A Study on the Rate of CO₂ Absorption in NaOH Solution–CO₂ Gas Jet Model System

By Sohichi INADA** and Tetsuya WATANABEE***

Synopsis

In gas–melt reactions of the system gas jet|molten metal, it is well known that the reaction efficiency is greatly influenced by the behaviour of gas jet impinging on liquid surface, hence lancing conditions are important to control the efficiency. There are, however, only few studies available which quantitatively describe the reaction efficiency in terms of lancing conditions.

This study has been directed to develop a mathematical model capable of estimating the absorption efficiency of gas in NaOH solution–CO₂ gas jet system. The mathematical model expressing the relationship between the apparent rate constant and the behaviour of gas jet is given by:

\[ A_k \cdot k_L = V_w \cdot d_z^2 \cdot (H_o + H_s)^{-1} = M_j \cdot (H_o + H_s)^{-1} \]

where,
- \( A \): surface area of bath
- \( V \): volume of liquid
- \( k_L \): apparent rate constant
- \( V_w \): volumetric gas flow rate
- \( d_z \): nozzle diameter
- \( H_o \): distance between the nozzle and the liquid surface
- \( H_s \): depth of crater formed by gas jet
- \( \alpha, \alpha' \): constant of proportionality
- \( M_j \): the momentum of gas jet.

The values of the apparent rate constant \( k_L \) determined by Bradshaw, et al. for the absorption of CO₂ in H₂O–CO₂ gas jet system have been examined by use of the present mathematical model, and the validity of the above equation has been confirmed.

I. Introduction

In the previous paper¹ the authors presented a mathematical representation to simulate the behaviour of gas jet impinging on liquid surface under reduced pressure. This model is well expressing dynamic characteristic of gas jet, especially cavity formation on liquid surface as influenced by the momentum of jet. For the understanding of gas–metal reactions occurring in gas jet/liquid iron system, it is stressed that the relation between the characteristic of jet and reaction efficiency should also be made clear. From this viewpoint following to the previous study the authors have undertaken to present a model for expressing the apparent rate constant relative to the momentum of gas jet.

The gas–liquid reaction by gas jet is of fundamental importance for the kinetics of the basic oxygen process, so there have been many studies up to this time. Andonié and Vainshtein¹¹ Davenport, Wakelin and Bradshaw¹² conducted model experiments by using (K₂CO₃+KCl+KIO₃) solution–HCl gas and water–CO₂ gas systems, respectively. These studies, however, do not give quantitative information on the behaviour of gas jet for evaluating the efficiency of gas liquid reaction. Mori and Matsushima⁴ conducted the same experiment using molten silver–oxygen gas jet system. Their study is very useful to simulate the role of gas jet on the kinetics of the basic oxygen process, but their experiment is aiming at simulating the conditions in LD converter with violent splashing and introduction of gas bubbles which is thought to play an important role on the reaction efficiency. The present authors have special interest in gas jet/liquid reaction which occurs at cavity surface formed by jet, because of the previous observation that, under soft blowing of gas, cavity was clearly formed on liquid surface but gas bubbles were not introduced into the solution. From this model test, decarburizing reaction under soft blowing of O₂ at iron melt is considered to take place mainly at the cavity, hence it may be important to make clear the gas absorption efficiency relative to the characteristic of gas jet in gas liquid reaction. Theoretical approach on this concept is worthwhile to attempt to exactly evaluating the role of gas jet in metallurgical processing.

In the VOD process for stainless steel making, gas blowing is considerably softer (i.e., 0.2–0.3 m³/t/min) than that of LD process (i.e., 3 m³/t/min).⁶

In the former case, oxygen absorption is reasonably considered to take place mainly on the cavity surface. Standing on this viewpoint the authors have conducted a model test on NaOH solution–CO₂ gas jet system. In the following, a mathematical model expressing the relation between the efficiency of gas absorption and characteristic of gas jet in gas/liquid reaction shall be presented.

