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Kyoichi Kameyama, Hiroshi Nishikawa, Makoto Aratani, Ryuichi Asaho, Nozomu Tamura, Koji Yamaguchi

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Kawasaki Steel has developed a new top oxygen blowing degassing method in the vacuum vessel, the KTB method, which is extremely effective in promoting the decarburization reaction rate in the vacuum vessel, lowering tap temperature, and enhancing productivity and quality in ultra-low carbon steel production. The KTB method, in which oxygen is blown onto the surface of molten steel by a top lance in the vacuum vessel during decarburization treatment, is effective both promoting the decarburization reaction in the initial stage of the vacuum decarburization treatment and in providing heat compensation during degassing treatment. The promotion of the decarburization reaction has been demonstrated by a decarburization reaction model considering the simultaneous mass transfer of 〔C〕 and 〔O〕. The analysis of the heat transfer model under vacuum pressure has proved that post-combustion and adiabatic effects provide great amount heat compensation.

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Mass Production of Ultra-low Carbon Steel by KTB Method Using Oxygen Top Blowing in the Vacuum Vessel*


Kyoichi Kameyama
Staff Assistant Manager, Steelmaking Sec. III, Steelmaking Dept., Chiba Works


Hiroshi Nishikawa
Staff Manager, Steelmaking Sec. I, Steelmaking Dept., Chiba Works


Makoto Aratani
West Plant New Construction Team, Chiba Works


Ryuichi Asaho
Manager, Steelmaking Technology Sec., Steelmaking Dept., Chiba Works


Nozomu Tamura
Staff Assistant Manager, Energy Technology Sec., Energy Dept., Chiba Works


Koji Yamaguchi
Steelmaking Lab., Ironmaking & Steelmaking Res. Dept., Iron & Steel Res. Labs.

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1 Introduction

With the continuous annealing process for cold-rolled steel sheets being widely adopted,[1] lowering the carbon content of conventional low-carbon aluminum-killed steels to ultra-low levels in the refining process to improve ductility, deep drawability, and the anti-aging property[2] has rapidly become a necessity. As is apparent from **Fig. 1**, the trend in the production ratio of ultra-low carbon steels in the No. 3 Steelmaking Shop at Chiba Works has increased remarkably over the past several years.

The most commonly adopted refining method for ultra-low carbon steels[3] is the converter-vacuum degasser process, in which undeoxidized steel is tapped from the converter after decarburization to an economical decarburization limit and the carbon content is further lowered to the desired level in the vacuum vessel.[4-11] This process has the following problems:

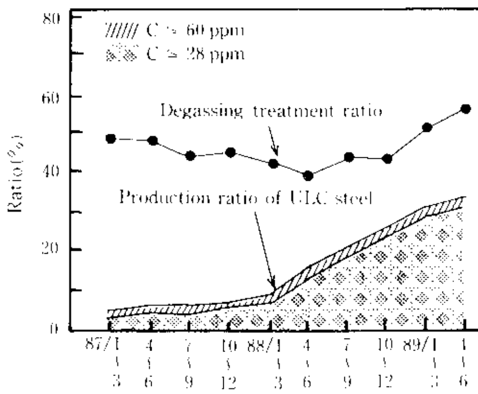

Fig. 1 Trend of production ratio of ULC steel at No. 3 steelmaking shop

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Table 1 Comparison between low-carbon aluminum-killed (LCAK) and ultra-low carbon (ULC) steelmaking (conventional method)

Item	LCAK	ULC
Tap temperature	(Base)	+48°C
Treatment time	(Base)	+12 min
Tap C	$4.5 \times 10^{-2}\%$	$2.6 \times 10^{-2}\%$

(1) Decarburization in the vacuum vessel requires a relatively long period. In addition, the temperature drop is large.
(2) In the low carbon range, in which the decarburization reaction is stagnant, the oxygen content of the steel and (T. Fe) of the slag rise abruptly; this causes a decrease in yield, damage to refractories, and an increase in inclusions (quality deterioration).
(3) High-temperature tapping is necessary to compensate for the temperature drop during vacuum degassing.

This refining method for ultr-low carbon steel is compared with the refining process for low carbon steels in **Table 1**.

