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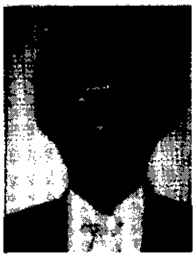
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1 Introduction

In addition to its conventional role as a stable producer of hot metal of specified quality, the blast furnace plays another important role as BF gas generator in optimizing the total energy balance of the integrated steelworks. When the new No. 3 Power Plant at Chiba Works was planned with a view to improving the energy balance of the Works, methods of blast furnace operation were sought which would efficiently increase BF gas generation under current production conditions.

To satisfy this requirement, high coke rate operation is necessary. In this method, coke in excess of the level of reducing and smelting the iron ore is burned by a part of blast air coming through tuyeres so as to recover CO gas. The high coke rate operation itself is nothing new. But it was used to raise the furnace temperature, or, as in foundry iron operation, to supplement [Si] reduction heat. There are entirely different from the subject case.

An increase in coke rate, under constant production, is accompanied by changes in BF gas generation volume, hot stove heat consumption, electric power consumption for blasting, and top-gas pressure generated electricity. Before raising the coke rate, it is important to evaluate the coke energy recovery efficiency of the blast furnace process, which is expressed by

$$\frac{\text{Increment of top gas latent heat} + \text{changes in top-gas pressure recovery electric power}}{\text{Increment of coke energy} + \text{changes in hot stove heat consumption} + \text{changes in electric power for BF blast}}$$

Technical requirements include establishing an operation method which will not only prevent the potential

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energy of coke charged from being lost in any such form as increases in Si, top gas temperatures, and heat losses, but will switch the potential losses into effective recovery. If coke energy recovery efficiency drops to 50% or below, raising the coke ratio becomes economically meaningless at the present energy prices.

This report describes high coke rate operation tests carried out under various conditions, and evaluates coke energy recovery efficiency in the blast furnace process.

2 Concept of High Coke Rate Operation

2.1 Heat Balance in Blast Furnace

One typical example of high coke rate operation is foundry iron operation. **Table 1** shows a comparison in operational particulars for a productivity of 1.8 (t/d · m^3) between hot metal smelting at the Chiba No. 6 blast furnace and foundry iron smelting at the Chiba No. 2 blast furnace. In general, a rise in coke rate results in a rise in hot metal temperatures and [Si], and a drop in gas utilization rate brings about a rise in top gas temperatures.

A comparison of the blast furnace heat balance between hot metal smelting and foundry iron smelting is shown in **Table 2**. In normal smelting operation, when the heat input total is, for instance, 3 815.9 × 10^3 kcal/t, unrecovered energy amounts to 344.1 × 10^3 kcal/t, and this includes the sensible heat of slag, the sensible heat of top gas, heat loss, and evaporation heat of moisture, indicating a blast furnace effective energy utilization of about 91%. Heat loss, here, is an unknown heat loss which is the calculated difference between heat output terms and heat input terms and corresponds to heat radiated from the furnace wall and hearth. Heat loss ranges from about 50 to 200 × 10^3 kcal/t, depending upon the operating conditions and blast furnace volume, and affects the effective energy utilization rate.

In foundry iron operation, the heat input total is 4 459.2 × 10^3 kcal/t, and the heat input energy increment due to an increased coke rate amounting to 643.3 × 10^3 kcal/t is consumed by the reduction heat of [Si], the sensible heat of top gas, and an increase in heat loss, besides raising the latent heat of the top gas. The ratio of recovered energy to changes in input heat energy at the blast furnace proper is defined by Eq. (1) below, where the first term is the recovery ratio of the latent heat of top gas, and the second term is the reductive heat ratio of [Si].

Table 1 Comparison of blast furnace operation between steelmaking iron and foundry iron

		Steelmaking iron	Foundry iron
Coke rate	(kg/t)	472.0	547.0
Blast wind rate	(Nm^3/t)	1 032.8	1 888.4
Blast temp.	(°C)	1 151.0	996.0
Blast moisture	(g/Nm^3)	27.9	29.8
Top gas temp.	(°C)	170.0	180.0
CO gas utilization	(%)	51.8	49.7
Hot metal temp.	(°C)	1 493.0	1 553.0
[Si]	(%)	0.37	2.32

Table 2 Comparison of heat balance in blast furnace between steelmaking and foundry iron smelting process (10^3 kcal/t)

		Steelmaking iron	Foundry iron	Difference	
Input	Combustion of carbon in coke	3 363.7	3 898.2		
	Sensible heat of blast	410.0	520.2		
	Productive heat of slag	42.1	40.9		
Output	Reduction heat of oxide of Fe	1 680.0	1 680.0		
	Reduction heat of oxide of [Si] etc.	39.8	183.6	143.8	22.3%
	Latent heat of the top gas	1 061.6	1 332.2	270.6	42.0%
	Sensible heat of the top gas	87.6	122.5	34.9	5.4%
	Sensible heat of pig	319.1	331.4	12.3	1.9%
	Sensible heat of slag	128.3	129.6		
	Latent heat of carbon in pig	367.6	371.7		
	Latent heat of carbon in dust	3.5	2.7		
	Evapolation heat of moisture in material	4.0	4.0		
	Heat loss	124.2	301.6	177.4	27.6%
Total		3 815.9	4 459.2	643.3	100%

$$\eta_{blast} = \eta_{BGAS} + \eta_{Si} = \frac{\text{Changes in latent heat of top gas}}{\text{Combustion heat of increment coke} + \text{changes in sensible heat of blast}} + \frac{\text{Increment of reductive heat of [Si] in pig iron}}{\text{Combustion heat of increment coke} + \text{changes in sensible heat of blast}} \quad \cdots\cdots (1)$$

Evaluation of high coke rate operation of foundry iron by Eq. (1) gives $\eta_{BGAS} = 42.0\%$, $\eta_{Si} = 22.3\%$, and η_{blast} (ratio of recovered energy to heat input increment)

= 64.8%. The high coke rate operation which aims at increasing top gas generation is intended to prevent the conversion of the increment of input heat energy into increases in hot metal temperature, [Si], or heat loss, and, rather, to recover it as latent heat of top gas. Ideally, the first term alone in Eq. (1) should approximate 100% as closely as possible.