II. Model Study on NaOH Solution–CO₂ Gas Jet System

1. Experimental Apparatus and Procedure

Figure 1 shows the apparatus used for the model study. The apparatus is composed of gas inlet, reaction vessel, and pH measuring and recording systems. The rate of CO₂ absorption can be determined by continuously measuring pH values of the solutions. The reaction vessel is cylindrical with 12 cm of diameter. The vessel made of transparent glass, is contained in a cover box. CO₂ gas is blown through copper nozzle with the length of 6 mm that is con-

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2. Relationship between CO$_2$ Gas Absorption and pH of Solution

The concentration of CO$_2$ absorbed into the solution was determined by measuring pH values and by using the following relationship between pH values and concentration of CO$_2$:

Let us define $X$ and $Y$ as follows:

$X = \text{NaOH concentration in solution (mol/l)}$ ..... (1)

$Y = \text{CO}_2 \text{ concentration absorbed in solution (mol/l)}$ ..... (2)

Consider the electric charge balance, one has

$[\text{Na}^+] + [\text{H}^+] = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{OH}^-]$ ....(11)

From Eqs. (7) and (11), Eq. (12) is obtained to express the relationship between $[\text{H}^+]$ and $Y$, provided that equilibria (4) to (6) are attained:

$Y = ([\text{H}^+] + X - K_{H_2O}[\text{H}^+]) \cdot (K_1 \cdot K_2 + K_1 \cdot [\text{H}^+])$ 

$+ ([\text{H}^+]^2)/(2K_1 \cdot K_2 + K_1 \cdot [\text{H}^+])$ .... (12)

where, $[\text{H}^+]$ is connected to pH by:

$\text{pH} = -\log [\text{H}^+]$ 

The equilibrium constants for Eqs. (4) to (6) at 25$^\circ$C are given as follows:

$K_1 = [\text{HCO}_3^-] \cdot [\text{H}^+] / [\text{H}_2\text{CO}_3] = 10^{-6.352}$ .... (7)

$K_2 = [\text{CO}_3^{2-}] \cdot [\text{H}^+] / [\text{H}_2\text{CO}_3] = 10^{-10.329}$ .... (8)

$K_{H_2O} = [\text{H}^+] \cdot [\text{OH}^-] = 10^{-14.00}$ .... (9)

2.3. Material balance

Consider the material balance in Eqs. (1) to (6), one gets

$X = [\text{Na}^+]$

$Y = [\text{H}_2\text{CO}_3] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]$ .... (10)

The ionic expression of CO$_2$ absorption reaction is given by:

$\text{NaOH} \rightarrow \text{Na}^+ + \text{OH}^-$ .... (3)

$\text{H}_2\text{CO}_3 \rightarrow \text{HCO}_3^- + \text{H}^+$ .... (4)

$\text{HCO}_3^- \rightarrow \text{H}^+ + \text{CO}_3^{2-}$ .... (5)

$\text{H}_2\text{O} \rightarrow \text{H}^+ + \text{OH}^-$ .... (6)
Equations (12), (13) and equilibrium values $K_1$, $K_2$ and $k_{H,0}$ given in Eqs. (7), (8) and (9), enable one to calculate the amount of CO$_2$ absorbed into the solution from observed values of pH of the solution.

In Fig. 4, the theoretical relationship, Eq. (12), between pH values and concentrations of CO$_2$ to be absorbed at initial NaOH concentration of $X$=0.02 mol/l is given.

This was utilized to determine the concentration of CO$_2$ absorbed into the solution in this model test. The rate of decarburization by blowing oxygen onto steel melt is controlled by the rate of oxygen supply at least during steady state of decarburization. In this context, the decarburization can be regarded as oxygen absorption which may be simulated by CO$_2$ absorption from gas jet into NaOH solution.

The model test is considered very convenient for investigating the gas absorption from impinging jet because of the capability of continuous measurement of CO$_2$ gas absorption.

3. Experimental Results

As a preliminary experiment to confirm the validity of Eq. (12), CO$_2$ gas was blown at different flow rate $V$ under the following conditions:

- Nozzle height $H$: 3 cm
- Nozzle diameter $d$: 0.10 cm
- $V$: 1.0~7.0 N/min
- Initial NaOH concentration: 0.02 mol/l
- Volume of solution: 1 000 cc

The results are shown in Fig. 5 which shows that under constant lancing condition the larger the gas feeding rate, the larger the decrease of the value of pH. Figure 6 shows increasing CO$_2$ content with the lapse of blowing time by converting observed pH values to CO$_2$ content according to Eq. (12). Figure 6 shows the data of CO$_2$ absorption down to the point of approximately pH=10 in Fig. 4 (marked × in Fig. 4). If the overall rate of absorption in the range indicated in Fig. 6 is assumed to be of pseudo first order kinetics, the following relation is applicable:

$$\ln (C_t - C_{eq})/C_t = -(A/V)k_t t \quad \ldots \ldots \ldots (14)$$

where,

- $C_t$: equilibrium content of CO$_2$ (mol/l)
- $C_{eq}$: CO$_2$ content absorbed after $t$ sec (mol/l)
- $A$: reaction surface area (cm$^2$)
- $V$: volume of NaOH solution (cm$^3$)
- $k_t$: apparent rate constant (cm$^3$·sec$^{-1}$)
- $t$: lapse time (sec).