To solve these problems, a technique for efficiently producing ultra-low carbon steels using a closed-circuit vacuum degasser into which a top oxygen lance is incorparated—the KTB method (Kawasaki Steel's new top oxygen blowing degassing method) was developed at No. 3 Steelmaking Shop at Chiba Works. This report presents the features and effects of the KTB method.

2 Outline of KTB Method

The equipment used in the KTB method is a vacuum degasser into which a water-cooled top oxygen lance (KTB lance) is incorporated. A schematic illustration of the KTB method is shown in **Fig. 2**.[12-14]

The top oxygen lance was adopted in the vacuum degassing treatment for the following two purposes:
(1) Decarburization is accelerated by blowing oxygen onto the bath surface in the vacuum vessel in the first half of the rimming reaction period, during which the decarburization reaction is controlled by the rate of oxygen supply.
(2) The CO gas generated during the decarburization reaction is consumed in a post-combustion reaction, providing heat compensation for the molten steel.

When these purposes are accomplished, it is possible to increase the decarburization rate, raise the [C] of steel tapped from the converter, and lower the tapping temperature.

3 Increase in Decarburization Rate by KTB Method

3.1 Improvement of Decarburization Treatment by KTB Method

The progress of the decarburization reaction during the rimming treatment in vacuum degassing is given by the following equation:

$$[C] = [C]_i \exp(-K_C t) \quad \cdots\cdots (1)$$

where [C]: Final carbon content
$[C]_i$: Initial carbon content at the start of decarburization treatment
K_C: Constant of apparent decarburization rate
t: Decarburization time

Figure 3 shows a comparison of the change in [C] during rimming treatment in the KTB process and the conventional method. Figure 3 is redrawn to show the change in $[C]/[C]_i$ to **Fig. 4**. When a comparison of the constant of the apparent decarburization rate K_C is made at the initial stage of a decarburization treatment

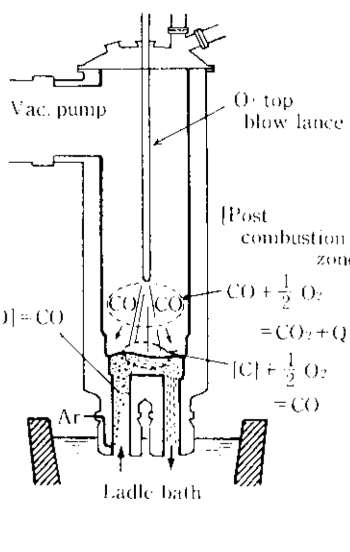


Fig. 2 Schematic illustration of KTB

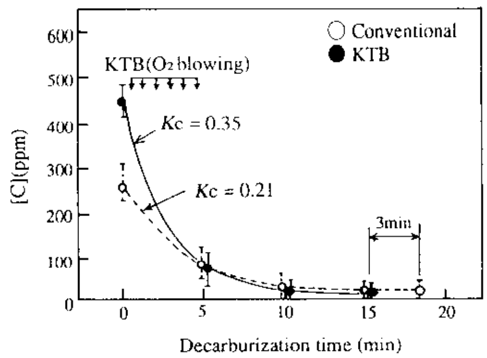


Fig. 3 Transition in carbon content during decarburization peroid

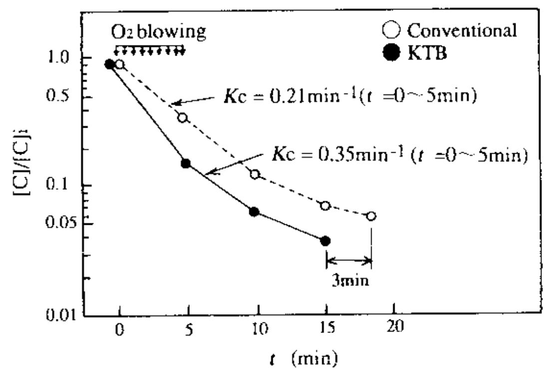


Fig. 4 Comparison of decarburization rate ($[C]/[C]_i$) between KTB and conventional methods

corresponding to the KTB treatment (top oxygen blowing), it is apparent that this constant is as large as $0.35\ \mathrm{min}^{-1}$ in the KTB method compared with $0.21\ \mathrm{min}^{-1}$ in the conventional method (without top oxygen blowing). As a result, in the KTB method decarburization time can be reduced by three minutes, compared with the conventional method even if the initial carbon content is much higher, as shown in Fig. 3.

