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Recent Progress in Top-and-Bottom Blown Converters at Kawasaki Steel Corporation

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Recent Progress in Top-and-Bottom Blown Converters at Kawasaki Steel Corporation*

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1 Introduction

The introduction of a bottom blown converter at Kawasaki Steel in 1977 and the subsequent improvement of bottom blowing technology demonstrated that the bottom blown converter can be operated economically on an industrial scale and that the characteristics of the metallurgical reaction in the bottom blown converter are far superior to those of the top blown converter. As a result of these efforts, intensive developmental work was carried out to improve the metallurgical reaction in the top blown converter by introducing bottom blowing technology. Kawasaki Steel developed two types of top-and-bottom blown converter, the K-BOP and the LD-KGC. The K-BOP is characterized by strong stirring of the molten steel by the high volume of bottom blowing of oxygen gas together with pulverized lime. Features of the LD-KGC, on the other hand, are its wide range controllability of the flow rate of the bottom blowing gas and moderate investment cost.

In this report, the following recent advances in K-BOP and LD-KGC technology at Kawasaki Steel will be discussed. Development of the LD-KGC, mixed-gas bottom blowing (IOD) in the K-BOP, use of CO as a stirring gas in the LD-KGC, and smelting reduction of chromium ore to produce stainless steel in the K-BOP.

The stirring characteristics of bottom blowing gas will be discussed in terms of the metallurgical reaction. In particular, the contributions of stirring force and the dilution of P_{CO} of the bottom blowing gas to the metallurgical reaction will be discussed on the basis of experiments conducted with a 5-t test converter.

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2 Development of Top-and-Bottom Blown Converter with Wide Range Gas Flow Rate for Stirring[1~3)]

To produce a wide range of steel grades from low carbon to high carbon steel in the same converter, in addition to the durability of the tuyeres, wide range control of the flow rate of the bottom blowing gas is necessary from the viewpoint of control of the iron oxide in the slag. To accomplish this, special tuyeres consisting of small steel pipes assembled in bundles have been used.[4)] This type of tuyere was, however, complicated and very expensive. Moreover, the range of the flow rates with this tuyere was not sufficient.

With the establishment of hot metal pretreatment facilities, the need for dephosphorization in the converter has been eliminated so that for low carbon steel, preferential decarburization can be performed through intensive stirring in the converter. In addition, use of a large amount of bottom blowing gas in the final stage of refining is desirable as it permits the smelting reduction of manganese ore in the top-and-bottom blown converter.

To meet these requirements, Kawasaki Steel developed a new type of top-and-bottom blown converter with wide control range of flow rates for bottom blowing gas (LD-KGC).

2.1 Fundamental Investigation of High-Pressure Gas Bottom Blowing with Cold and Hot Model Experiments

Figure 1 is a schematic drawing of gas flow through a tuyere. The flow rate of compressive fluid in the tube is described by the following equation[5)]:

$$L = \frac{D}{\lambda}\left[\frac{1}{\kappa}\left(\frac{1}{M_1^2} - 1\right) + \left(\frac{\kappa+1}{2\kappa}\right)\ln\left\{\frac{\frac{(\kappa+1)}{2}M_1^2}{1 + \frac{(\kappa-1)}{2}M_1^2}\right\}\right] \cdots\cdots (1)$$

$$T_1 = T_0/[1 + \{(\kappa-1)/2\}M_1^2] \cdots\cdots (2)$$

$$P_1 = P_0/[1 + \{(\kappa-1)/2\}M_1^2]^{1/(\kappa-1)} \cdots\cdots (3)$$

$$m = (\kappa/RT_1)^{1/2}P_1M_1\left(\frac{\pi}{4}D^2\right) \cdots\cdots (4)$$

Where, L and D are the length and diameter of the tube(m), λ is the coefficient of friction, R is a gas constant, κ is the specific heat ratio, M_1 and M are the mach numbers at the inlet and outlet of the tube, m is the mass flow rate of the gas, and P_1 and T_1 are the pressure and temperature of the gas at the tube inlet.

Equations (1) to (4) show that the flow rate can be controlled over a wide range by changing the gas pressure at the inlet of the tube because of the proportionality between the gas pressure and mass flow rate.

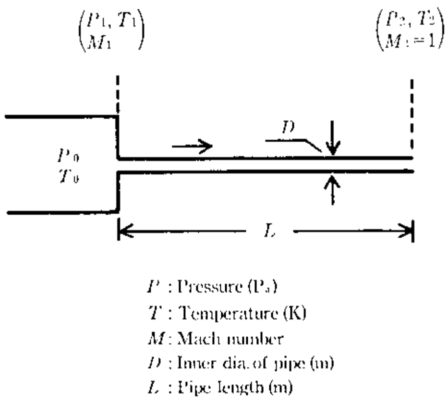

Fig. 1 Schematic drawing of gas flow through tuyere

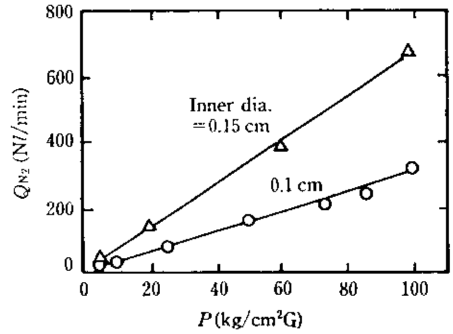

Fig. 2 Relationship between base pressure and gas flow rate

To verify Eqs. (1) to (4), experiments with a water model and hot model were carried out[3)]. First, the water model experiments were carried out. This experiments revealed that the flow rate of the gas through the tube is proportional to the pressure at the inlet of the tube from 5 to 100 atm. Second, a stainless steel pipe was installed at the bottom of the 5-t converter and nitrogen was injected through the pipe. The diameter and length were 0.1 cm to 0.15 cm and 45 cm, respectively. **Figure 2** shows the relation between the flow rate of the bottom blowing gas, Q_{N_2} and the pressure in the pipe, P.