2.2 Energy Balance of Blast Furnace

A conceptual diagram of the energy balance of a blast furnace system consisting of blower, hot stove, blast furnace, and top-pressure revovery electric power generation is shown in **Fig. 1**. If blast furnace operation is changed to high coke rate operation, power energy for both the blast furnace proper and its auxiliary facilities also greatly change. An increment of coke energy is accompanied by a drop in unit heat consumption of the hot stove, increase in power convertible to blast attributed to the combustion of increment coke, and an increase in recovered electric power arising from the increase in BF gas generation. It thus becomes necessary to consider an overall blast furnace coke energy recovery efficiency plan which will incorporate all these above factors. Coke energy recovery efficiency (changes in output energy/changes in input energy) of the blast furnace process is evaluated by Eq. (2) below.

$$\eta_{all} = \frac{\Delta BGAS + \Delta TRT}{\Delta CR + \Delta HS + \Delta BV + \Delta O_2 + \Delta BM} \quad \cdots\cdots (2)$$

where

ΔBGAS: Increment of latent heat of top gas

ΔTRT: Changes in BF top gas pressure recovered electric power

ΔCR: Increment of coke energy

ΔHS: Changes in hot stove heat consumption

ΔBV: Changes in power for blast

ΔO_2: Changes in power for oxygen enrichment

ΔBM: Changes in moisture-adjusted steam

To minimize the total energy cost of a steel mill, it is necessary to maximize coke energy recovery efficiency in the blast furnace system. As the necessay conditions for this among the heat balance factors in the blast furnace proper, it is important to maintain low η_{Si} and high η_{BGAS} levels.

3 Operation Design for High Coke Rate Operation

In formulating an operation design, the following matters have been studied and an operation test plan set up:

(1) Comparison in operation method between foundry iron operation and high coke rate operation aiming at BF gas generation
(2) Prediction of blast-furnace coke energy recovery efficiency under constant heat loss conditions based on the blast furnace heat balance model
(3) Location of problems in operating techniques

3.1 Comparison with Foundry Iron Operation Method

In general, absorption of [Si] into hot metal is a transition reaction proceeding by way of SiO gas and in a process where SiO gas and is first generated, and then [Si] is absorbed from it, as follows:

$$SiO_2(l) + C(s) \longrightarrow SiO(g) + CO(g) \quad \cdots\cdots (3)$$

$$SiO(g) + \underline{C} \longrightarrow \underline{Si} + CO(g) \quad \cdots\cdots (4)$$

A comparison of calculations of various in-furnace variables obtained using the non-steady, unidimensional [Si] simulation mode,[1] developed by Kawasaki Steel, is shown in **Fig. 2**. Using this simulation model, the mechanism of the [Si] transition process in high coke rate operation is explained below.

A portion of the high-temperature gas, which burns in front of the tuyeres, heats the descending coke by solid-gas heat transfer and generates SiO(g) in Eq. (3)

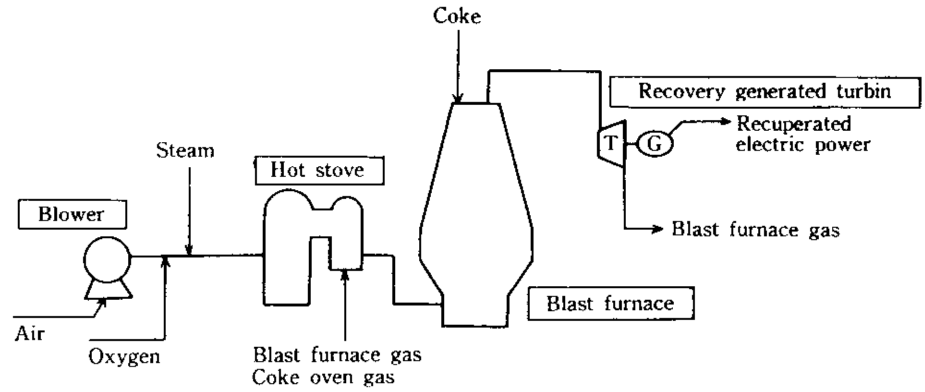
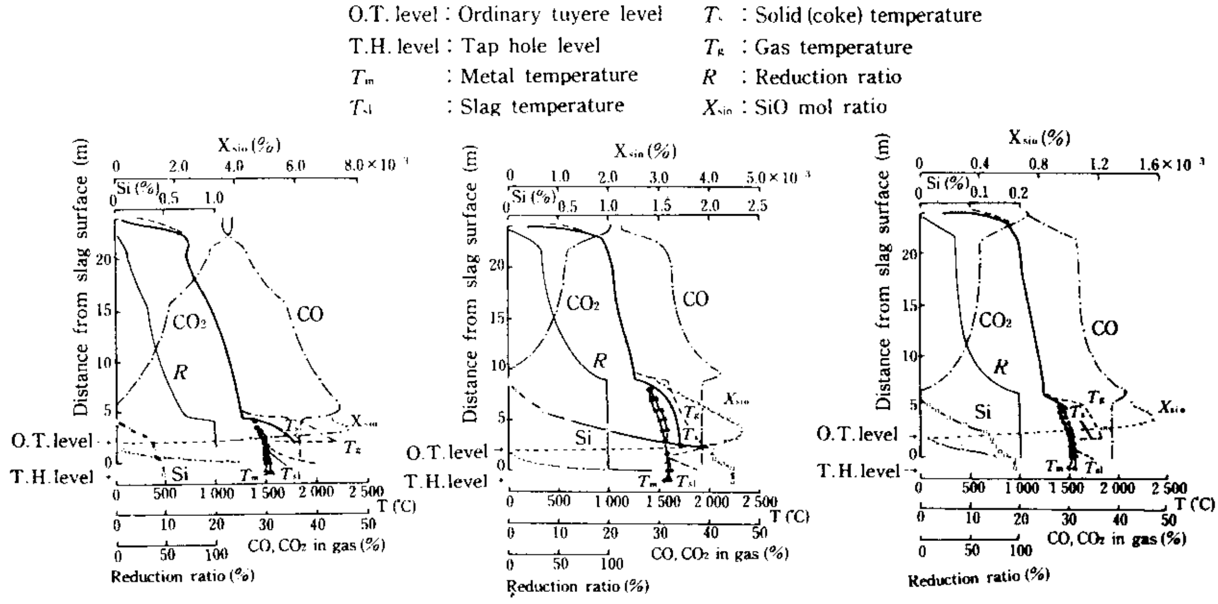


