Limits of Oxygen Enrichment, Tuyere Fuel Injection, and Prospect of Stack Gas Injection in an Experimental Furnace*

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Synopsis

The phenomena taking place in applying oxygen enrichment to blast furnaces were studied by using an experimental furnace (0.63 m^3). A slight decrease in the coke rate was obtained at the ratio less than 4% oxygen enrichment, but beyond this rate, it increased by more than 2.5 kg/tHM for every 1% of enrichment due to the increase in direct reduction. Beyond the ratio of 9% oxygen enrichment, the temperature of the thermal reserve zone decreased up to 15%. Although an appropriate amount of fuel injection through normal tuyeres improves this condition, there existed a possible operation range restricted by the upper limit of the heat content ratio, a lower limit of the theoretical flame temperature, and a lower limit of the excess oxygen ratio. The limit of tuyere fuel injection, even with more than 4% of oxygen enrichment, was estimated to be about 110 kg/tHM of fuel oil.

Reformed gas was produced by partial combustion of oil with oxygen injected into the stack of an enlarged experimental furnace (3.2 m^3). The coke rate was decreased from 570 to 361 kg/tHM by injecting $628\text{ Nm}^3/\text{tHM}$ of gas. This decrease was proved to come from the increase in gaseous reduction of 20%, the sensible heat of the injected gas, and the decrease in heat loss. The stack gas injection of $512\text{ Nm}^3/\text{tHM}$ together with 7% of oxygen enrichment prevented the retardation of the heat exchange caused by oxygen enrichment and achieved a high productivity without any increase in the coke rate.

I. Introduction

Tuyere fuel injection with oxygen enrichment has become economical in Japan due to the recent rise in the price of coking coal. Studies so far made on the effect of oxygen enrichment are the theoretical research conducted by J. Michard¹⁾ and experiments carried out in experimental furnaces of CRM²⁾ and of the U.S. Bureau of Mines.³⁾ According to the previous reports,^{4,5)} it should be noted that the limit of tuyere injection would be about 110 kg/tHM of auxiliary fuel even with more than 4% of oxygen enrichment.

Fuel injection beyond this limit was achieved by injecting the reformed gas into the furnace stack. The aim of this technique is to reduce the ore burden by the cheap reformed gas produced from various hydrocarbons in the shaft of the blast furnace; the minimum amount of coke that can be saved would amount to approximately 200 kg/tHM.^{6,23)} In the blast furnace, the inevitable difficulties in a shaft reduction of ores can be avoided by small amounts of coke acting in the form of inert material as the reducing agent. Experimental operation with reformed gas injection has already been tested in Pompey,⁷⁾ the U.S. Bureau of Mines,⁸⁾ Nippon Steel,⁹⁾ and CRM¹⁰⁾ but it is still in the development stage.

II. Experimental Procedures¹¹⁾

An original experimental furnace (Fig. 1) of two pebble stoves, heating the air up to 1100°C and with an automatic conveyor charging system capable of 2 000 charges per day, was built in 1967. In 1969, the furnace was enlarged to six times as large as its original scale (Fig. 1) and heavy insulation was adopted to keep the heat loss level on a par with that of a commercial furnace. Thus the enlarged furnace can be operated at about 550 kg/tHM of coke rate with 100% of self fluxed sinter.

III. Phenomena of Oxygen Enrichment and Its Limit

The effect of oxygen enrichment for increasing production is a well-known fact, but there are two opposite results^{12,13)} reported for the coke rate. In order to explain quantitatively the phenomena of the influence of oxygen enrichment and its limit, the ex-

Fig. 1. Experimental furnaces (originally built and enlarged)

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periments have been made by using the gas of 19% oxygen enriched for a constant bosh gas volume in the original experimental furnace.