These experiments made it clear that the flow rate of the bottom blowing gas is proportional to the pressure in the pipe, even in hot model experiments. The flow rate of the bottom blowing gas can be controlled from 40 to 800 Nl/min by changing the pressure from 5 to 100 atm with a stainless steel pipe 0.15 cm in inner diameter. In this case, neither leakage of liquid iron into the tuyere nor drilling of the gas jet through the bath was observed.

2.2 Installation of High-Pressure Gas Blowing in Commercial Converter

A compressor was installed in the bottom blowing gas line of the 150-t converter at No. 2 Steelmaking Shop at Chiba Works in 1984 to realize high pressure gas blow-

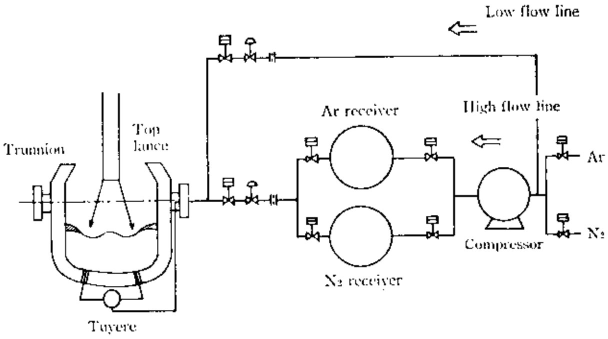

Fig. 3 Conceptional view of LD-KGC

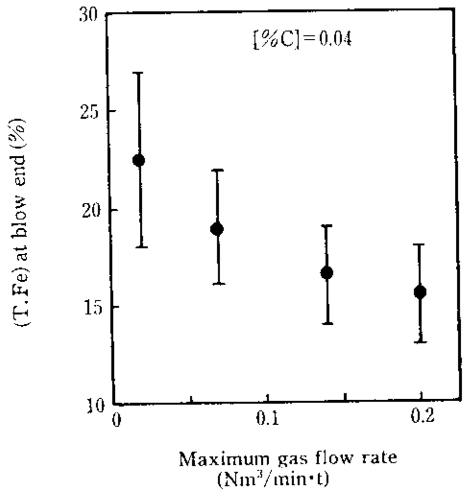

Fig. 4 Relationship between maximum bottom gas flow rate and (%T.Fe) in slag

ing at rates up to 50 atm. After confirmation of the wide controllability of bottom blowing gas flow rates, similar equipment was installed at the 180-t converters at Mizushima Works, where the bottom blowing gas was pressurized to 43 atm.

Figure 3 shows an outline of the facility. The nitrogen and argon used as bottom blowing gases are pressurized to 50 atm and stored in receiver tanks.

The range of flow rates of bottom blowing gas at Chiba Works is 0.01 to 0.14 Nm^3/min per ton of steel. On the basis of the experimental results at Chiba Works, the range of flow rates at Mizushima Works was enlarged to 0.005 to 0.2 Nm^3/min per ton of steel[2].

Adoption of high-pressure gas blowing makes it possible to secure the metallurgical benefits of bottom blowing by enlarging the range of flow rates while avoiding problems such as tuyere clogging and tuyere erosion.

In addition, the cost of process gas for bottom blowing can be reduced by decreasing the bottom gas flow rate to the minimum amount during the first and middle stages of blowing without causing tuyere clogging.

2.3 Metallurgical Characteristics of LD-KGC

In routine operation, the bottom blowing gas flow rate is kept low through the first and middle stages of refining to prevent slopping. The gas flow rate is then increased to the maximum value to prevent excess oxidation of iron and to promote preferential decarburization.

Figure 4 shows the effect of the bottom blowing gas flow rate during the final stage of refining on the iron content of the slag, (%T.Fe). The values of (%T.Fe) decrease with increases in the flow rate, resulting in improvement of iron yield.

It was reported previously that the optimum flow rate of bottom blowing gas for improvement of the characteristics of the metallurgical reaction is approximately 0.1 Nm^3/min per ton of steel[6]. Nevertheless, it became evident from experimental data that the characteristics of the metallurgical reaction can be improved by increasing the flow rate of blowing gas above 0.1 Nm^3/min per ton of steel.

Based on these experimental results at Chiba Works, the maximum flow rate of the bottom blowing gas was increased to 0.2 Nm^3/min per ton of steel in the 180-t LD-KGC at No. 1 Steelmaking Shop at Mizushima Works. The (T.Fe) in the 180-t LD-KGC at Mizushima Works is also shown in Fig. 4. It is clear that the values of (T.Fe) in the LD-KGC can be decreased to a level equivalent to those in the Q-BOP or K-BOP for low carbon steel. Similar improvement in manganese yield and oxygen content at blow end has also been obtained by increasing the gas flow rate.