3.2 Effect of Top-Blown Oxygen on Decarburization Reaction in Vacuum Degassing Vessel

Conditions under which top-blown oxygen is effective in accelerating the decarburization reaction were examined using a reaction model in which not only the mass transfer of [C] but also that of [O] was considered. The reaction model[15] was set up on the basis of the following three assumptions:

(1) The molten steel in the ladle and vacuum vessel is perfectly mixed.
(2) [C] and [O] are in equilibrium with the partial pressure of CO, P_{CO}, on the molten steel surface in the vacuum vessel.
(3) The decarburization reaction is controlled by the rate of mass transfer of [C] and [O].

The following equations are derived from these assumptions:

Material balance of the moleten steel in the ladle:

$$V\frac{dC_L}{dt} = Q(C_V - C_L) \quad \cdots\cdots(2)$$

$$V\frac{dO_L}{dt} = Q(O_V - O_L) \quad \cdots\cdots(3)$$

Material balance of the molten steel in the vacuum vessel:

$$v\frac{dC_V}{dt} = Q(C_L - C_V) - ak_C(C_V - C_e) \quad \cdots(4)$$

$$v\frac{dO_V}{dt} = Q(O_L - O_V) - ak_O(O_V - O_e) + 3.401\beta F_{O_2} \quad \cdots\cdots(5)$$

$$\frac{ak_C}{12}(C_V - C_e) = \frac{ak_O}{16}(O_V - C_e) \quad \cdots\cdots(6)$$

Equilibrium relation of reactions of [C] and [O]:

$$\log\frac{1.013C_e\cdot O_e\cdot 10^{-3}}{P_{CO}} = -\left(\frac{1\,160}{T} + 2.003\right) \quad \cdots(7)$$

where V, v: Molten steel volume in the ladle and vacuum vessel, respectively (m^3)
C_L, C_V: [C] value in the ladle and vacuum vessel, respectively (ppm)
O_L, O_V: [O] value in the ladle and vacuum vessel, respectively (ppm)
ak_C, ak_O: Volumetric coefficient of [C] and [O], respectively, during melting in the vacuum vessel (m^3/s)
C_e, O_e: Value of [C] and [O], respectively, at the gas-metal reaction interface (ppm)
Q: Circulation rate of molten steel (m^2/s)
P_{CO}: Partial pressure of CO in the vacuum vessel (P_a)
T: Molten steel temperature (K)
F_{O_2}: Rate of oxygen supply to the vacuum vessel (m^3-norm/min)
β: Efficiency of oxygen absorption in the molten steel in the vacuum vessel

Although it is considered that the volumetric coefficient of the mass transfer of [C] and [O][5] depends on the flow of molten steel and other factors, the ratio of the values of this coefficient $\alpha(= ak_O/vk_O)$ are considered to stand in a fixed relation to the ratio of the diffusion coefficient (D_O/D_C). Suzuki et al.[16] obtained $\alpha = 0.69$ in a crucible experiment and reported that this value was close to $(D_O/D_C)^{1/2}$. When operational results of the vacuum degasser at Chiba Works were analyzed using a conventional model in which only [C] transfer control is considered, $ak_C \fallingdotseq 0.6$ (m^3/s) is obtained. Therefore, this value is used in the present model.

$$\alpha = \frac{ak_O}{ak_C} = 0.69, \quad ak_C = 0.6\ (\mathrm{m^3/s}) \cdots\cdots (8)$$

On the assumption that all the top-blown oxygen gas except that used for post combustion is absorbed by the bath and then reacts with the carbon in the molten steel, the efficiency of oxygen absorption in the molten steel in the vacuum vessel, β, is expressed by the following equation:

$$\beta = 1 - \eta \cdots\cdots (9)$$

$$\eta = \frac{G_{CO+CO_2} \cdot \gamma}{2F_{O_2}} \cdots\cdots (10)$$

$$\gamma = \frac{CO_2}{CO + CO_2} \cdots\cdots (11)$$

where η: Efficiency of oxygen in post-combustion
G_{CO+CO_2}: Generation rate of ($CO + CO_2$) ($\mathrm{m^3}$- norm/min)
γ: Post-combustion rate

When F_{O_2} of 25 ($\mathrm{m^3}$-norm/min), γ of 0.60 (described later) and G_{CO+CO_2} of 35 ($\mathrm{m^3}$-norm/min) are used as the data on the KTB method in vacuum degassing, $\eta \fallingdotseq 0.4$ and $\beta \fallingdotseq 0.6$. In the reaction model, β of 0.6 is adopted.