Fig. 1 Energy flow sheet for blast furnace process



(a) Steelmaking iron operation (b) Foundry iron operation (c) High coke rate operation

Fig. 2 Comparison of distribution of in-furnace variables among steelmaking iron operation, and foundry iron operation, and high coke rate operation

according to the reaction rate constant K in Eq. (5) corresponding to the solid coke temperature T_S.

$$K = A \exp\left(-\frac{Q}{R \cdot T_S}\right) \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

The remaining high temperature gas also promotes the endothermic reaction in Eq. (3). As a result, a well-balanced coke temperature T_S is determined, and the hot metal temperature is regulated by solid-liquid transfer.

The figure indicates that the coke temperature T_S for foundry iron operation in Fig. 2 (b) starts at a higher level than that for the steelmaking iron operation, shown in Fig. 2 (a). This indicates that in foundry iron operation, as shown in Table 1, excess heat input has occurred, in spite of drastic reduction of the ore/coke load, because lowering of blast temperature is minimal. Consequently, the heat input promotes the transition to the right side of Eq. (3), in addition providing the thermal energy necessary for raising the hot metal temperature. The level at which the temperature increase begins is therefore raised while the coke solid temperature T_S hardly changes, thereby expanding the high temperature region. Here, the level at which the temperature increase begins may well be considered to be on the melting zone bottom-end level, and has risen to a position higher than that in steelmaking operation. Thus it can be said that since it requires a relatively long period for hot metal to drip through the high-SiO-mol-ratio-gas in the foundry iron operation, the [Si] content of the hot metal rises.[2]

On the other hand, Fig. 2(c) shows the distribution of various in-furnace variable in an operation which is based on the foundry iron operation. Blast temperature is lowered until the hot metal temperature is the same as in the steelmaking iron operation. Compared with furnace temperature distribution of steelmaking hot metal in Fig. 2(a), it was found that the melting zone level was high, but gas temperature T_S was lower, and thus the solid coke temperature T_S also became lower; the amount of SiO generated under melting zone level showed as a conspicuous decrease and there was no rise in [Si] was observed in the foundry iron operation.

As mentioned above, the fundamental difference between the foundry iron operation and high coke rate operation is that in foundry iron operation, it is desirable to maximize tuyere heat input per unit weight of pig iron, while the aim of high coke operation is to minimize this input.

3.2 Operation Prediction by Blast Furnace Balance Model

Quantitative determination of energy recovery efficiency in high coke rate operation has been examined using a heat and material balance model of the blast furnace. A scheme of the blast furnace balance model is shown in **Fig. 3**. It is static balance model based on the assumption that a thermal reserve zone exists.[3] By using the CO gas utilization ratio α^*, which is presumed to coexists with wustite in the thermal reserve zone, after correction for the hydrogen content in front of the tuyere (H_2), thermal flow ratio (WER), and heat loss (QL), the unit consumption of blast wind and coke rate

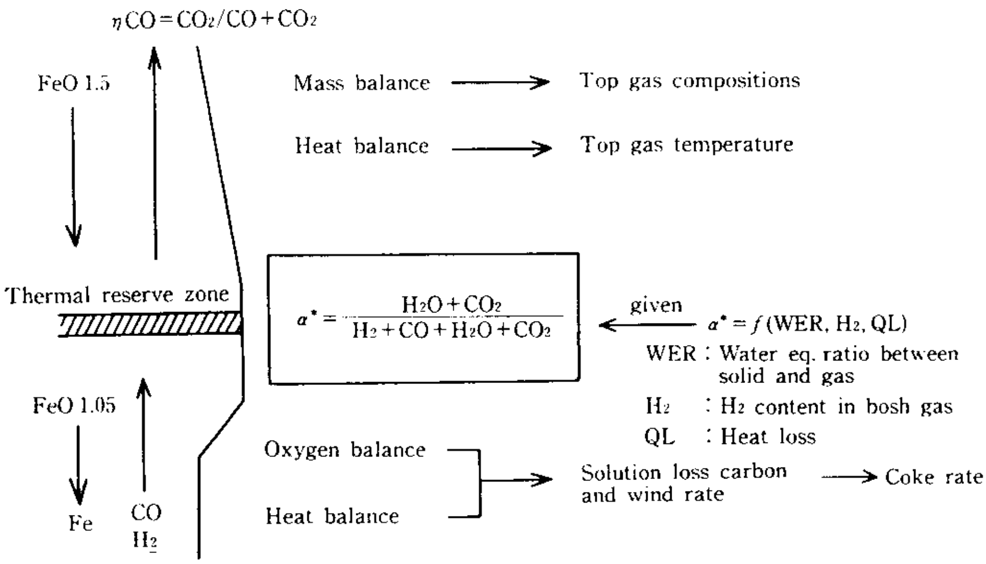


Fig. 3 Schema of the calculated heat and material balance model

can be obtained from the heat balance and oxygen balance in the lower part of the furnace, and the top gas temperature and top gas calorie can be obtained from the heat balance and material balance in the upper part of the furnace. Correction coefficients of α^* are 0.82%/1.0% for H_2, 0.8%/0.1 for WER, and 0.75%/10^4 kcal/t for QL. Here, changes in [Si] due to operation changes are predicted using influence coefficients[4] such as productivity, thermal flow ratio, theoretical flame temperature, and H_2 content in front of the tuyere.