1. The Effect of Oxygen Enrichment on the Coke Rate

From the results^{11,14)} obtained in the original furnace, shown in Fig. 2, the coke rate decreased slightly at the range of oxygen content less than 25%, but beyond that, an increase of more than 2.5 kg/tHM for every 1% oxygen enrichment was encountered due mainly to the increase in the loss of the solution carbon. As shown in Fig. 3, a relatively large decrease in the heat loss at the refining zone resulted in a saving in coke at the content of 25% oxygen, but in the latter range, the increase in direct reduction was higher. At the content of 36% oxygen, the shaft efficiency became greater owing to the decrease in the amount of reducing agent, but in the case of direct reduction, it became smaller and the amount of oxygen removed increased.

Fig. 2. Increase in the coke rate and the solution loss carbon according to the oxygen enrichment

Fig. 3. Decreases of heat loss (Δp), direct reduction (y_d), and shaft efficiency (r), according to the different oxygen enriched ratio

2. The Limit of Oxygen Enrichment due to the Retardation of the Heat Exchange in the Shaft

As shown in Fig. 4, the gas temperature in the shaft dropped at an oxygen content of more than 30%, and the thermal reserve zone, tended to vanish at the content more than 36% oxygen. These reproducible results¹⁴⁾ were obtained in the enlarged experimental furnace.

The heat transfer equations¹⁴⁾ for the counter current packed bed can be applied to the blast furnace shaft, assuming the plug flow of gas and solids and the overall transfer coefficient to be 2 000 (kcal/bed·m³·deg·hr) as constant, while ignoring ununiformity of gas and solid distributions in the radial direction.

The heat content ratio defined by Eq. (1) is the most important factor.

$$u = mc/Gk \dots\dots\dots(1)$$

where,

k, c : specific heat of the gas and solids (kcal/kg·deg)

G, m : mass flow rate of the gas and solids (kg/hr).

Fig. 4. Effect of oxygen enrichment on the gas temperature profile

Fig. 5. Effect of oxygen enrichment on the length of thermal reserve zone and on u from calculated and observed results

Fig. 6. Staged heat balances and observed temperature profiles at 0 and 15% oxygen enrichment

Average heat content mc can be calculated by applying the figures of specific heat, $0.22 \text{ (kcal/kg}\cdot\text{deg)}^{15)}$ for the coke and $0.20 \text{ (kcal/kg}\cdot\text{deg)}^{15)}$ for the ore.

$$mc = 0.22 \cdot m_{\text{coke}} + 0.20 \cdot m_{\text{ore}} \dots\dots\dots(2)$$

where,

$m_{\text{coke}}, m_{\text{ore}}$: mass flow rates of coke and ore.

The calculated gas and solid temperatures for the different oxygen enrichments are shown in Fig. 5. Thus the theory¹⁴⁾ stated that depending on the increase of the oxygen enrichment, the lengths of the thermal reserve zone become shorter and that the temperature of the gas and solids in the preparation zone are lowered, was proved to be correct.

The heat content ratio, u , is an important factor that the heat exchange at the shaft increases to 0.75, which was close to the limit of the heat exchange in the original furnace. This limit can easily be explained from the staged heat balances¹⁶⁾ calculated for the standard period and the content of 36% oxygen which corresponds to the gas temperature profiles as shown in Fig. 6, where the critical point R at the least heat margin moved to the upper shaft and the excess heat decreased.

3. Direct Reduction Increase due to the Temperature Profile Changes

Since the gas film resistance is almost negligible in furnace stacks, the ore reduction rate along the furnace height was calculated by putting the gas temperatures and compositions in Eq. (3) (Fig. 7):

$$R_{\text{CO}} = \frac{3}{d_o r_o} \cdot \frac{(C_{\text{CO}} - C_{\text{CO}}^{\text{eq}})}{r_o \cdot \frac{1 - (1 - F)^{1/3}}{(1 - F)^{1/3}} + \frac{1}{k_{\text{CO}}(1 - F)^{2/3}(1 + 1/K_{\text{CO}})}} \dots\dots(3)$$