Decarburization behavior was calculated from the reaction model by varying C_L, O_L, P_{CO}, and F_{O_2}, and the constant of apparent decarburization rate K_C was found using Eq. (12).

$$K_C = \frac{ak_C}{V} \cdot \frac{(C_V - C_e)}{C_L} \cdots\cdots (12)$$

Figures 5 and **6** respectively show for the conventional method (without top oxygen blowing) and the KTB method ($F_{O_2} = 25$ $\mathrm{m^3}$-norm/min), the regions of C_L and O_L in which $K_C > 0.25$, 0.20 and 0.15 $\mathrm{min^{-1}}$, K_C being derived from a model calculation using the condition of $P_{CO} = 6.66 \times 10^3$ Pa corresponding to the degree of vacuum in the vacuum degassing vessel at the initial stage of the decarburization reaction. The hatched portions in the figures indicate actual values of the movement of the C_L-O_L region that occurs with the progress of the reaction at a degree of vacuum $\geqq 6.66 \times 10^3$ Pa in the vacuum vessel at the initial stage of decarburization treatment. Figures 5 and 6 suggest the following considerations:

(1) When oxygen top blowing is not conducted, O_L has a great effect on K_C at a relatively high O_L of about 400 ppm.
(2) In the KTB method, the O_L at which K_C decreases is lower than in the conventional method even if the [C] value is the same.
(3) At a relatively low degree of vacuum $P_{CO} = 6.66 \times 10^3$ Pa, K_C decreases with decreasing O_L because the product of [C] concentration and [O] concentration decreases with decreasing C_L and the drive force of decarburization decreases. This tendency is

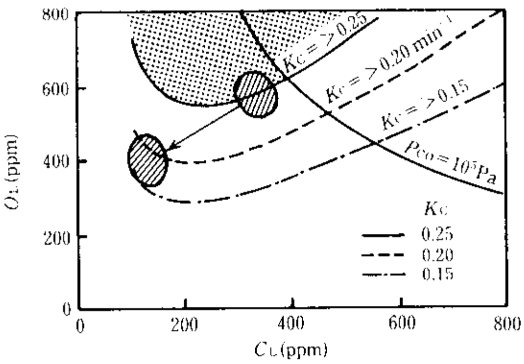


Fig. 5 Calculated value of K_C in conventional method
($P_{CO} = 6.66 \times 10^3$ Pa, $F_{O_2} = 0$)

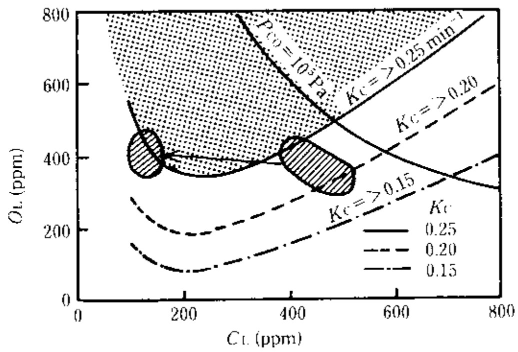


Fig. 6 Calculated value of K_C in KTB method
($P_{CO} = 6.66 \times 10^3$ Pa, $F_{O_2} = 25$ $\mathrm{m^3}$-norm/min)

stronger when oxygen top blowing is not conducted; without oxygen top blowing, a high initial oxygen content is necessary to maintain K_C.
(4) When oxygen top blowing is not conducted, an increase in the initial C_L, i.e., an increase in the [C] in the steel tapped from the converter causes an increase in the initial O_L, thus resulting in a decrease in K_C. In the KTB method, however, this decrease in K_C can be prevented because oxygen is supplied to the molten steel in the vacuum vessel even if the [C] in steel increases and the initial O_L decreases.