In **Table 3**, prediction results for high coke rate operation, when blast temperature is lowered and blast wind moisture is increased, are shown as a typical calculation example, in comparison with measured results. The measured value of [Si] is higher than the calculated value by 0.04%, and that heat loss is 2.5×10^3 kcal/t than calculated. The error in coke rate with respect to the calculated value, i.e., [(calculated value–measured value)/measured value], is +0.6%, and the error in the generated amount of the top gas with respect to the calculated value is about 1.4%. **Table. 4** shows the result of a trial calculation of energy recovery efficiency in the blast furnace system, using these calculation results. Assuming that the heat exchange ratio at the hot stove is 85%, electric power required for blast is 120 kcal/Nm^3-air, electric power for oxygen generation is 1 760 kcal/Nm^3-O_2, moisture adjustment is 730 kcal/kg, and top-pressure recovered electric power (1 kW · h = 2 450 kcal) is proportionate to the volume of the top gas, then the coke energy recovery efficiency of the blast furnace will be 73.1%, and the energy loss in the blast furnace process will be 36×10^3 kcal/t. If the heat loss of the blast furnace proper is increased by 10^4 kcal/t, energy recovery efficiency will drop by about 7.5%. Moreover, if [Si] is

Table 3 Comparison between calculated operational factors and actual operational results at high coke rate operation

	Base	Calculation	Operated results
Productivity (t/m^2·d)	52.22	59.44	59.44
Coke rate (kg/t)	472.1	491.9	489.2
Wind rate (+O_2) (Nm^3/t)	1 032.8	1 067.8 (+10.2)	1 069.7 (+10.2)
Blast temp. (°C)	1 151.0	1 005.0	1 005.0
Blast moisture (g/Nm^3)	27.9	41.5	41.5
Theoret. flame temp. (°C)	2 372	2 198	2 198
Top gas volume (Nm^3/t)	1 529.2	1 600.0	1 599.3
B gas calorie (kcal/Nm^3)	695.6	724.3	735.0
CO gas utilization (%)	51.84	50.87	49.97
Top gas temp. (°C)	166.6	195.8	189.0
[Si] (%)	0.37	0.23[1)]	0.27
Heat loss (10^3 kcal/t)	72.9	72.9	75.4
Water equiv. ratio	0.820	0.790	0.795
H_2 in front of tuyere (%)	3.39	4.53	4.53
α^* (%)	26.44	27.17[2)]	27.59

1) Influence coefficient of [Si]
0.15%/10 t/m^2·d
0.07%/100°C TFT
−0.04%/1% H_2
−0.03%/0.01 WER

2) Correct coefficient of α^*
0.82%/1% H_2
0.80%/0.10 WER
0.74%/10^4 kcal/t QL

Table 4 An example of energy balance in blast furnace process under high coke rate operation

Factors	Calculation of change of energy	Results
ΔCR	$(491.9-472.1)$ kg/t × 7 200 kcal/kg	142.6×10^3 kcal/t
ΔHS	(1 005°C × 1 067.8 Nm^3/t − 1 151°C × 1 032.8 Nm^3/t) × 0.3 kcal/Nm^3°C/0.85	-40.8×10^3 kcal/t
ΔBV	$(1\,067.8-10.2-1\,032.8)$ Nm^3_{air}/t × 120 kcal/Nm^3_{air}	3.0×10^3 kcal/t
ΔO_2	$(10.2-0)$ $Nm^3_{O_2}$/t × 1 760 kcal/$Nm^3_{O_2}$	18.0×10^3 kcal/t
ΔBM	(1 067.8 Nm^3/t × 41.5 g/Nm^3 − 1 032.8 Nm^3/t × 27.9 g/Nm^3) × 720 kcal/1 000 g	11.2×10^3 kcal/t
$\Delta BGAS$	724.3 kcal/Nm^3 × 1 600.0 Nm^3/t − 695.6 kcal/Nm^3 × 1 529.2 Nm^3/t	95.2×10^3 kcal/t
ΔTRT	24.5 kW·h/t × (1 600.0 Nm^3/t/1 529.2 Nm^3/t − 1) × 2 450 kcal/kW·h	2.8×10^3 kcal/t
Energy recovery efficiency; $\eta_{all} = \dfrac{\Delta BGAS + \Delta TRT}{\Delta CR + \Delta HS + \Delta BV + \Delta O_2 + \Delta BM}$		73.1%

increased by 0.1%, which corresponds to an increase in heat loss of about 7.5 × 10^3 kcal/t, energy recovery efficiency will drop by about 5.5%.

3.3 Experimental Operation Plans

As mentioned above, very important factors in avoiding drops in energy recovery efficiency are preventing increases in the [Si] content of hot metal and in heat loss. In actuality, however, lowering of the thermal flow ratio tends to increase the heat loss, as shown in **Fig. 4**. Therefore, in addition to stave thermal load control by normal burden distribution control for suppressing increases in heat loss and [Si] during high coke rate operation, the following experimental operation plans were devised.

There were two methods of coke gasification besides the ordinary method of buring coke with blast air ($C + 1/2\,O_2 + N_2 \rightarrow CO + N_2$):

(1) A water gas reaction using blast moisture ($C + H_2O \rightarrow CO + H_2$)

(2) Burning of coke with enrichment oxygen ($C + 1/2\,O_2 \rightarrow CO$)

Method (1) is applied when productivity is low and [Si] is high; method (2) when productivity is high and the blast volume is larger.