2.4 Tuyere Durability in LD-KGC[7]

The durability of bottom blowing tuyeres has been improved markedly by improving the refractory materials in the bottom area of the vessel, the configuration of the tuyere, and slag coating practice.

High pressure gas effectively prevents the tuyere from clogging during the slag coating operation, so that deterioration in the characteristics of the metallurgical reaction is not observed[2].

Today the life of the tuyeres in the 180-t LD-KGC at Mizushima Works is over 6000 charges without a tuyere change, even when high-flow rate bottom blowing of up to 0.2 Nm^3/min per ton of steel is conducted.

3 Development of CO Gas Bottom Blowing Process in Combined Blown Converter[8]

The gases used for bottom blowing in the LD-KGC have conventionally been either N_2 or Ar. However, nitrogen cannot be used in producing low nitrogen steel due to nitrogen pick up. The use of Ar gas for bottom blowing is effective for lowering the nitrogen content of

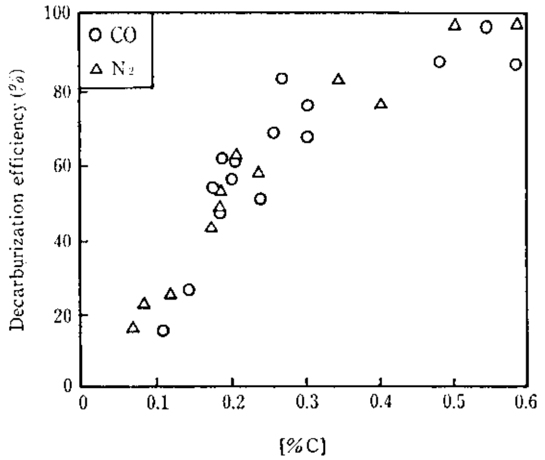

Fig. 5 Relationship between utilization efficiency of oxygen gas for decarburization and [%C]

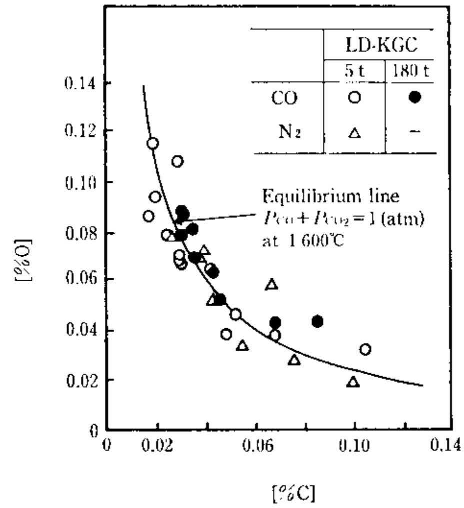

Fig. 6 Relationship between [%C] and [%O]

the steel, but Ar gas is expensive.

Research and development to produce CO gas at reasonable cost were therefore intensively pursued. These R&D efforts yielded an economical process termed COPISA (CO pressure induced selective adsorption)[9], which makes it possible to purify converter off-gas to a high purity CO gas of ca. 99%.

When high purity CO gas became available at reasonable price, the metallurgical characteristics of CO bottom blowing were investigated with a 5-t converter to clarify the possibility of the use of CO gas as a bottom blowing gas. Based on the experimental results, commercial use of CO gas as a bottom blowing gas has been adopted at the 180-t LD-KGC at No. 1 Steelmaking Shop at Mizushima Works.

3.1 Experiments with CO Gas Bottom Blowing in 5-t Test Converter

The relationship between the oxygen utilization efficiency for decarburization and [%C] is shown in **Fig. 5**. The efficiency with CO is equivalent to that with N_2. According to this result, the rate of CO dissolution into the steel melt is small, and hence CO can be used as a bottom blowing gas.

As shown in **Fig. 6**, the relationship between [%C] and [%O] at the blow end for CO blowing is the same to that for N_2 blowing, being in equilibrium with a gas phase of $P_{CO} + P_{CO_2} = 1$ atm. In addition to the above results, no difference was observed between the metallurgical reaction for CO blowing and that for N_2 or Ar blowing.

3.2 Application of CO Gas Bottom Blowing to Commercial LD-KGC

Commercial use of CO as a bottom blowing gas began at the LD-KGC at No. 1 Steelmaking Shop at Mizushima Works in June 1985 after the experimental studies with the 5-t converter. The flow chart of this system is shown in **Fig. 7**. The COPISA facility at Mizushima has a capacity of 410 Nm^3CO/h, of which 250 Nm^3/h is supplied to a chemical plant for synthetic chemical use and the rest of the LD-KGC shop.