Therefore, it can be understood that the KTB method, i.e., the supply of top-blow oxygen, is an effective means of improving the decarburization rate in the initial stage of the decarburization reaction, not to mention in the case of oxygen transfer control when C_L is high relative to O_L. The scope of application of the KTB method in vacuum degassing is shown in **Fig. 7**.

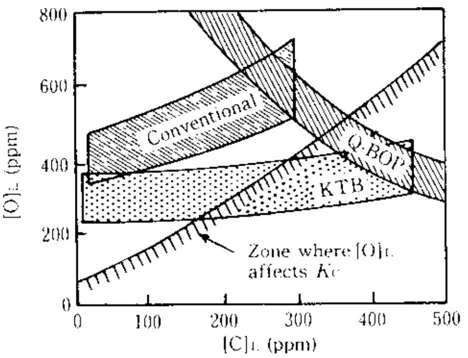


Fig. 7 Oxygen content at blow end in Q-BOP and changes in oxygen content during vacuum decarburization treatment

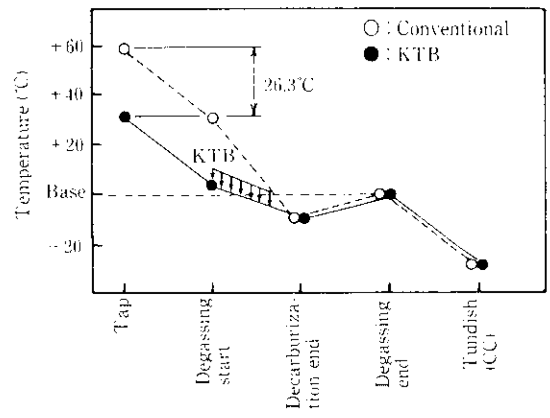


Fig. 9 Effect of KTB on the reduction of tap temperature

4 Heat Compensation by KTB Method

4.1 Heat Compensation Effect

The most significant feature of the KTB method is its effectiveness in providing heat compensation during the treatment. The heat compensation effect is mainly due to the post-combustion of the CO gas generated during the decarburization reaction in the vacuum vessel. **Figure 8** shows a comparison of changes in the CO and CO_2 concentrations in the waste gas during the decarburization treatment with the KTB method and the conventional method. It is apparent that post-combustion during the decarburization treatment is virtually impossible in the conventional method, while in the KTB method the post-combustion rate η has a high value of 0.60 (60%) even in the first half of the decarburization period, when a large volume of CO is generated.

Figure 9 shows how the steel bath temperature of an ultra-low carbon steel changes in the process from tapping from the converter to continuous casting. In the KTB method, the temperature drop is small because of the heat compensation supplied during treatment. It is therefore possible to set the steel bath temperature at the start of degassing at a relatively low level. For this reason, it is possible to adopt a lower tapping temperature than in the conventional method. It has become possible to lower the tapping temperature by more than 20°C on average in the KTB method, in comparison with the conventional method. The heat compensation effect is attributable mainly to:

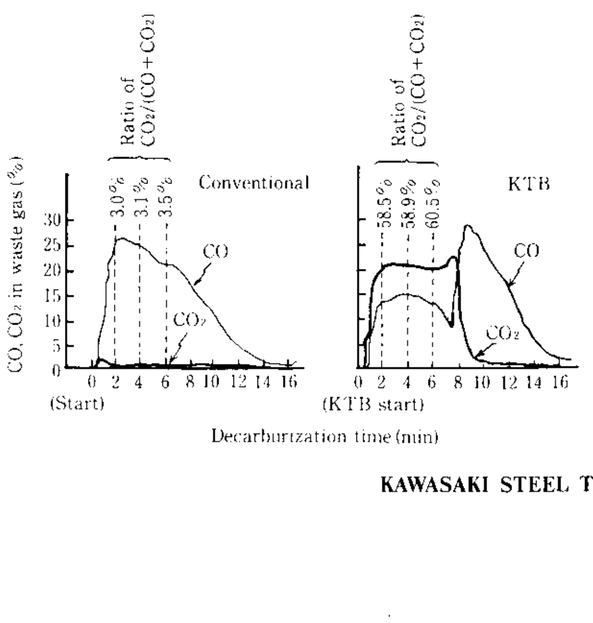
(1) Transfer of the heat of the post-combustion reaction of CO gas to the molten steel
(2) The adiabatic effect resulting from an increase in the temperature of the refractories in the vessel