Figure 7 shows linear relationship between log $(C_t - C_{eq})/C_t$ and $t$ for the range indicated in Fig. 6. It is apparent from Fig. 7 that Eq. (14) is valid for the present experimental range indicated in Fig. 4. It is to be noted that all test runs were carried out at constant solution volume $V$ of 1 000 cc. Regarding surface area $A$, it might have changed to some extent because of the difference in cavity profile under different blowing condition, but the effect of the difference on the estimation of the rate is thought to be negligibly small. Therefore, the term $A k_t$ in Eq. (14) is taken to be apparent rate constant in treating the experimental results of this study.


**Fig. 7.** Relationships between log \((C_e - C_{e,1})/C_e\) and time for various \(CO_2\) flow rates

**Fig. 8.** Effect of the gas flow rate on the apparent rate constant

**Fig. 9.** Effect of the nozzle height on the apparent rate constant

### Table 1. Experimental conditions

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× \(d_n = 0.04\) (glass nozzle)  \(d_n\): nozzle diameter (cm)

○ 0.10 (copper nozzle)  \(V_m\): gas flow rate (NL/min)

0.15 ( \(\ldots\) )  \(H_o\): nozzle height (cm)

△ 0.20 ( \(\ldots\) )

□ 0.25 ( \(\ldots\) )

Subsequent test runs were made to find the influence of lancing conditions on the value of \(A_{KL}\) under the conditions given in Table 1.

Figure 8 shows the relationship between \(V_m\) and \(A_{KL}\), as obtained from the tangent of log \((C_e - C_{e,1})/C_e\) plots against \(t\) for the different lancing conditions.

Figure 9 shows the relationship between \(A_{KL}\) and \(H_o\) for various \(d_n\) and \(V_m\) conditions.

These results indicate that the rate of gas absorption is increased with increasing \(V_m\) and decreasing \(d_n\).

### III. Discussions

1. **Consideration on the Works by Other Investigators**

The problem of the gas absorption by gas jet in gas/liquid reaction has been investigated by many researchers. Before discussing the present results, let us consider the concepts of other works.

Typical studies are introduced in the following:

(1) Davenport, et al.\(^3\) conducted the experiment for investigating the effect of lance height on the apparent rate constant in gas/liquid reaction using water-\(CO_2\) gas jet model and concluded that the efficiency of gas absorption by jet was largely dependent on the surface velocity of liquid at the cavity area.

(2) Kuwano, et al.\(^8\) Nakanishi, et al.\(^9\) and Tohge, et al.\(^10\) conducted the studies on vacuum decarburization of molten stainless steel in laboratory-scale. In their papers, they qualitatively pointed out remarkable influence of lancing conditions on the efficiency of decarburization.

(3) Masui\(^11\) investigated the mechanism of decarburization in the basic oxygen process and introduced a revolution equation for the decarburization. The equation showed that the rate of decarburization was dependent on the velocity of gas jet at fire point. This equation, however, was an experimental equation, not a theoretical one.

(4) As mentioned in the introduction, Matsumiia, et al.\(^4\) introduced from the model test on molten silver-oxygen jet system an equation that was capable of quantitatively evaluating the relationship between the characteristic of gas jet and the rate of absorption. Their model included, however, the influences of splashing and gas bubbles both of which were thought to give major contribution to the reaction efficiency.

Through the above mentioned consideration on other works, it can be said that these studies do not quantitatively explain the role of gas jet in gas liquid
reaction. It should be recognized, however, that the common feature in these works can be deduced for defining the dependency of gas jet on the efficiency of the absorption reaction. These studies seem to be illustrating the effective influence of the jet force on the efficiency of reaction. For example, Davenport, et al.3) concluded that the rate of gas absorption depends on the flow of liquid surface that is considered to be ruled by the momentum of gas jet impinging on the liquid surface. In the previous paper10) the authors have demonstrated a model of dynamic characteristic of jet. The model explains the depth of cavity on liquid surface as a function of the momentum of gas jet. This representation seems to suggest that the gas absorption in gas jet/liquid system can be expressed in terms of the distance between lance and crater surface \((H_e+H_w)\), not of lance height \(H_e\).