Table 1 shows the specifications of the converter off-gas and the CO gas purified by COPISA. The average

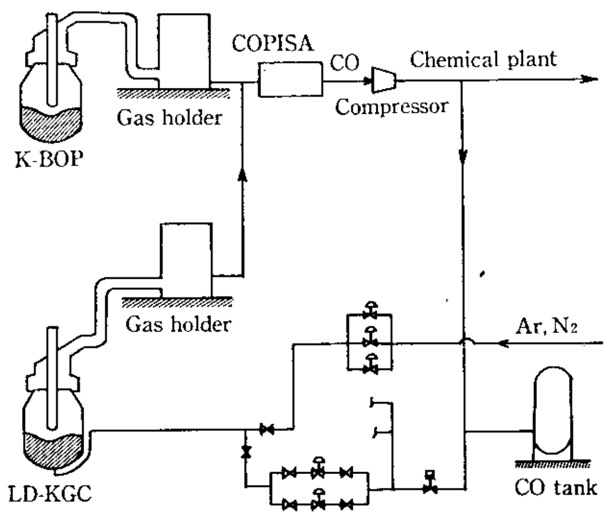

Fig. 7 Schematic drawing of process gas supply system in Mizushima Works

Table 1 Specifications of gas composition (%)

	CO	CO_2	N_2	H_2	O_2
BOF gas	>71	<14	<13	<1.2	0.2~0.3
Product	>98	<0.4	<1.6	—	<1 ppm

nitrogen content of the purified CO gas is about 1%, but no difference was observed between the nitrogen content at blow end for CO blowing and that for Ar blowing.

As confirmed with the 5-t converter, there is no difference between the metallurgical reaction in CO bottom blowing and in argon or nitrogen bottom blowing, even in the commercial LD-KGC. As shown in Fig. 6, the relation between [%C] and [%O] for CO blowing in the 180-t LD-KGC is similar to that in the 5-t LD-KGC.

Use of CO contributes to improvement in iron and manganese yields by preventing excess oxidation while reducing the operational cost for bottom blowing gas.

4 Effect of Gas Species for Mixed Gas Blowing (IOD Practice) in K-BOP on Characteristics of Metallurgical Reaction

In comparison with the LD-KGC, one third of the oxygen necessary for decarburization is blown through the bottom tuyeres in the K-BOP process, and hence a high flow rate bottom blowing can be realized to stir molten steel without any cost penalty for stirring gas. The stirring intensity of the oxygen, however, depends on the rate of CO generation in the decarburization reaction, and gradually decreases with decreasing carbon content over the course of refining.

Mixing of inert gas with the bottom blown oxygen in the final stage of refining has been successfully practiced with the 250-t K-BOP to prevent the above-mentioned decrease in stirring intensity[10]. This method, termed IOD (inert and oxygen gas decarburization), shows the same metallurgical characteristics as those in the OBM/Q-BOP process.

It has been considered that the following two effects of the bottom blowing gas in the combined blown converter decrease [%O] and (%T.Fe): the enhancement of bath stirring and hence decrease in difference between operational values and thermodynamic equilibrium values, and the dilution of the partial pressure of CO gas in the converter resulting in the changes in thermodynamic equilibrium values. From the latter point of view, inert gas such as Ar or N_2 may be superior to CO or CO_2 gas.

According to the operational results of the top-and-bottom blown converters at Kawasaki Steel, however, improvement of the metallurgical reaction by the use of bottom blowing does not depend on the gas species used, but on its flow rate.

To quantitatively evaluate the effect of gas species on the characteristics of the metallurgical reaction, experiments were carried out with the 5-t converter using two kinds of gases as the mixed gas in IOD practice, namely Ar and CO_2.

4.1 IOD Experiments in 5-t Converter

A schematic diagram of the 5-t K-BOP is shown in **Fig. 8**. Oxygen gas is blown through the inner tube of the bottom tuyeres with pulverized lime in the first and middle stage of refining, and mixed gas in the final stage. Propane gas is blown through the outer annulus of the tuyeres as a protective coolant. Through the top lance, only oxygen is supplied to the iron melt bath.

Improvement in the efficiency of oxygen for decarburization and a decrease in [%O] and (%T.Fe) are observed in IOD practice. However, no difference is observed between the characteristics of the metallurgical reaction in the IOD mode with CO_2 and that with Ar or N_2.

The relationship between [%C] and [%O] at blow end is shown in **Fig. 9**. The [%C] vs. [%O] relationship in the IOD mode is equivalent to the value calculated thermodynamically on the assumption that $P_{CO} + P_{CO_2} = 0.5$ to 0.6 atm. It is interesting that there is no effective difference between the [%C] vs. [%O] relationship in IOD practice with CO_2 mixing and that with Ar mixing, although a large difference exists between the dilution

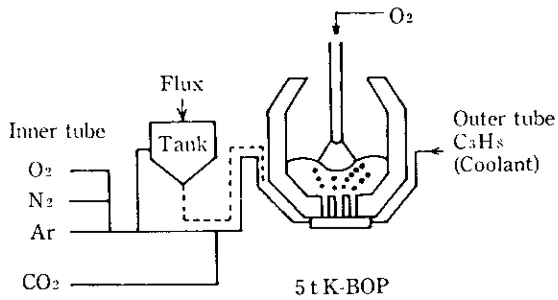

Fig. 8 Schematic picture of the 5-t K-BOP used for experiments

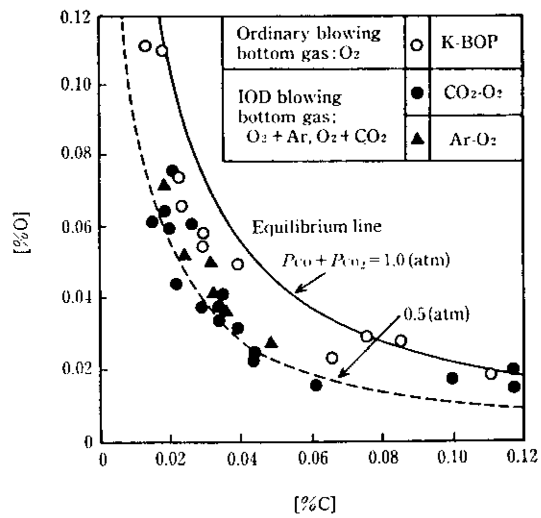

Fig. 9 Relationship between [%C] and [%O] in 5-t K-BOP

of CO gas pressure by CO_2 and that by Ar.