4.2 Model Analysis of Heat Transfer under Reduced Pressure

The effect of heat compensation described in the preceding subsection was examined using an analysis model for heat transfer under reduced pressure. **Figure 10** shows an outline of this model, in which the interior of the vacuum vessel is divided into five zones, zones 0, 1, 2, 3, and 4. The model has the following features:

(1) "Radiation control" is assumed in order to include heat transfer in a high-temperature field.

Fig. 8 Component of waste gas during decarburization



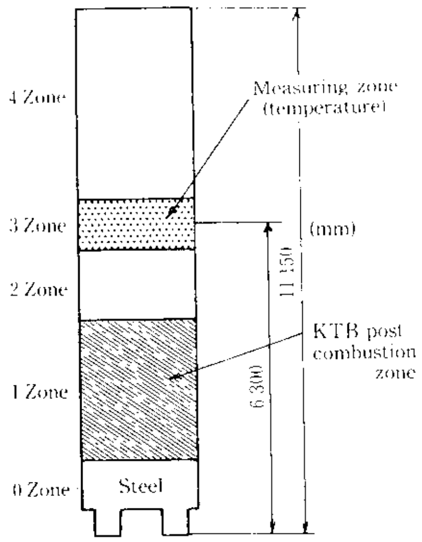


Fig. 10 Schematic illustration of zone distribution for the heat analysis

(2) The interior of the vacuum degassing vessel is divided into five zones in the vertical direction, and the zoning method is employed for the analysis.
(3) Zone 1 is the post-combustion zone in which the KTB oxygen is consumed. The height of this zone changes depending on the lance height, making the model suitable for describing actual vessels.
(4) The parameters of the model (gas radiation rate and heat-receiving area of the steel bath in the vessel) are determined based on the temperature measurement in zone 3.
(5) A method for solving an equation for unsteady heat conduction, including the refractories in the vessel, is adopted to calculate changes with time in the transfer of heat to the steel bath in consideration of the unsteady heat conduction of the vessel refractories.

The basic equations of this model are shown below.

Equation of heat transfer by radiation:

$$G_i = \varepsilon_i \cdot E_i - (1 - \varepsilon_i) \cdot J_i \cdots\cdots (13)$$

$$J_i = \sum_{j=0}^{n} (F_{ij} \cdot G_i) + \varepsilon_g \cdot E_g \cdots\cdots (14)$$

$$Q_i = \varepsilon_i \cdot (J_i - E_i) \cdot A_i \cdots\cdots (15)$$

$$E_i = \sigma \cdot T_i^4 \cdots\cdots (16)$$

$$E_g = \sigma \cdot T_g^4 \cdots\cdots (17)$$

Heat balance of exhaust gas in the furnace:

(a) Combustion zone (m-th zone, $m = 1$)

$$\begin{aligned} &V(CO + Ar) \cdot C_p(CO + Ar) \cdot T(CO + Ar) \\ &+ V(O_2) \cdot C_p(O_2) \cdot T(O_2) \\ &+ V'(CO) \cdot \{-\varDelta H(CO \rightarrow O_2)\} \\ &= V(CO + CO_2 + Ar) \times T_{g(m=1)} \\ &+ \sum_{i=0}^{n} Q_{i(m=1)} \cdots\cdots (18) \end{aligned}$$

(b) Noncombustion zone (m-th zone, $m = 2$ to 4)

$$\begin{aligned} &V(CO + CO_2 + Ar) \cdot C_p(CO + CO_2 + AR) \cdot T_{g(m-1)} \\ &= V(CO + CO_2 + Ar) \cdot C_p(CO + CO_2 + Ar) \cdot T_{g(m)} \\ &+ \sum_{i=0}^{n} Q_{i(m)} \cdots\cdots (19) \end{aligned}$$