Fig. 7. Effect of oxygen enrichment on the progress of iron ore reduction in the furnace shaft

where,

- F : reduction rate of ore (—)
- r_o : initial ore size (cm)
- d_o : specific oxygen concentration, $6.66 \times 10^{-2} \text{ (mol/cm}^3\text{)}$
- $C_{\text{CO}}, C_{\text{CO}}^{\text{eq}}$: concentration of CO in the bulk and concentration of CO equilibrated to wüstite at $1\,000^\circ\text{C}$ (mol/cm^3)
- K_{CO} : equilibrium constant of CO and wüstite
- D : diffusion coefficient (cm^2/sec)
- k_{CO} : rate coefficient of CO reduction.

The terms of D and k_{CO} were experimentally obtained from the reduction of the same kind of sinter in $\text{CO-CO}_2\text{-N}_2$ gas at 800° to $1\,000^\circ\text{C}$ which was used in the experimental operation. Thus, the activation energy was 8.35 kcal/mol and the value of D was $2.49 \text{ cm}^2/\text{sec}$.

$$k_{\text{CO}}^{14)} = 40.4 \exp (-4\,200/T) \dots\dots\dots(4)$$

As the result calculated from Eq. (3), at the content of 36% oxygen, more than 45% of unreduced iron oxide descended into the lower shaft 1.6 m under the stock line and was reduced by direct reduction. As the ratio of oxygen enrichment increased, the amount of reduction decreased and the residual iron oxide was finally reduced by direct reduction in the lower part of the furnace. Investigations¹⁷⁾ revealed that after nitrogen quenching the reduction rate of ore reached more than 95% (plotted points) in this area at the content of 21% O_2 , at which point the burden started to melt. A large amount of descent of the unheated and unreduced burden according to the retardation of heat exchange would affect the metallurgical reaction in the crucible. Thus, another limit of oxygen enrichment in a blast furnace is clearly possible in the reduction process of ore.

IV. The Limit of the Fuel Injection through Normal Tuyeres with Oxygen Enrichment

Advantages of oxygen enrichment are mentioned as follows:

(1) Productivity can be increased without increasing the gas flow rate.

(2) Flame temperature which is important in injecting auxiliary fuel can be maintained at a constant temperature.

(3) Combustion rate can be improved due to high oxygen potential.

Some disadvantages of oxygen enrichment, as derived from the description in Chapter III, are as follows:

(4) The retardation of heat transfer at the upper shaft.

(5) An increase in direct reduction at the lower shaft.

The necessary conditions for injecting a large amount of fuel through normal tuyeres are as follows:

(A) Heat must be supplemented to compensate for the heat dissociation and preheating of the fuel.

(B) Prevention of soot formation when the fuel burns at tuyeres.

However some advantages from fuel injection may be expected.

(C) An increase in the gas amount as H_2 produced by the combustion of the fuel.

(D) An increase in the amount of reducing agent such as H_2 and the ability to promote the reduction at low temperatures.

Among the items mentioned above, (2) and (A), (3) and (B), (4) and (C), and (5) and (D) are mutually compensated when a large amount of fuel is injected together with an appropriate amount of oxygen enrichment. However, certain limits exist in the fuel injection through a normal tuyere even with oxygen enrichment on account of the following limitations.

1. The Limits of the Flame Temperature and the Heat Content Ratio

The limit for the heat content ratio was considered to be about 0.82¹⁸⁾ in a commercial furnace, which was investigated for comparison⁵⁾ in modern furnace operations. It is clear from Fig. 6 that the heat content ratio becomes greater as a result of decreasing excess heat below 1 000°C due to the decrease in gas volume (Nm^3/tHM) when the flame temperature was raised while keeping the coke rate constant. From this fact, the upper limit of the flame temperature is closely correlated to the limit of the heat content ratio. The lower limit of the flame temperature which is important to maintain the necessary reaction temperature is determined in the correlation of the heat balance at the refining zone.