4.2 Commercial Operation of IOD in 250-t K-BOP at Mizushima Works

Mixing equipment was installed in the bottom blowing gas line of the 250-t K-BOP at Mizushima Works to automatically control the ratio of oxygen to inert gas depending on the carbon content of the melt through the course of refining[11]. Preferential decarburization has been achieved by IOD, resulting in lower [%O] and (%T.Fe) at blow end than with the conventional K-BOP[10]. The IOD process is being used in routine operation and contributes to the improvement of iron and manganese yield in low carbon steel production.

Based on the experimental results with the 5-t converter, CO_2 is now used as the mixing gas in the IOD mode with the K-BOP in commercial production.

5 Effect of Bottom Blowing Gas on Characteristics of Metallurgical Reaction in Converter[12]

5.1 Mathematical Model Describing Decarburization and Deoxidation in Converter

The above-mentioned experimental results made it clear that the decrease in [%O] at blow end in the combined blown converter is not affected by the P_{CO} of the bottom blown gas, but is affected by its stirring force.

However there is no study which explains the fact that [%O] at blow end in the combined blown converter is not determined by P_{CO} in the gas phase. That is, the phenomenon that [%O] at blow end is independent of the kind of the bottom blowing gas has not been satisfactorily elucidated. To clarify this phenomenon, a new mathematical model[12] for describing decarburization and deoxidation in the converter was proposed below.

The major part of the oxygen supplied to the iron melt bath is consumed for decarburization; the remainder accumulates as dissolved oxygen in the steel and as iron oxide in the slag. Expanding the theory of Hsieh and others[13] for estimating the circulating flow rate of molten steel in the converter, a new reaction model has been developed. (A detailed interpretation of the reaction model is provided in reference (12)). Using various assumptions, the mass balances of carbon and oxygen in the bath and that of iron oxide in the slag can be written as:

$$W(dC_{O,b}/dt) = q(C_O^* - C_{O,b}) + J(C_O^{**} - C_{O,b}) \cdots (5)$$

$$W(dC_{C,b}/dt) = q(C_C^* - C_{C,b}) \cdots (6)$$

$$\frac{W_S}{100} \times \frac{dC_{FeO,b}}{dt} = N_{FeO} - \frac{C_{FeO,b}}{100} \times \frac{dW_S}{dt} + \frac{71.9}{16} \times \frac{1}{100} \times J \times (C_{O,b} - C_O^{**}) \cdots (7)$$

Where, W is mass of the molten steel (kg), q is the circulating flow rate of the molten steel (kg/min), J is a factor which determines the mass transfer rate between the metal phase and slag phase (kg/min), N_{FeO} is the production rate of iron oxide (i.e. FeO) in the reaction zone by the supplied oxygen (kg/min), C_j, b is the concentration of component j in the metal or slag (%) (the subscripts j denote C, O or FeO), C_j^* is the concentration of component j in the reaction zone (%) and Co** is the dissolved oxygen concentration in equilibrium with a_{FeO} in the slag (%), which is calculated with the thermodynamical value recommended by the Japan Society for the Promotion of Science[14].

Assuming furthermore that excess oxygen exists in the reaction zone which corresponds to the hot spot formed by the oxygen jet, a_{FeO} in the reaction zone is taken as unity (i.e., 1). Assuming that the concentration of carbon and oxygen in the reaction zone is in equilibrium with a_{FeO} (=1) in the reaction zone, these factors can be calculated for P_{CO} in the hot spot.

Using the carbon and oxygen concentrations in the reaction zone, calculated as described above, mass balances of carbon, oxygen, and iron oxide in the reaction zone are given by Eqs. (8), (9) and (10). Equation (10) is the overall oxygen balance in the reaction zone.

$$q(C_{C,b} - C_C^*) = I(C_C^* - C_{C,e}) \cdots (8)$$

$$q(C_{O,b} - C_O^*) = I(C_O^* - C_{O,e}) \cdots (9)$$

$$N_{FeO} = \frac{71.9}{11.2}Q + \frac{71.9}{16} \times \frac{1}{100} \times I \times (C_O^* - C_{O,e}) - \frac{71.9}{12} \times \frac{1}{100} \times I \times (C_C^* - C_{C,e}) \cdots (10)$$

Where, I is a factor representing the intensity of mixing in the reaction zone (kg/min) and Q is the feed rate of oxygen (Nm^3/min).

Under these conditions, carbon in the metal, $C_{c,b}$, oxygen in the metal, $C_{o,b}$, and iron oxide in the slag, $C_{FeO,b}$ were calculated numerically at a given time step. For the purpose of the calculation, the circulating flow rate of metal, q, is given by Eq. (11)[15], using the measured value of mixing time, τ, of the bath.

$$q = \frac{60}{\tau} \times 3 \times W \cdots (11)$$

In these calculations, two parameters, namely I and J, were determined as follows: The first assumption is that J is proportional to I. The values of I for three types of converters were determined to obtain reasonable agreement between the oxygen utilization efficiency for decarburization given by the mathematical model and observed values.