Method (1), the blast moisture method, is an endothermic reaction in which it is possible to maintain a lower theoretical flame temperature and a higher degree of SiO (g) generation suppression than when the coke rate is increased by lowering sensible blast heat. In method (2), the oxygen enrichment method, unnecessary N_2 is nil and the bosh gas increment small compared with simple coke burning by blast air; this prevents a drop in the thermal flow ratio.

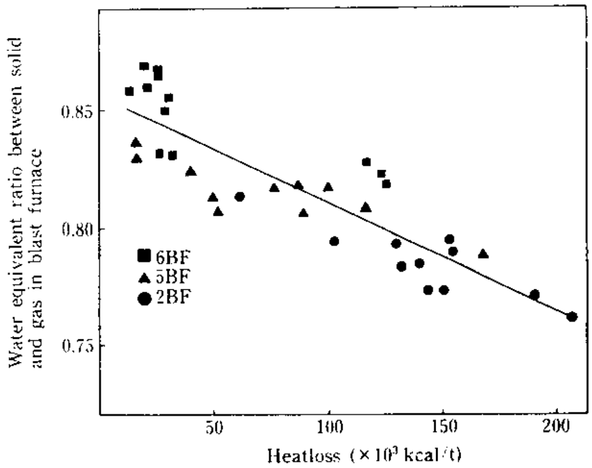


Fig. 4 Effect of water equivalent ratio on heat loss for solid and gas

Table 5 Comparison of experimental operating plans at Chiba Nos. 5 and 6 BF

Productivity (t/d·m^3)	1.4*1)			1.7*1)		2.0*2)	
Experimental plan	Case 1			Case 2		Case 3	
	(Base)	Step 1	Step 2	(Base)		(Base)	
Coke rate (kg/t)	500	525	535	520	540	480	495
Blast moisture (g/Nm^3)	25	25	45	30~35	30~35	40	40
Blast temp. (°C)	1 100	900~950	900~950	1 100	850	1 100	950~1 000
Blast wind (Nm^3/min)	3 000	3 250	3 200	3 750	4 100	6 600	6 600
Oxygen enrichment (Nm^3/h)	0	0	0	0	0	0	6 000

*1) No. 5BF (2 584 m^3)
*2) No. 6BF (4 500 m^3)

In **Table 5**, a comparison is made of 3 cases given as an example of high coke rate operation plans in furnaces set up for the methods discussed above. In the Table, case 1, step 2 corresponds to the blast moisture method, and case 3 to the oxygen enrichment method.