Unsteady heat conduction and heat dissipation of the refractories in the vacuum vessel (each zone):

$$\frac{\partial T_r}{\partial t} = a(T_r) \cdot \left(\frac{\partial^2 T_r}{\partial R^2} + \frac{1}{R} \cdot \frac{\partial T_r}{\partial R} \right) \cdots\cdots (20)$$

$$\begin{bmatrix} t = 0, & R \geqq R_{in}; & T_r = f(R) \\ t \geqq 0, & R = R_{in}; & \lambda(T_r) \cdot \dfrac{\partial T_r}{\partial R} = \dfrac{Q_i}{A_i} \\ t \geqq 0, & R = R_{out}; & \lambda(T_r) \cdot \dfrac{\partial T_r}{\partial R} = U_i \cdot (T_r - T_\infty) \end{bmatrix}$$

where A_i: Surface area of the refractories or molten steel (m^2)
i (or j): Zone No.
$a(T)$: Thermal diffusivity of the refractories (m^2/s)
$C_p(\ )$: Specific heat (J/kg · K)
E_i: Potential energy of radiation ($W/m^2 \cdot K$)
E_g: Energy flux of the combustion gas ($W/m^2 \cdot K$)
F_{ij}: View factor between i and j
G_i: Discharged energy ($W/m^2 \cdot K$)
J_i: Absorbed energy ($W/m^2 \cdot K$)
Q_i: Quantity of heat by heat transfer by radiation (W)
R: Radius (m)
R_{in}: Inside radius of the refractories (m)
R_{out}: Outside radius of the refractories (m)
T_i: Temperature of the refractories or molten steel (K)
T_g: Temperature of the combustion gas
$T(\ )$: Temperature of a non-mixed gas or mixed gas (K)
T_r: Temperature of the refractories (K)
T_∞: Temperature of the atmospheric air (K)
t: Time (s)
U_i: Heat transfer coefficient between the shell of the degassing vessel and the atmospheric air ($W/m^2 \cdot K$)
$V(\ )$: Gas flow rate (m^3/s)
$V'(\ )$: Flow rate of gas which burns (m^3/s)
$-\varDelta H(\rightarrow)$: Heat of combustion ($J/m^2$)
ε_i: Radiation rate of the refractories or molten steel
ε_g: Radiation rate of the combustion gas
$\lambda(T)$: Heat conductivity of the refractories (W/m · K)
σ: Stefan-Boltzmann constant

An example of the results of a calculation using this model is shown in **Fig. 11**. It will be understood from this figure that the adiabatic effect of the molten steel resulting from an increase in the temperature of the re-

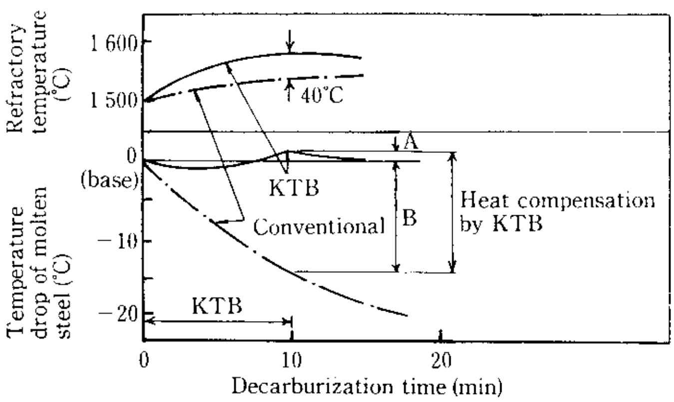


Fig. 11 Calculation results of heat analysis with KTB practice (temperature drop of molten steel due to heat transfer to exhaust gas and refractory; temperature of refractory surface calculated at No. 1 zone; and heat compensation by KTB)

fractories in the post-combustion region plays a great role in heat compensation by the KTB method.

5 Industrial Effects of KTB Method

Figure 12 shows the trend in the [C] and tapping temperature of ultra-low carbon steels ([C] $\leq$ 28 ppm) tapped from the converter in the No. 3 Steelmaking Shop at Chiba Works. The KTB method was translated into commercial production equipment in April 1988. As a result, a remarkable increase in the [C] of tapped steel and a drop in the tapping temperature have both been achieved.

A comparison of the unit consumption index of FeMn ferroalloy in vacuum degassing in the conventional method and the KTB method is shown in **Fig. 13**. The KTB method has made it possible to switch ferroalloys from expensive low-carbon (LC) FeMn to inexpensive high-carbon (HC) FeMn.