5.2 Results Calculated Using Mathematical Model

Table 2 shows the values of the parameters used in calculation. In the following calculations, we assumed that $P_{CO} + P_{CO_2} = 1$ atm. **Figure 10** shows the behaviors of [%C] and [%O] calculated during blowing in the LD-KGC, K-BOP and Q-BOP, using these parameter values.

As the intensity of stirring by the bottom blowing gas increases, [%O] calculated by the reaction model

Table 2 Values of parameter used in calculation

	Q (kg/min)	I (kg/min)	J (kg/min)
LD-KGC	2.4×10^4	8.0×10^3	5.0×10^4
K-BOP	4.5×10^4	1.0×10^4	6.25×10^4
Q-BOP	6.0×10^4	1.2×10^4	7.5×10^4

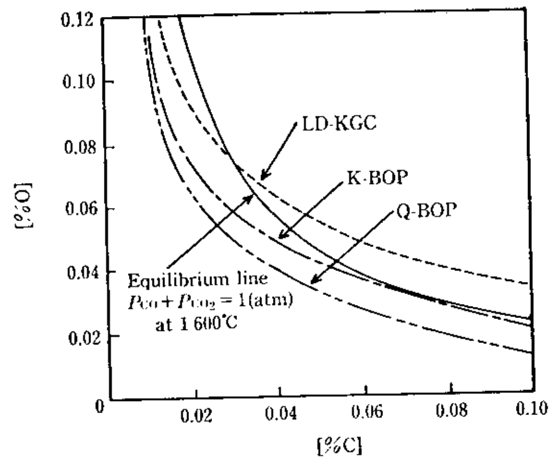

Fig. 10 Decarburization behaviors of LD-KGC, K-BOP and Q-BOP calculated by the reaction model

decreases. The product of [%C] and [%O] calculated by the reaction model is less than the equilibrium value calculated thermodynamically on the assumption that $P_{CO} + P_{CO_2} = 1$ atm.

These results are explained as follows: With increasing intensity of stirring by the bottom blowing gas, the decarburization rate in the reaction zone increases, while the rate of iron oxide production in the reaction zone decreases. Consequently, the oxygen potential of the slag becomes smaller than that of the metal, and oxygen transfer from the metal to the slag occurs. The amount of oxygen transfer increases as the difference between the oxygen potential in the metal and slag becomes greater.

The difference between the two becomes larger with decreasing carbon concentration because of the rapid increase in the oxygen potential of the metal. It also becomes larger as the stirring force of the bottom blowing gas increases, because the rate of iron oxide formation decreases. Therefore, the amount of oxygen transfer increases with increasing stirring force of the bottom blowing gas or with decreasing carbon concentration in the molten steel.

The reason why decarburization and deoxidation proceed to a point below the values calculated thermodynamically on the assumption that $P_{CO} + P_{CO_2} = 1$ atm can be explained by the oxygen transfer from metal to slag. The effect of the partial pressure of CO on the decarburization rate is small because decarburization proceeds

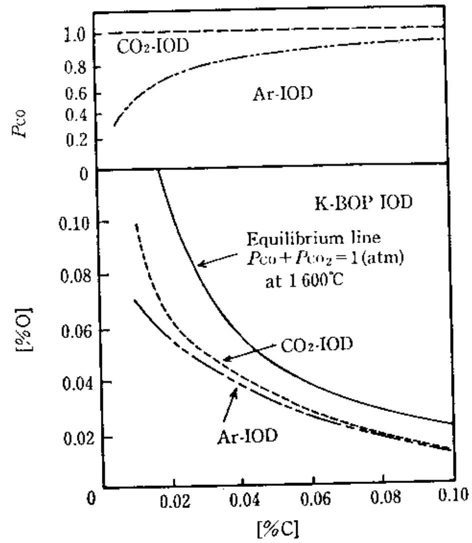

Fig. 11 Effect of P_{CO} on decarburization behaviors calculated by the reaction model

in the hot spot, where a_{FeO} is unity.

Behaviors of (T.Fe) in the slag during blowing in the three types of converters were also calculated. The (T.Fe) calculated by the mathematical model decreases with increasing stirring intensity, and agrees qualitatively with the observed values in the 5-t converter and commercial converters[10]. The mathematical model gives a reasonable explanation of the behaviors of both [%O] in the steel and (%T.Fe) in the slag during blowing.

Behaviors of [%O] and (%T.Fe) in the IOD mode were also calculated, taking into consideration the effect of P_{CO}. Stirring intensity in the IOD mode in the low carbon range improved compared with oxygen bottom-blowing in the K-BOP. Hence, assuming that the stirring intensity in the IOD mode is similar to that in the Q-BOP process, q, I and J in the Q-BOP process may be used as a basis for calculations regarding the IOD mode. **Figure 11** shows the behavior of [%O] calculated by the mathematical model during operation in the IOD mode with Ar ($P_{CO} + P_{CO_2} < 1$ atm) and with CO_2 ($P_{CO} + P_{CO_2} = 1$ atm). Figure 11 also shows the change in P_{CO} during blowing. There seemed to be little difference between the two, except that in the ultra low carbon region $[\%C] < 0.02$. Excellent agreement was obtained between these computed results and results observed with the 5-t K-BOP, as shown in Fig. 9. Hence, the decrease of oxygen and (%T.Fe) in the IOD mode is considered to be the contribution of the increase in stirring intensity obtained by mixing inert gas into the bottom blowing gas.