4 Operation Results and Discussion

4.1 Comparison of Heat Balance of Blast Furnaces and Comparison of Energy Recovery Efficiency of Blast Furnace Process

A comparison of the heat balances of the blast furnace

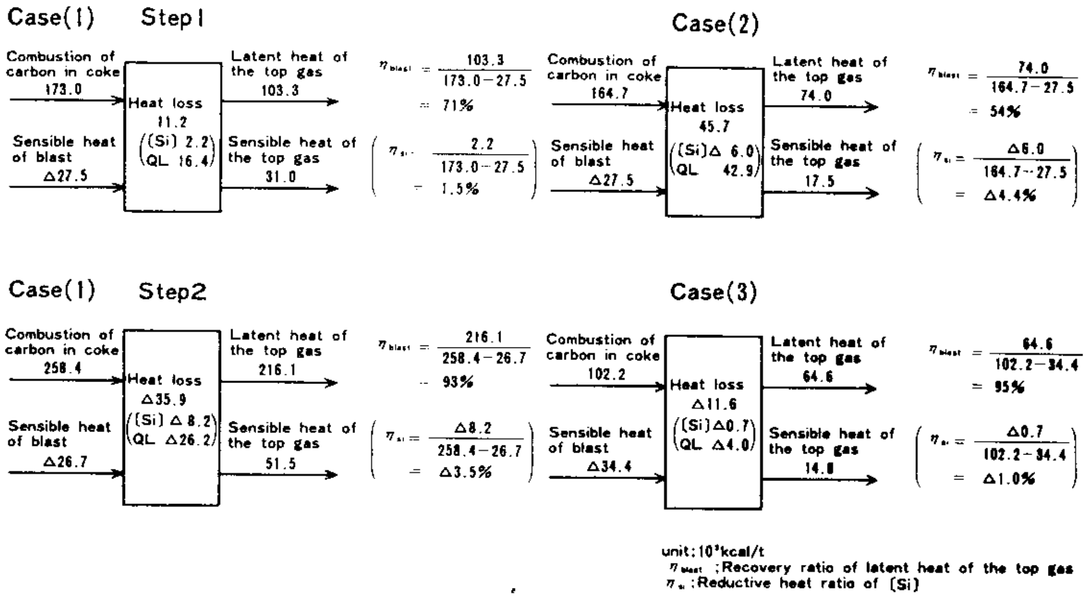


Fig. 5 Comparison of energy balances at blast furnace

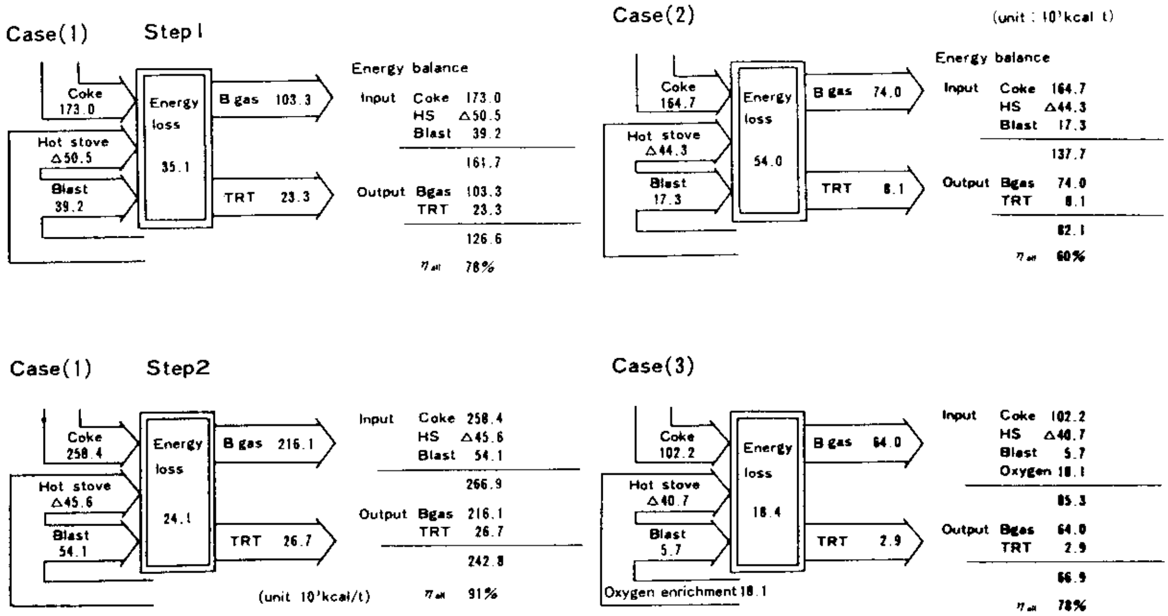


Fig. 6 Comparison of energy balance and recovery coke energy efficiency in blast furnace process

proper in various experimental steps is shown in **Fig. 5**; a comparison of energy recovery efficiency values in the blast furnace system is shown **Fig. 6**. In case 2, where the heat loss of the blast furnace proper greatly increased, the top gas latent-heat recovery ratio η_{BGAS} in the first term of Eq. (1) was as low as 54%, although η_{Si}, which was defined by the second term of Eq. (1) was as low as −4.4%, and energy recovery efficiency η_{all} as defined in Eq. (2) reached only 60%. On the other hand, in two cases, namely, case 1, step 2 where the heat loss of the blast furnace proper dropped greatly, followed by a drop in Si in hot metal; and case 3 where an increase in thermal flow ratio due to oxygen enrichment made a lowering of heat input possible, the top gas latent-heat recovery ratio η_{BGAS} of the blast furnace proper as indicated in Eq. (1) came to achieve a high efficiency of 93 to 95%.

The energy recovery efficiency η_{all} of the blast furnace system defined in Eq. (2) reached 91% in case 1, step 2, where heat loss dropped, and reached 78% in case 3, where electric power was required for oxygen enrichment. These results suggest that in case 1, step 1, and in case 3, it is possible to achieve a blast-furnace energy recovery efficiency of 70 to 80%, depending upon productivity. These results show fairly good agreement with the values calculated on the basis of the blast furnace heat and material balances.

4.2 Heat Loss Control of Blast Furnace Proper

Case 1, step 1 was not different from case 2 in fundamental operation method, as in both coke was gasified by blast air in the same blast furnace. In spite of this, a great increase in heat loss was incurred in case 2. Therefore, heat loss control in the blast furnace was examined.

4.2.1 Relation between operating conditions and burden distribution control

The conventional heat loss control method for the blast furnace is burden distribution control. By this method, control indices of heat loss such as furnace body temperatures at the bosh and stack, or, stave thermal load obtainable from the temperature difference between the supply and discharge waters to and from the stave and the volume of cooling water, are controlled at proper values adequate to operational levels.

In **Fig. 7**, operation changes under all coke operation at Chiba No. 6 blast furnace are shown in a graph having coke rate as the abscissa and productivity as a parameter on the ordinate. Gas distribution in the furnace radial direction for the typical operation periods I, II, and III in Fig. 7 are shown in **Fig. 8**. When production changed from period I, decreased production at a low coke rate to period II, increased production, the CO gas distribution was adjusted to suppress the peripheral flow with an increased η_{CO} at the furnace wall. In period III, increased production at a high coke rate, the CO gas distribution adopted was a central flow (and suppression of peripheral flow) with lower η_{CO} at the center, thereby preventing an increase in stave thermal load.