2. The Limit from the Excess Oxygen Ratio

Combustion of the oil particles atomized at the tuyeres progresses in the following stages: heat increase in oil particles; the evaporation and combustion of volatile matter; the rise in heat of residual carbon particles and the combustion. The time required for the first and third stages are very short, therefore, the last stage governs the whole reaction. According to Essenhigh,¹⁹⁾ assuming that the combustion mechanism of fine particles is obeyed to diffusion control, the mass transfer coefficient can be given as D/a

(D , a : the diffusion coefficient and the diameter of particle), thus this is obeyed to the square law. The combustion progress of oil particles can be calculated if the five assumptions listed below are adopted.

(1) The above three stage-stage reactions continue until the oil particles arrive at the end of tuyere nose.

(2) Residual carbon particles and raceway coke are consumed by the following three reactions. Their reaction rates are controlled by the gas film diffusion of O_2 , CO_2 , and H_2O .

(3) Gas compositions generated in raceway are controlled by the combustion of raceway coke.

(4) Variation of gas amount in raceway can be ignored.

(5) Mass transfer coefficients of O_2 , CO_2 , and H_2O are considered to be equal.

Compositions of gas and the burning oil particle diameter at any point along the distance l from tuyere nozzle can be calculated by the following fundamental equations.

$$\text{For } O_2, \quad G(dx_1/dl) = -a_p(k_f P/RT) \dots\dots\dots(5)$$

$$\text{For } CO_2, \quad G(dx_2/dl) = a_p(k_f P/RT)(x_1 - x_2) \dots\dots\dots(6)$$

$$\text{For } H_2O, \quad G(dx_3/dl) = -a_p(k_f P/RT)x_3 \dots\dots\dots(7)$$

For the residual carbon burnt oil particle,

$$da/dl = -(M_c/\sigma)(DP/aRT)(\varepsilon P/RT)(x_1 + x_2 + x_3) \dots\dots(8)$$

where,

- x_1, x_2, x_3 : mole fractions of O_2 , CO_2 , and H_2O
- (-)
- a : radius of residual carbon burnt oil particle (m)
- l : distance from tuyere nose (m)
- a_p, ε : specific surface of raceway coke (m^2/m^3) and void fraction (-)
- k_f, D : mass transfer coefficients of O_2 , CO_2 , and H_2O (m/hr) and diffusion coefficient (m^2/hr)
- G : mole velocity of gas ($kg \cdot mole/m^2 \cdot hr$)
- R : universal gas constant ($m^3 \cdot atm/kg \cdot mole \cdot ^\circ K$)
- P, T : pressure (atm) and temperature ($^\circ K$) of gas
- M_c : the molecular weight of carbon ($kg/kg \cdot mole$)
- σ : apparent specific density of residual carbon (kg/m^3).

Initial conditions can be adopted at tuyere nose based on the above assumptions as follows:

$$x_1 = x_{10}, \quad x_2 = x_{20}, \quad x_3 = x_{30}, \quad \text{and } a = a_0 \quad \text{at } l = 0 \quad (\text{tuyere noze})$$

Thus, Eqs. (5), (6), (7), and (8) can be solved to obtain Eq. (9).

$$a_o^2 - a^2 = (k_s/4k_c) \{ (2x_{10} + x_{20} + x_{30}) - (x_{10}k_cl + x_{20} + x_{30}) \exp(-k_cl) \} \dots\dots\dots(9)$$

where,

$$k_c = a_p (k_f/GRT) \text{ and } k_s = 8 (M_c/\sigma) (DP/RT) (\varepsilon P/RT).$$

k_c, k_s : rate of combustion of raceway coke and residual carbon burnt oil particle.