Standing on this viewpoint, the authors shall try to introduce an absorption model for gas jet/liquid reaction in the following.

2. Effect of \((H_e+H_w)\) on \(A_k\)

Davenport, \textit{et al.}3) and Turkdogan12) studied cavity formation by gas jet, and Davenport, \textit{et al.} presented the following equation to evaluate \(H_e\):

\[
H_e = \left( \frac{H_e+H_w}{H_e} \right)^2 = k_{e0} \cdot \frac{M_j}{2\pi \cdot g \cdot \rho \cdot H_e^3} \quad \text{(15)}
\]

where,

\[
M_j = \left( \frac{\pi \cdot d_e^2 \cdot \rho_s \cdot u_e}{2} \right) / V_e^2 / \left( \rho_s \cdot d_e^2 \right) \quad \text{(16)}
\]

\[
k_{e0} : \text{jet constant (} \approx 15\text{)}
\]

\[
M_j : \text{momentum of gas jet (g-cm - sec }^2\text{)}
\]

\[
g : \text{gravitational acceleration (cm - sec }^{-2}\text{)}
\]

\[
\rho_s : \text{density of solution (g-cm }^{-3}\text{)}
\]

\[
\rho_e : \text{density of gas (g-cm }^{-3}\text{)}
\]

\[
u_e : \text{mean jet velocity (cm - sec }^{-1}\text{)}
\]

For the evaluation of \(H_e\) formed by jet under reduced pressure, the authors have given the following equation:10)

\[
H_e = \left( \frac{H_e+H_w}{H_e} \right)^2 = k_{e0} \cdot \frac{M_j}{2\pi \cdot g \cdot \rho \cdot H_e^3} \cdot V_e^2 \cdot 5.5 \\
\times 10^{-10} \cdot \rho_s^1 \quad \text{.................(17)}
\]

where, \(\rho_s\) is the density of gas at reduced pressure \(\text{(g-cm }^{-3}\text{)}\).

The validity of Eq. (15) has already been confirmed in the previous work.10)

Figure 10 shows the relationship between \(A_k\) and \((H_e+H_w)\) for the experimental conditions shown in Table 1. The values of \(H_e\) were calculated by Eq. (15). The tangent of the lines in Fig. 10 was taken intentionally as \(-1\) by using logarithm scale for \((H_e+H_w)\).

The results shown in Fig. 10 are well demonstrating that \(A_k\) in gas jet/liquid reaction is inverse proportional to \((H_e+H_w)\) for the given \(d_e\) and \(V_w\) conditions. This suggests that for considering the effect of jet characteristics on \(A_k\) in absorption reaction either the momentum of gas jet or the maximum velocity of gas jet along jet axis12) might be the suitable parameter. For example, Davenport, \textit{et al.}3) derived the values of apparent rate constant for water-CO\(_2\) gas absorption reaction from the speed of liquid flow at the cavity. The authors shall review the work of Davenport later by introducing the momentum of gas jet.

3. Effect of \(V_w\) and \(d_e\) on \(A_k\)

In the previous section the effect of \((H_e+H_w)\) on \(A_k\) was made clear. In Eqs. (15) and (16), however, the terms of \(V_w\) and \(d_e\) are included. It is necessary, therefore, to introduce the dependence of \(A_k\) on these values separate from that on \((H_e+H_w)\). By choosing a new apparent rate constant, \(A_k(H_e+H_w)\), the relationship between \(V_w\) and \(A_k(H_e+H_w)\) was obtained as shown in Fig. 11 for the different \(d_e\) conditions. As shown in this figure the relation between \(V_w\) and \(\log A_k(H_e+H_w)\) is linear with tangent of \(+2\). This means that the new apparent rate constant is proportional to \(V_w^2\). Now let us consider the effect of \(d_e\) on the apparent rate constant in the same way. In this case, the results are plotted on \(A_k(H_e+H_w)V_w^2\) vs. \(d_e\) coordinates as shown in Fig. 12. As shown in this figure, the relation between \(A_k(H_e+H_w)V_w^2\) and \(d_e\) can be expressed by the straight line with tangent of \(-2\).