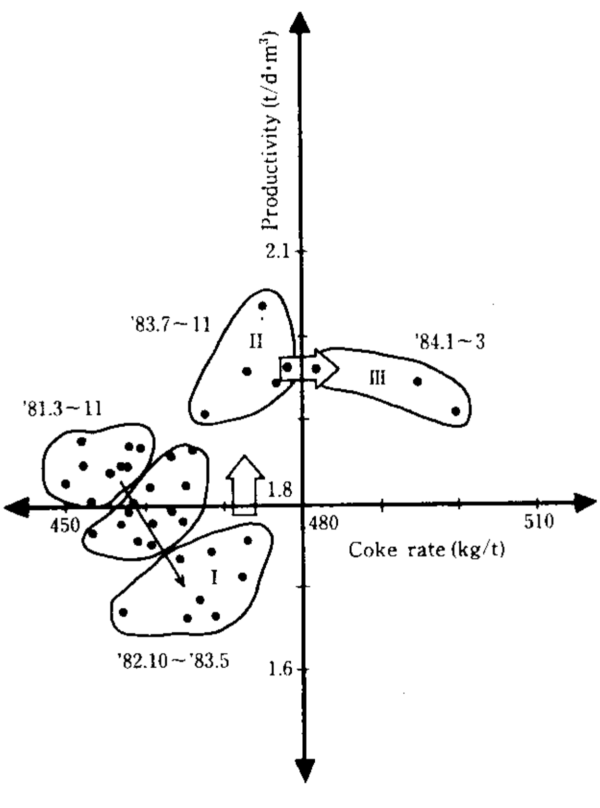


Fig. 7 Changes in coke ratio and productivity at No. 6BF

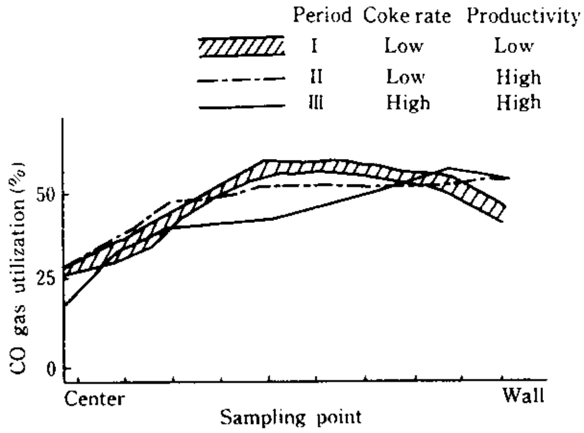


Fig. 8 Comparison of typical gas distribution between respective periods; i.e., period I, II, and III in Fig. 7

Such operation results were evaluated by physical indices, using the thermal flow ratio indicated heat exchange ratio between burden heat capacity and top gas thermal capacity instead of the coke rate, and using the bosh gas volume instead of productivity, with a view to using reduction gas volume per unit time. The results are summarized in **Fig. 9**. Numerals in the figure indicate the layer thickness ratios[5] of coke and ore at the furnace wall calculated from soundings; these ratios are indices to be adjusted in line with changes in the bell-less pattern, charging sequence, and stock line. Straight lines in the figure show an equal-percentage L_o/L_c conceptual chart.

This chart suggests that when the bosh gas volume increases, indicating increased production, and the thermal flow ratio decreases, as with a high coke rate, heat exchange ratio in the furnace decreases and stave thermal load at the furnace wall rises, thus requiring an increase in the layer thickness ratio at the furnance wall, which will result in a suppression of peripheral flow. The chart also suggests that during decreased production when the bosh gas volume decreases, or in oxygen enrichment operation in which the thermal flow ratio is high, and in low coke rate operation, peripheral flow due to lowering of L_o/L_c is required, in order to suppress the growth of the non-active zone near the furnace wall.[4]

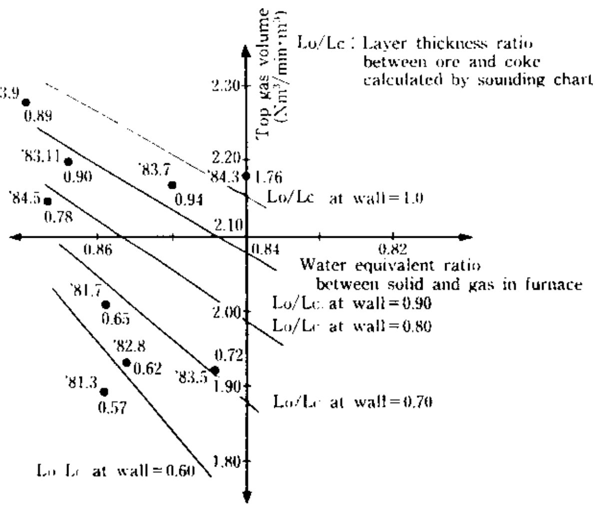


Fig. 9 Equal-percentage L_O/L_C conceptual chart using water equivalent ratio between solid and gas, and furnace gas volume as parameters

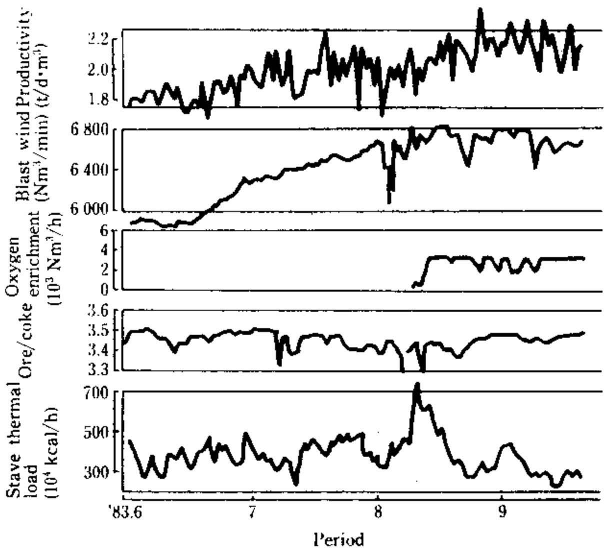


Fig. 10 Changes in operational variables with increasing productivity of No. 6BF

Stave thermal load, on the other hand, greatly depends on bosh gas volume, thermal flow ratio, and layer thickness ratio at the furnace wall. The relation of these factors is given by the result of a multiple correlation analysis:

Stave thermal load (10^4 kcal/h) = 540 (bosh gas volume) − 11 000 (thermal flow ratio) − 380 (L_o/L_c) + 9 000 ($N = 9, \gamma = 0.8$) ··················(6)

The absolute value of stave thermal load may vary with the residual thickness of furnace refractories and the productivity. In high coke rate operation in which stave thermal load is constant, however, it is important to restrict heat loss through control of three important operating conditions, bosh gas volume, thermal flow ratio, and layer thickness ratio.

4.2.2 Bosh gas volume and heat loss

Changes in operational variables of the Chiba No. 6 blast furnace during an increased production period are shown in **Fig. 10**. In particular, stave thermal load shows a good correspondence to the heat loss rise when blast volume is around 6 700 Nm^3/min and oxygen enrichment is later used. Top gas volume at this time is about 9 400 Nm^3/min, which is converted to a blast furnace unit internal volume of about 2.10 $Nm^3/min \cdot m^3$. Top gas volumes in various experimental periods, shown earlier in Table 5, were 1.7 to 1.8 $Nm^3/min \cdot m^3$ for case 1, 2.25 $Nm^3/min \cdot m^3$ for case 2, and 2.05 $Nm^3/min \cdot m^3$ for case 3. In case 2, top gas volume is increased above that for the increased production period shown in Fig. 10. The limit of top gas volume has been examined by various workers,[6] but has not yet been quantitatively determined.