A critical burnt oil particle having no soot formation can be calculated by Eq. (9) if 'a' approaches to '0' when 'l' approaches to ∞ .

$$a_o = \sqrt{(k_s/4k_c)(2x_{10} + x_{20} + x_{30})} \dots\dots\dots(10)$$

In the laboratory scale experiments a relationship of $(2a_o/d_d)^3 = 0.20$ was obtained for the fraction of the residual carbon in oil. The critical oil particle which forms soot d_d (m) can be calculated by substituting this into Eq. (10).

$$d_d = 1.7 \sqrt{(k_s/k_c)(2x_{10} + x_{20} + x_{30})} \dots\dots\dots(11)$$

Figure 8 shows the effect of the oxygen enrichment ratio on the critical excess oxygen ratio (total amount of oxygen entering through tuyeres/necessary amount of oxygen for the complete combustion of oil, $2.2 \text{ Nm}^3/\text{kg oil}$) calculated by Eq. (11). Almost all of the recent results from commercial furnaces fall within this calculated line. In Fig. 9, these data were plotted according to the relationship between oil rate and oxygen enrichment. The theoretical limit was assumed to be 36μ in critical oil particle, which is sufficiently small in ordinary atomization and well explains the possible oil rate with oxygen enrichment.

Without oxygen enrichment, the maximum amount of tuyere oil injection is considered to be about 60 kg/tHM . For the case of 4% oxygen enrichment, the maximum limit will reach 110 kg/tHM at the

Fig. 8. Relationship between excess oxygen ratio and oxygen enrichment for tuyere oil injection with slight soot formation

excess oxygen ratio 1.0, even though the oxygen enrichment ratio is further increased, as shown in Fig. 8. Therefore, oxygen enrichment up to 3% greatly effects the increase in the limit. If the total amount of oxygen through tuyeres decreases, this maximum limit would be less than 110 kg/tHM .

3. The Limit of the Tuyere Fuel Injection with Oxygen Enrichment

If it is assumed that the limit of heat content ratio is 0.8, and if the limit of excess oxygen ratio is given in Fig. 8, the possible operating area in the oil injection with oxygen enrichment is given in Fig. 9. Almost all the recent data from commercial furnaces fall within this area. This area is represented by the polyhedron shown in Fig. 10, calculated for different

Fig. 9. Possible operational ranges with tuyere oil injection together with oxygen enrichment

Fig. 10. Possible operational ranges at different oil rate oxygen enrichment and blast temperature

blast temperatures, oil rates and oxygen enrichment ratios at a constant humidity. When the blast temperature rises, the possible operation range is found to be narrower. Below 35 kg/tHM of oil, it cannot be injected without additional steam at 1 400°C, since it exceeds the limit of heat content ratio.

V. Reformed Gas Injection into the Enlarged Experimental Furnace Stack

1. The Effect of the Amount of Injected Gas on the Coke Rate

The reformed gas injection was tested in the enlarged experimental furnace²⁰⁾ and its operating results are shown in Table 1. The coke rate decreased from about 570 kg/tHM for the standard period to 361 kg/tHM as the minimum when 628 Nm³/tHM of reformed gas was injected and the production increased by about 7.5% for every 100 Nm³/tHM of the gas injected from the corrected data of wind leakage. Table 1 shows the results of the reformed gas injection with constant wind rate, the gas injection through a nozzle of 1.5 m above the normal injected level, and the appropriate gas injection with the oxygen enrichment keeping the bosh gas volume constant. Reformed gas was produced by the partial combustion of oil with oxygen. The gas contained about 4% of soot for oil carbon and was injected at the temperatures of 1 200° to 1 300°C.

