed layer

The fourteenth test operation, the last test operation, was conducted in November 2008, five years after the implementation of the thirteenth test operation. To realize the high productivity and low reducing agent rate, the effect of the mixed layer of ore and coke (proximate arrangement of ore and carbonaceous material) on reactivity and permeability was evaluated.[33] For the implementation of this test, in addition to the then existing hoppers for coke and ore use, an additional hopper was installed for charging the mixed materials of ore and coke which had been previously blended according to the predetermined weight ratio (Fig. 10).

Table 6 Layer structures of test cases

Base	Case1	Case2	Case3
Ore (10-25mm)	Mix (C:15-25mm) (O:10-25mm)	Mix (C:**10-15mm**) (O:10-25mm)	Mix (C:15-25mm) (O:10-25mm)
Coke (15-25mm)			
Ore (10-25mm)	Ore (10-25mm)	Ore (10-25mm)	
Coke (15-25mm)	Coke (15-25mm)	Coke (15-25mm)	

Table 6 shows the layer structure for each test case. The conventional layer structure of ore and coke charging is taken as the basis for comparison, and the following three cases of mixed layer arrangement were prepared: Case 1: half of the entire charging materials in terms of weight are mixed (partly mixed condition); Case 2: the coke of the mixed layer of Case 1 is grain-refined (partly refined-coke mixed condition); and Case 3: fully mixed case of Case 1 (completely mixed condition).

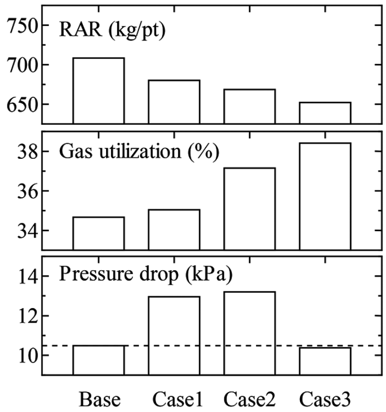

Fig. 26 Influence of layer structure on reducing agent rate, gas utilization and pressure drop

Figure 26 shows the result of each case of the test operation with respect to the reducing agent rate, top gas utilization efficiency, and the in-furnace pressure drop. Together with the order of increase in the mixing ratio, or the charging layer structure change from the conventional layer arrangement to the partial mixing and the complete mixing arrangement, the top gas utilization is improved and the reducing agent rate is enhanced. From the result of the measurement by the vertical probe, as compared with the base case of the conventional layer structure, in Case 3 of complete mixing, the thermal reserve zone temperature and the top gas temperature are lower, and improvement in the top gas utilization was confirmed. Furthermore, in the result of the dissection survey of the experimental blast furnace, in the mixed layer of coke and ore, the bedrock-like fusioned ore layer normally observed in the conventional ore/coke layer structure was not confirmed. This is considered to be attributed to the aggregate effect of the mixed coke. In the experimental blast furnace wherein the load exerted by the burden is smaller than that of a commercial blast furnace, the lowering of the pressure drop was not confirmed. In the cases of partial mixing, the pressure drop is higher than that of the base case, the phenomenon of which is considered to be attributed to the decrease in the void fraction of the packed bed, and the increase in the slag holdup caused by the coex-

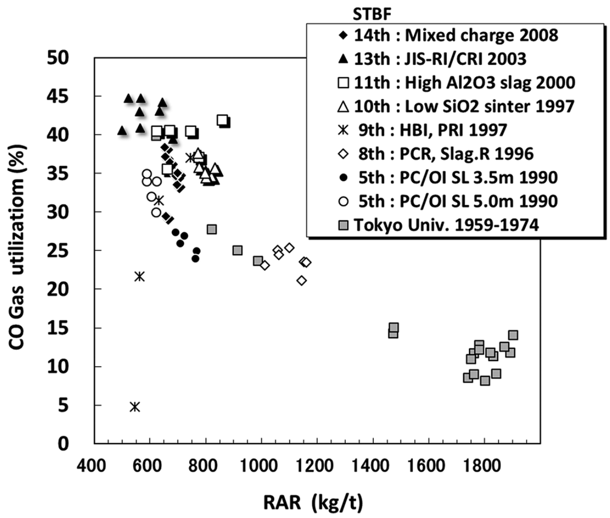

Fig. 27 Relationship between reducing agent rate and gas utilization of experimental blast furnaces

istence of the mixed coke of remarkably decreased grain size due to prior solution loss reaction and the relatively sound slit coke in the dripping zone.

4. Conclusion

Much information was obtained from the experimental blast furnace of Nippon Steel constructed in Hasaki after those in Higashida, Tobata, and that of the University of Tokyo which have supported the development of blast furnace operation technologies, and the information obtained continues to be used up to the present day. As for the problem of dissimilarity which is inevitable in a small-scale experimental blast furnace, thanks to the development of equipment and operation technologies, improvements in the reducing agent rate and the gas utilization have been achieved, approaching the commercial blast furnace levels as shown in **Fig. 27**.

Furthermore, owing to today's highly accurate mathematical models, the issue of dissimilarity has been considerably complemented, and the precise estimation of the operation of commercial blast furnaces based on the quantitative analysis of the operation result obtained from the experimental blast furnace has become possible. However, there is still room for further study on the effects of the in-furnace load on the difference in the ore-softening and shrinking behaviors of iron ore, and on the permeability. Therefore, the significance of the R&D method using an experimental blast furnace, together with the fundamental experiments and the utilization of mathematical models and the investigation on commercial blast furnaces, continues to be relevant.

The Hasaki experimental blast furnace, built in 1982 and used for the development and study of technologies including those of new processes for a quarter of a century, terminated its service in 2008, and was dismantled and removed with the hot stove included in 2018 after the completion of the technology transfer to the Kimitsu experimental blast furnace (furnace volume 12 m^3, completed in 2015) that was newly constructed for the COURSE50 Project.[4] To close this article, we wish to express herein our sincere gratitude to all who participated in the development and operation of Nippon Steel's experimental blast furnace.

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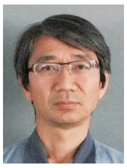
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