From the results illustrated in Figs. 9 to 11, \(A_k\) can quantitatively be expressed as follows:

\[
A_k = \alpha \cdot V_w^2 \cdot d_e^{-2} \cdot (H_e+H_w)^{-1} \\
= \alpha' \cdot M_j \cdot (H_e+H_w)^{-1}
\]

where, \(\alpha, \alpha'\) : constant of proportionality.

Now let us consider in Eq. (18) theoretical meaning of \(A_k\) in the present model test. This study is dealing with gas absorption in the gas jet/liquid reaction with soft jetting condition which does not create splashing and bubbles. This makes it possible to separately evaluate the area of reaction surface \((\text{i.e., cavity surface})\) and free surface. The surface area of the cavity can be calculated from the value of \(H_e\) obtainable from
Eq. (15) by supposing that the shape of the cavity is ellipsoidal. As the next step, the surface phenomena are considered in conjunction with the momentum of gas jet for the evaluation of \( A \). It is apparent that the major part of mass transfer takes place on the cavity surface. On the other hand, it can be thought that the mass transfer might also take place on the free surface in different degree in accordance with the momentum of gas jet which causes the surface revolution of the solution. Thus, the apparent rate constant, \( A_k_L \), in this case involves all the factors related to the surface phenomena caused by the momentum of gas jet. Based on the above consideration, the values of \( A_k_L \) are taken as the apparent rate constant to treat the results shown in Figs. 10 to 12 by use of Eq. (18). Figure 13 shows the relation between \( A_k_L \) and the characteristic of gas jet. From this figure it can be seen that all the measuring points fall on the line of tangent (+1).

4. Consideration on the Applicability of the Present Model to Metallurgical Process

In the previous sections, the mathematical representation of the efficiency of gas absorption in gas jet/liquid system has been introduced. In the following, further consideration on the applicability of the present model to metallurgical process will be made.

First of all, to confirm the applicability of the model to interpret the data of other works, the work by Davenport, et al. shall be reviewed with reference to the present model. As reproduced in Fig. 14, a figure in their paper on water-CO\(_2\) gas jet model test shows the relationship between the apparent mass transfer coefficient of CO\(_2\) and \( H_c \) at different jet momentum which is determined from the surface flow of the solution. Their results seem in accord with the present ones shown in Fig. 9. It can be seen, however, that marked points (3, 4, 5) extremely deviate from the present results. It is possible to illustrate their data on \( k_L \) vs. \( M_j/(H_c+H_L) \) coordinates by applying Eq. (15) of the present model. This is given in Fig. 15 which shows that most of their data lie, in accordance
with the tendency in Fig. 13, on the straight line with tangent (+1) except points No. 1 to No. 5. The reason why points No. 1 and No. 2 are deviated from the line may be that these are the points obtained at too small a jet momentum. Thus, the data by Davenport can be explained by the present model.

NaOH solution—CO₂ gas jet model seems to be very convenient and effective means for investigating the fundamentals of gas—liquid reactions because of the capability of continuous measuring of the gas absorption. The rate of CO₂ absorption on free surface is considered to be extremely sluggish compared with that on the cavity, hence the former rate can be ignored and the effect of jet characteristic can be detected independently.

It should be recognized, however, that the model only gives relative, not absolute, values of the rate of absorption. It is necessary to evaluate clearly many factors which may influence the absolute values of the rate constant. For example, the difference in the reaction mechanism between “reaction absorption” and “physical absorption”, and the knowledge of detailed properties of gas and solution might be needed to establish the model capable of expressing absolute rate of reaction. These factors could be included as the coefficients in the model, which were introduced conveniently as α and α’ in Eq. (18).

At the last step, the authors have tried to apply the model to the decarburizing reaction of iron melt. The decarburizing reaction of high carbon iron melt by oxidizing gas is considered to be controlled in the stirring melt by the mass transfer of oxygen in gas phase. The rate of decarburization is then expressed as follows:

\[ -\frac{d[c]}{dt} = \frac{A}{V} \cdot k \cdot (P_{o_2} - P_{o_2}) \]  

where, \( k \): rate constant (cm·sec⁻¹)

\( P_{o_2} \): oxygen potential in gas phase

\( P_{o_2} \): oxygen potential at gas—melt boundary,

assuming \( P_{o_2} \approx P_{o_2} \).