Experimental results were plotted in Fig. 11 which shows the relationship between the oil equivalent rate and the coke rate and the replacement ratio. The dotted line shows the corrections of the factors such as the sensible heat of the injected gas, temperature and

Fig. 11. Effect of the reducing gas on the coke rate (a) and the replacement ratio (b)

Table 1. Results of stack gas injection in the enlarged furnace

		Standard period	Reducing gas injection				R.G. injection with oxygen enrichment	
			Normal level injection			High level		
Production	(kg/day)	8 904	9 881	11 612	11 888	10 287	12 182	12 828
Corrected production		8 904	(10 289)	(12 452)	(13 108)	(13 087)	(14 502)	(16 428)
Coke rate	(kg/t HM)	571	483	426	374	434	437	439
Oil rate	(kg/t HM)	0	138	174	220	194	146	173
Reducing gas	(Nm ³ /t HM)	0	366	508	628	554	433	512
Oxygen rate	(Nm ³ /t HM)	0	123	162	166	167	114	134
Slag rate	(kg/t HM)	412	427	433	435	388	403	411
Dust rate	(kg/t HM)	3.5	9.6	12.1	9.5	19.4	8.2	8.2
Blast volume	(Nm ³ /min)	9.67	9.29	9.02	8.74	7.45	7.41	6.83
	(Nm ³ /t HM)	1 564	1 329	1 137	1 087	1 135	890	779
Blast temperature	(°C)	973	967	977	966	985	948	949
Blast pressure	(kg/cm ²)	0.139	0.152	0.173	0.177	0.147	0.167	0.172
Moisture in blast	(g/Nm ³)	3.3	4.8	3.5	4.2	7.7	6.8	6.7
Oxygen enrichment	(%)	0	0	0	0	0	4	7
Top gas amount	(Nm ³ /tHM)	2 110	2 125	2 012	1 978	2 308	1 726	1 738
Top gas temperature	(°C)	155	205	232	276	315	212	212
Reducing gas temperature	(°C)	0	1 163	1 315	1 312	1 250	1 204	1 215
R.G. composition,	H ₂ (vol%)		39.9	42.1	43.9	43.5	43.1	44.3
	CO (vol%)		47.2	48.7	49.1	48.6	47.7	48.2
	CO ₂ (vol%)		5.8	3.6	3.2	3.7	3.4	2.8
	N ₂ (vol%)		6.8	5.5	3.6	3.1	5.5	4.2
Hot metal temperature	(°C)	1 414	1 395	1 391	1 388	1 413	1 405	1 427
Molten slag temperature	(°C)	1 489	1 462	1 468	1 460	1 476	1 476	1 479
Si% in Hot metal		1.30	1.08	0.75	0.70	1.22	0.90	1.10
S% in Hot metal		0.046	0.067	0.060	0.063	0.060	0.069	0.067
Slag basicity, CaO/SiO ₂		1.16	1.11	1.16	1.14	1.16	1.16	1.11

composition of the hot metal and slag based on a heat balance above 1 000°C level. The replacement ratio changed from 0.75 to 0.82. The coke rate in the case of gas injection with oxygen enrichment decreased along the same line obtained from the gas injection only. But in the case of injection from a 1.5 m higher position, the replacement ratio decreased about 0.1 and less effect was obtained.

2. The Progress in the Reduction Reaction in the Furnace

The following facts were obtained from the material balance (Table 2.)

- (1) Gas injection rate increased when the total amount of gas (Nm³/tHM) was kept almost constant, but the blast volume decreased.
- (2) Total amount of (CO+H₂) increased.
- (3) Gas utilization was about 40% for CO and 35 to 40% for H₂ in the normal level injection but they decreased in the injection at 1.5 m higher level.
- (4) Amount of oxygen removed by direct reduction decreased from 0.21 in O atom/Fe atom.
- (5) Shaft efficiency²¹⁾ was almost constant at 0.80 to 0.83 but decreased to 0.78 in the case of 1.5 m higher level injection.

As shown in Fig. 12, when the amount of injected gas increased, the decrease in direct reduction was replaced by the increased in H₂ reduction. However, the calculation was made by assuming that water gas reaction reached equilibrium at 600°C, and that some parts of the hematite and magnetite were reduced to wüstite by hydrogen. It may be right to say that the reduction by (CO+H₂) gas increased from 65 to 85% by the reformed gas injection.