As a general method, the channeling limit is trialcalculated from resistance of furnace permeability using Carman's equation:

$$\Delta P/L = \Phi \cdot \mu^{\beta} \cdot \rho_g^{1-\beta} \cdot u^{2-\beta} \quad \cdots\cdots\cdots\cdots (7)$$

where ΔP is a pressure drop between low and high stacks, L is distance, μ is gas viscosity, and ρ_g is gas density. Using gas velocity $G = \rho_g \cdot u$, Eq. (7) is transformed into

$$\Phi = (\Delta P/L) \cdot \rho_g/\mu^{0.3} G^{1.7} \quad \cdots\cdots\cdots\cdots (8)$$

By substituting into Eq. (8) the values of variables before the rise in stave thermal load shown in Fig. 10, i.e., $\Delta P/L = 0.2328$ g/cm³, $\rho_g = 1.1252 \times 10^{-3}$ g/cm³, $G = 0.1335$ g/cm²·s, and $\mu = 420 \times 10^{-6}$ g/cm·s, the value of $\Phi = 0.0828$ is obtained.

Now assuming that the channeling limit is $\Delta P/L = \rho_{coke} = 0.5$ g/cm³, $G = 0.2092$ g/cm²·s is obtained, and assuming that the throat areas of Chiba Nos. 5 and 6 blast furnaces are 50 and 87 m² respectively, the channeling limit gas volumes will be 5 600 and 9 700 Nm^3/min respectively. Top gas volumes per unit inner volume are 2.17 and 2.16 $Nm^3/m^3 \cdot min$, respectively.

As blast furnace operation is a process with uneven radial permeability the above calculation results cannot confirm that channeling has in reality occurred, but it at least can be said that the channeling limit has been approximated. If this condition occurs at a location which is localized in the radial direction, there is a high possibility that channeling cannot be controlled by burden distribution control. To prevent heat loss increase during high coke rate operation, effective means include not only the above-mentioned peripheral flow control by burden distribution control, but also blast moisture addition at as in case 1, step 2 and coke gasification by oxygen enrichment as in case 3 in which an increase in the top gas volume is suppressed. This has been confirmed by the fact that the heat loss of the blast furnace proper was lowered, even though slightly, in the above two cases, as described in Fig. 5.

4.3 Low [Si] Smelting under High Coke Rate Operation

The relation between [Si] in hot metal and hot metal temperature during case 1, step 2 is shown in **Fig. 11**, which indicates that lowering [Si] by about 0.1% is possible with the same hot metal temperature maintained. All three other cases also show no such great increase in [Si] as was observed in the [Si] reduction heat usage ratio η_{Si} shown in Fig. 5. The reason for this may be the fact that in all cases the sensible heat of blast was lower compared with base operation, and this condition suppresses the reaction shown in Eq. (2). This proves that it is possible to conduct low [Si] smelting, even in high coke rate operation where the thermal flow ratio is low and the melting level is high, by lowering the tuyere heat input as far as possible.

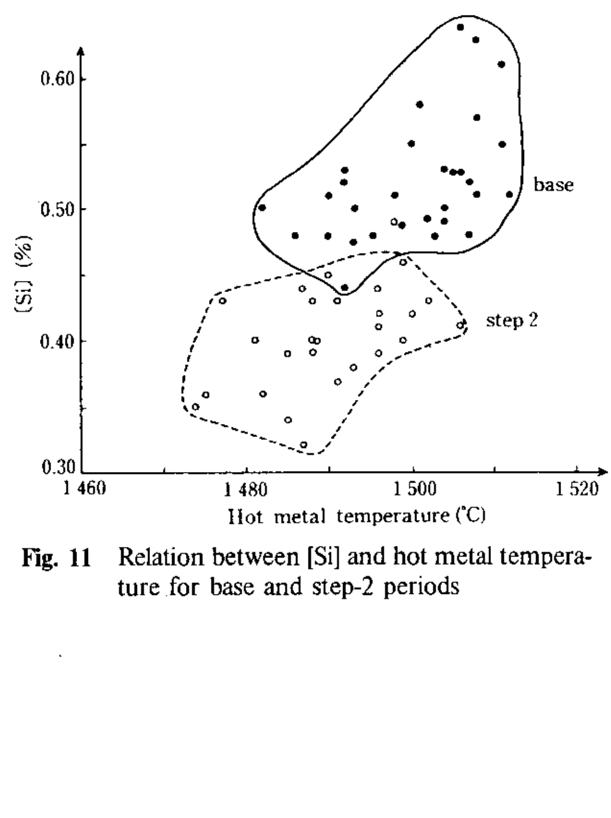


Fig. 11 Relation between [Si] and hot metal temperature for base and step-2 periods

5 Conclusions

To satisfy the needs of increasing a BF gas generation to prepare for the commissioning of the new No. 3 Power Plant, various high coke rate operation experiments were planned at Chiba Nos. 5 and 6 blast furnaces, with attempts made to determine the coke energy recovery efficiency of the blast furnaces. Results of the experiments are summarized below.

(1) Even in high coke rate operation, an increase in [Si] in hot metal can be prevented by lowering heat input in front of the tuyere.
(2) Peripheral flow suppression by burden distribution control and the combined use of oxygen enrichment and blast moisture addition in view of bosh gas volume can prevent the heat loss increase accompanying high coke rate operation.
(3) While the heat loss and [Si] are constant and productivity remains within the range of 1.4 to 2.0 $t/d \cdot m^3$, it is possible to achieve a coke energy recovery efficiency of 70 to 80%, which is near the theoretical value.

On the basis of these findings, it has been possible to conduct continuous, stable high coke rate operation, thereby greatly contributing to the realization of the energy strategy of the steelworks.

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