6 Quality Improvement by Application of KTB Method

The relationship between the (T.Fe) in slag in the ladle and the oxygen content of the steel bath $[O]_T$ at the end of the degassing treatment is shown in **Fig. 14**. In the KTB method, it has become possible to stabilize (T.Fe) and $[O]_T$ at low levels owing to the increase in the [C] of tapped steel and the reduction in the tapping temperature. As a result, clogging of the immersion nozzle caused by Al_2O_3 was improved in the continuous casting

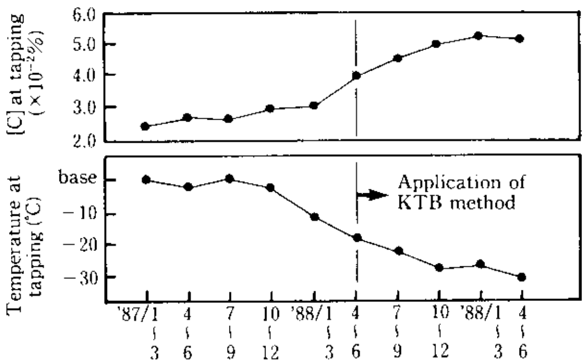


Fig. 12 Average quarterly trends of [C] content and temperature at tapping of converter for making ULC steel ([C] < 28 ppm)

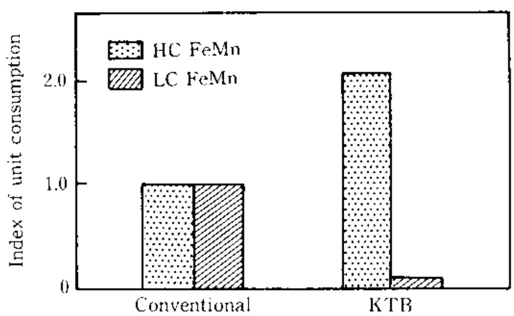


Fig. 13 Comparison of FeMn unit consumption in conventional and KTB practice

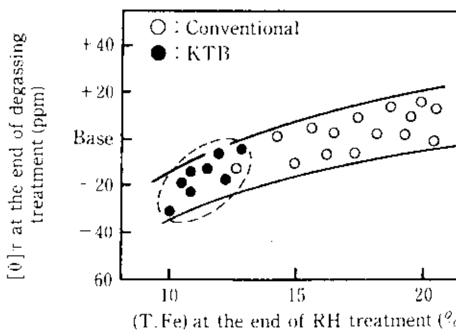


Fig. 14 Relation between (T. Fe) and $[O]_T$ at the end of degassing treatment

process, along with an improvement in slab surface quality which has contributed to the elimination of slab conditioning.

7 Conclusions

To meet the demand for continuous mass production of ultra-low carbon steels, Kawasaki Steel developed the KTB method, in which an oxygen top blowing technique is used in vacuum degassing, thus establishing a mass production process for ultra-low carbon steels. The results obtained during the technical development are summarized below.

(1) The KTB method involves supplying oxygen to the steel bath in the vacuum vessel in the first half of the rimming treatment period in which the decarburization reaction is controlled by the rate of oxygen supply, and thereby accelerating decarburization. This effect was demonstrated using a decarburization reaction model in which the simultaneous mass transfer of [C] and [O] is considered.

(2) In the KTB method, the effect of heat compensation during treatment is remarkable. Heat compensation is mainly due to the transfer of the post-combustion heat to the molten steel and the adiabatic effect resulting from an increase in the temperature of the refractories in the vessel. This heat compensation effect was demonstrated by an analysis model for heat transfer under reduced pressure.

(3) The KTB method was translated into commercial production equipment, making possible a remarkable rise in the [C] of tapped steel and a reduction in the tapping temperature. It has now become possible to use inexpensive high-carbon FeMn alloys in the degassing process.

(4) The application of the KTB method made possible a reduction in the (T.Fe) in slag and [O] in steel at the end of degassing. This reduced the clogging of the immersion nozzle in continuous casting and contributed to better slab surface quality.

The KTB method has been translated into commercial production equipment on a company-wide scale as the company's standard process for refining ultra-low carbon steels.

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