The results for the standard period (solid line) and for 628 Nm³/tHM of reformed gas injection (dotted line) are shown as operating lines in Fig. 13, according to the reformed gas injection equilibrium point *W* moved to *W'* due to the effect of H₂, although the amount of the oxygen removed by direct reduction decreased from *Y_D* to *Y'_D*, total moles of reducing agent per Fe atom increased due to the decrease in direct reduction. But a decrease in the coke rate proportional to the decrease in the gradient was obtained. Parts of CO₂ and H₂O inevitably contained in the gas will consume by coke as shown in the effect of *Y_{GD}* qualitatively. Therefore, the reformed gas must contain as little CO₂ and H₂O as possible and

its price must be cheaper because of the increase in the total moles of the reducing agents.

Fig. 12. Effect of reducing gas on the reduction process

Fig. 13. Operating lines of standard period and reducing gas injection

Table 2. Material balances

		Standard period	Reducing gas injection				R.G.+O ₂ enrichment	
			Normal level injection		High level		O ₂ 4%	O ₂ 7%
Reducing gas	(Nm ³ /tHM)	0	366	508	628	554	433	512
Total gas volume	(Nm ³ /tHM)	2 121	2 193	2 099	2 114	2 152	1 814	1 823
CO+H ₂	(%)	42.0	51.3	56.2	58.6	58.0	60.4	65.3
Utilization of CO	(%)	40.6	39.4	40.6	40.8	36.6	39.4	39.4
Utilization of H ₂	(%)	32.8	36.5	34.6	40.1	34.5	35.7	29.6
Indirect reduction rate		67.4	75.8	75.7	84.2	76.1	73.7	74.6
Oxygen removed by direct. red. (O atm/Fe atm)		0.470	0.346	0.351	0.209	0.342	0.374	0.364
Shaft efficiency		0.823	0.837	0.799	0.837	0.786	0.795	0.769

The distributions of reduction along the furnace height were calculated from the observed temperatures and compositions according to Eqs. (3) for CO reduction and (12) for H₂ reduction. For H₂ reduction, only the chemical reaction control was assumed, since the resistances of diffusion of H₂ through gas film and within reacted core are smaller than that of the chemical reaction.

$$R_{H_2} = (3/d_o r_o) \cdot k_{H_2} (1-F)^{2/3} (1 + 1/K_{H_2})(C_{H_2} - C_{H_2}^{eq}) \dots (12)$$

K_{H_2} : equilibrium constant of H₂ and wüstite at 1 000°C

$C_{H_2}, C_{H_2}^{eq}$: concentrations of H₂ in the bulk gas and at the equilibrium to wüstite at 1 000°C (mol/cm³)

The velocity of H₂ reduction was obtained from the reduction test of the same kind of ore used in the test operation as follows:

$$k_{H_2}^{200} = 181.3 \exp (-6\ 158/T) \dots \dots \dots (13)$$

Assuming that the additive property of H₂ reduction and CO reduction is correct, the progress of the reduction can be calculated by Eq. (14) for the mixed gas reduction.

$$dF/d\theta = R_{CO} + R_{H_2} \dots \dots \dots (14)$$

The reduction rate calculated by Eq. (14) in relation to the dimensionless retention time is shown in Fig. 14. Ore reduced in the same retention time increased by two times, with 628 Nm³/tHM of gas injection. The calculated reduction rate agreed with the observed rates¹⁷⁾ in the study of the quenched furnace.

3. Considerations from the Heat Balances

The staged heat balance calculations¹⁶⁾ made by assuming that H₂ reduction takes place between 400° and 900°C for gas injection period at 628 Nm³/tHM are shown in Fig. 15. In this figure, it shows that the heat supply (a dot-dash-line) generated from the burning of coke crosses necessary heat at about 950°C

Fig. 14. Reduction progress with and without reducing gas injection to the dimensionless retention time

(dotted line) when gas is injected. However, this heat shortage was covered by the sensible heat of the injected gas. From this fact, a reformed gas injection will be effective if it is injected the lower shaft where the temperature is higher than 950°C. The temperature should be higher than that of the injected zone, otherwise, the sensible heat of the injected gas will be exhausted, necessitating an increase in top gas temperature or additional coke to bring up the gas heat.