6 Development of Smelting Reduction of Chromium Ore for Stainless Steel Production in K-BOP[16]

Recently, intensive study of the possibility of the smelting reduction of chromium ore in the converter has been carried out, aimed at producing stainless steel without the use of ferrochromium[17,18]. This problem was also studied with the 5-t converter, mainly to clarify the effect of various methods of adding chromium ore on its rate of reduction. Based on these experiments, a stainless steel production system using two 85-t K-BOPs at the No. 1 Steelmaking Shop in Chiba Works has been developed with the use of smelting reduction process[19].

6.1 Smelting Reduction of Chromium Ore in 5-t Converter

Experiments were carried out with the 5-t converter to determine suitable conditions for smelting reduction with the K-BOP converter. After 5t of hot metal were charged, ferro-chromium alloy and coke (or coal) were added to the metal and oxygen was blown through the bottom tuyeres and top lance to adjust the temperature, carbon, $[\%C]_0$, and chromium concentration, $[\%Cr]_0$, to the aimed values. Chromium ore and carbonaceous material were then continuously charged during oxygen blowing, and the actual experiment on smelting reduction was begun. Temperature and carbon concentration in the iron melt were kept at the aimed value throughout blowing by changing the feed rates of the carbonaceous material and chromium ore. Two types of chromium ore were used, a sand-like ore with an average diameter of less than 0.5 mm and pre-reduced chromium pellets.

Figure 12 shows the effects of temperature and [%C] on the concentration of chromium oxide ($\%Cr_2O_3$), remaining in slag when the pre-reduced chromium pellets were used. The conditions for attaining a chromium oxide concentration of less than 3% are shown in the shadowed area, where the yield of chromium recovery in the iron melt is estimated to be higher than 96%.

The equilibrium value calculated by Eq. (12)[20] and that calculated by Eq. (13)[14] are also shown in Fig. 12.

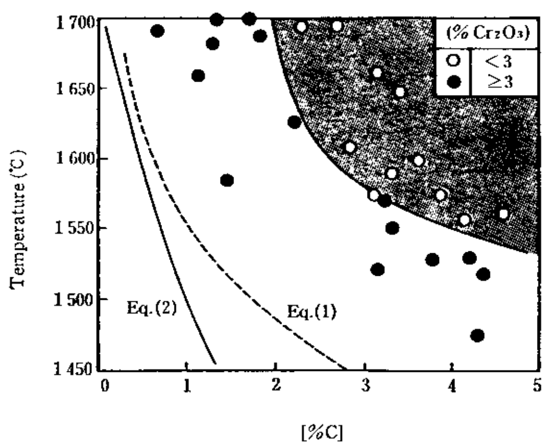

Fig. 12 Effects of [%C] and temperature on reduction of (Cr_2O_3)

$$\log \frac{\%Cr}{\%C} = 8.76 - \frac{13\,800}{T} \quad (12)$$

$$\log \frac{a_{Cr} P_{CO}}{a_C} = 8.48 - \frac{13\,520}{T} \quad (13)$$

The observed carbon concentration and temperature required to reduce chromium ore is higher than these equilibrium values. According to these results, in addition to thermodynamic conditions, promotion of the rate of dissolution of the chromium ore and its rate of reduction is considered important to obtain a high chromium ore recovery rate.

When raw chromium ore is injected through the bottom tuyeres, its recovery in the metal is about 30–50%. Recovery of chromium ore crushed to 14 μm is 80–90% at $[\%Cr]_0 = 0$. However, recovery decreases as $[\%Cr]_0$ becomes higher. Because these results indicated that the promotion of chromium ore melting is important, the injection of chromium ore with oxygen into the hot spot through a triple concentric tuyere was examined. By this method, a high rate of raw chromium ore recovery was obtained independently of $[\%Cr]_0$. This process using the triple concentric tuyere is effective for obtaining a high chromium ore recovery rate, but wear of the tube transporting the chromium ore poses a practical problem, which was solved by blasting the chromium ore through the top lance. This newly developed technique was termed the flash smelting process.

Figure 13 shows the effect of bath temperature on the content of chromium oxide remaining in slag with vari-

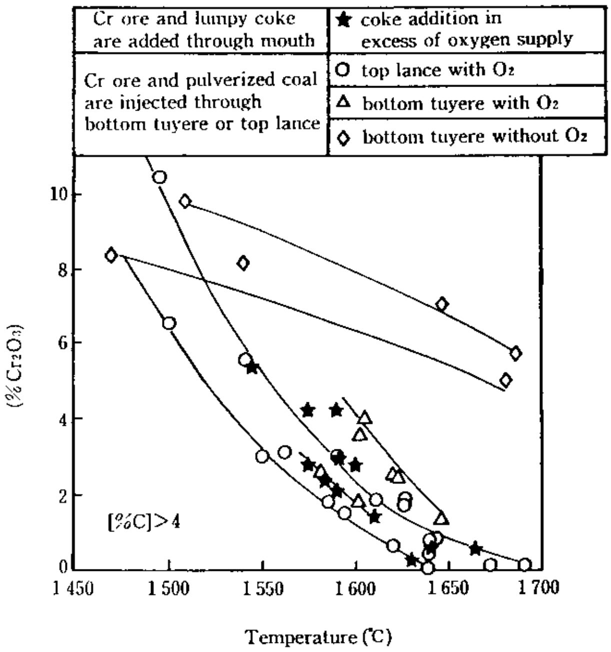

Fig. 13 Relationship between temperature and ($\%Cr_2O_3$) in slag in various addition methods of carbonaceous material and chromium ore