Gunji, et al.¹⁶ decarburized Fe—C melt by blowing Ar/O₂ mixed gas while changing oxygen potential, nozzle diameter and gas supplying rate. They measured the activation energy for the decarburization which varied from 3.7 to 25.2 kcal/mol according to the blowing conditions. They pointed out that the effect of hydrodynamics should be taken into account in order to thoroughly understand the decarburizing reaction. From this point of view, the present model has been applied to explain the effect of hydrodynamics of gas jet on decarburization of the potential VOD stainless making process.

From Eqs. (18) and (20), decarburizing rate can be expressed according to the present model by assuming that the rate of decarburization of iron melt at steady state is controlled by the absorption of oxygen from gas jet:

\[ -\frac{dc}{dt} \approx rV_2^3 \cdot D_2^3 \cdot (H_o + H_c)^{-1} = rN \]  

where, \( r \): constant of proportionality

\( D_2 \): diameter of lance

\( N \): parameter denoting decarburizing rate.

The decarburizing reaction in this study was carried out with considerably mild blowing condition as mentioned in the introduction to make the present model applicable to the investigation of the decarburizing reaction in the steady state of the VOD process.

In Eq. (21), \( N \) can be taken as a parameter used for the control of decarburizing rate, because it contains lancing conditions, \( H_o \) and \( D_2 \), and oxygen blowing condition \( V_2 \). Under reduced pressure, the depth of the cavity increases with reducing surrounding pressure. This effect has been already made clear in the previous paper.¹¹ It is possible to evaluate \( H_o \) and hence \( (H_o + H_c) \) from Eq. (17).

From the above mentioned assumption, let us consider the applicability of Eq. (21) to practical operation of VOD stainless steel making process. In this case the operation conditions are as follows.

1) Temperature of molten metal at the beginning of vacuum decarburization: 1600°C

2) Approximate composition of bath (%):

- C: 0.30
- Si: 0.05
- Mn: 1.0
- Ni: 9
- Cr: 18

3) Weight of molten bath: 60 t

The lancing conditions and blowing conditions were intentionally changed so as to give different values of \( N \) for each test operation as shown in Table 2. The pressure at the steady state of decarburizing period was about 20 mmHg. From these given conditions, the distance between lance and cavity surface \( (H_o + H_c) \) can be determined by use of the cavity profile model under reduced pressure according to the previous work.¹¹

Figure 16(a) shows the rate of deizationcarbur during the operation at steady state period, though
the rate of decarburization was not completely constant. The rate of decarburization was measured by the continuous detecting system developed by the authors. 

In Fig. 16(b), the relation between the rate of decarburization and parameter \( N \) is shown. It may be difficult to estimate the phenomena quantitatively because available data are limited. It may be, however, suggested that the rate of decarburization is proportional to \( N \) and that the decarburizing characteristic in the practical VOD operation can be reasonably interpreted by the present liquid-gas jet model. Furthermore, it can be concluded from the above consideration that the present model can be applied semi-quantitatively to the practical operation such as VOD decarburizing process operating under mild gas jet condition.

5. Concluding Remarks

The efficiency of absorption in liquid-gas jet system was investigated by NaOH solution-CO\(_2\) gas jet model test, and the effect of gas jet characteristic on the apparent rate constant was considered. The results are summarized as follows:

1) The NaOH solution-CO\(_2\) gas jet model seems effective to investigate the fundamentals of gas jet-liquid reaction.

2) The apparent rate of gas absorption in gas jet-liquid reaction is found to be influenced by the characteristic of gas jet as a function of \( \alpha V_{\text{a}}d_{\text{a}}^{-2}(H_a+H_j)^{-1} \) or \( \alpha' M_f/(H_a+H_j)^{-1} \).

3) The values of the apparent rate constant of CO\(_2\) absorption in water-CO\(_2\) system as investigated by Bradshaw, et al. have been examined in terms of the present mathematical model, and the validity of the present model is confirmed. Further the practical application of the present model to the VOD process for stainless steel making has been considered, and it was concluded that the model can be applied semi-quantitatively to the practical decarburizing operation.

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REFERENCES

7) Japan Chemical Society: Kagaku-Binran, II, Maruzen.

Table 2. Blowing conditions VOD

<table>
<thead>
<tr>
<th>( D_{\text{a}} )</th>
<th>( H_a )</th>
<th>( V_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>1.6</td>
<td>130</td>
</tr>
</tbody>
</table>

Fig. 16(a). Rates of decarburization for several blowing conditions (Table 2). (Broken lines indicate the stable decarburization period and average rate.)

Fig. 16(b). Effect of blowing parameter \( N \) on the average rate of decarburization