The heat balances calculated above 1 000°C (Fig. 16) are convenient to investigate the contribution of the reformed gas injection on a blast furnace heat requirement. In the period of the gas injection only,

Fig. 15. Staged heat balances with or without reducing gas injection

Fig. 16. Heat balances at 1000°C standard for tested operation

Fig. 17. Temperature profiles of reducing gas injection with and without oxygen enrichment

the contribution came from the decrease in the heat of the solution loss reaction, ⑥; heat loss, ⑦; and an increase in the sensible heat of injected gas, ⑨. When the gas is injected at a 1.5 m higher level, the decrease in the heat of the solution loss reaction ⑥ was smaller in spite of the gas injection of $554 \text{ Nm}^3/\text{tHM}$. In the case of an oxygen enriched gas injection, the decrease in the heat loss had a larger effect.

4. Improvements of the Temperature Profile in the Furnace

Excess oxygen enrichment retarded the heat exchange in the upper shaft and increased the amount of direct reduction. Tuyere fuel injection improves these conditions, however, this has a certain limit, described previously. As shown in Fig. 17, when $512 \text{ Nm}^3/\text{tHM}$ of gas was injected together with 7% of oxygen enrichment, the temperature stability of the thermal reserve zone could be maintained in spite of low coke rate and high productivity. Thus, the limitations of oxygen enrichment may be overcome by stack gas injection.

Permeability through the furnace melting zone could also be improved by comparing the distance of the calculated points^{20,22)} from the flooding condition (Fig. 18), though these were less successful than a previous operation²³⁾ with prereduced pellets.

VI. Conclusions

(1) When the oxygen enrichment ratio was increased with constant bosh gas volume, the coke rate dropped due to the effect of the decrease in heat loss. However, beyond a certain limit, an increase in direct reduction exceeded the effect of raising the coke rate. This limit in the original experimental furnace (0.63 m^3) was at 4% oxygen enrichment, and it differs in the productivity and coke rate.

(2) The length of thermal reserve zone became shorter and the temperature decreased according to the oxygen enrichment. Beyond 15% of oxygen en-

Fig. 18. Advantage of reducing gas injection and prereduced burden for fluid flow at bosh

richment, the reserve zone vanished to reach the limit from the heat exchange in the upper furnace shaft. Those temperature changes caused an increase in direct reduction.

(3) Tuyere fuel injection and the oxygen enrichment can compensate their mutual disadvantages within the limited conditions defined by the lower limit of the flame temperature, the upper limit of the heat content ratio, and the lower limit of the excess oxygen ratio. Even with more than 4% of oxygen enrichment, about 110 kg/tHM of oil injection was considered to be the limit for commercial furnace operation.

(4) In the experimental operation tested in the enlarged furnace (3.2 m^3) which was designed to simulate the material and heat balances and the reaction in a commercial furnace, the coke rate was decreased from about 570 kg/tHM to 361 kg/tHM by 628 Nm^3 of injected gas produced by the reforming of oil with oxygen. The replacement ratio was 0.75 to 0.82.

(5) In a reformed gas injection less than $628 \text{ Nm}^3/\text{tHM}$, the oxygen of iron oxide removed by direct reduction was decreased from 0.47 to 0.20 (O atom/Fe atom) and the gaseous reduction by $(\text{CO} + \text{H}_2)$ was increased from 65 to 85%.

(6) Stack gas injection combined with oxygen enrichment cancelled the disadvantages of oxygen enrichment in operating a furnace for high productivity without any increase in the coke rate. Permeability through melting zone was improved.

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