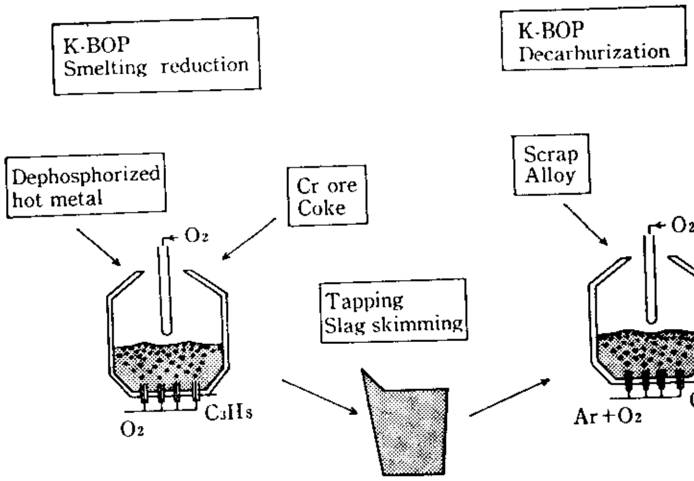

Fig. 14 Schematic illustration of stainless steel production system in Chiba Works with the use of smelting reduction process

ous methods of adding the raw chromium ore and carbonaceous material. Flash smelting is more effective in reducing the chromium ore than the process using the triple concentric tuyere.

As most chromium ore is produced in powder form, an efficient method of feeding chromium ore into the converter is important. Flash smelting has the advantage of high efficiency in this respect.

Addition of a stoichiometrically excess amount of coke, however, also enhances the reduction atomosphere and increases the number of reaction sites between coke and chromium oxide in the slag, as shown in Fig. 13. A similar effect on the reduction rate of iron ore was also observed[21).

6.2 Smelting Reduction of Chromium Ore in 85-t K-BOP[19)

The results of basic studies conducted with the 5-t converter were incorporated in a commercial production line with two 85-t K-BOP vessels at No. 1 Steelmaking Shop in Chiba Works. The flow of the process is shown in **Fig. 14**. Time available for smelting reduction is limited by the operation of the downstream continuous casting facilities. Pre-reduced chromium pellets are used because reduction of this material requires less heat than raw chromium ore.

Dephosphorized hot metal is used and pre-reduced chromium pellets and lumpy coke are added through the mouth of the converter. After smelting reduction, chromium-containing hot metal is tapped, slag is skimmed, and the hot metal is charged into a second K-BOP. This process makes it possible to replace expensive chromium alloy with chromium ore, with significant economic advantages.

6.3 Decarburization of Stainless Steel in K-BOP[22)

In the production of stainless steel at Kawasaki Steel, two converters are used, one for the smelting reduction of chromium ore and the other for decarburization, as shown in Fig. 14. Both converters are of the K-BOP type, which has the following advantages as a decarburization process for stainless steel: (1) Not only mixed gas, (O_2 + Ar), but also pure oxygen can be injected for refining because the bottom tuyeres are protected by a coolant gas such as propane. This means that ordinary steel can be economically refined in the same converter by stopping the mixing of inert gas. (2) Top-and-bottom blowing permits the supply of oxygen at higher flow rates, and hence high-speed decarburization can be achieved.

7 Conclusions

Recent advances in top-and-bottom blown converter technology at Kawasaki Steel Corp. were reviewed, and may be summarized as follows:

(1) By introducing bottom blowing of high pressure inert gas up to 50 atm, wide range controllability of the flow rate of bottom blowing inert gas has been realized in the LD-KGC converter, making it possible to produce steels of low to high carbon contents in the same converter.
(2) Experiments were carried out with a 5-t converter in order to evaluate the effects of stirring force and the dilution of P_{CO} by the bottom blowing-gas on the characteristics of the metallurgical reaction in the converter. Experimental results made it clear that the effect of the dilution of P_{CO} by the bottom blowing gas is small. Based on these results, carbon monoxide has been used as a bottom blowing gas to reduce the gas cost for stirring the steel bath in LD-KGC, with the same metallurgical effects as argon or nitrogen. Mixing of inert gas or carbon dioxide with oxygen in the final stage of refining in the K-BOP has been commercialized and effectively

prevents excess oxidation of iron in low carbon steel production.

(3) A new reaction model was proposed, and convincingly explains the metallurgical reaction in the converter when bottom blowing gas is used. The model suggests that the phenomena that oxygen concentration reduces to a point below the equilibrium value on the assumption that $P_{CO} + P_{CO_2} = 1$ atm can be explained by the transfer of oxygen from the metal to the slag.

(4) Experiments were carried out with a 5-t converter to determine suitable conditions for smelting reduction in the K-BOP. Based on these results, a smelting reduction process for chromium ore has been commercialized for the production of stainless steel in the K-BOP vessels at No. 1 Steelmaking Shop in Chiba Works to reduce the consumption of expensive chromium alloy.

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