Investigation of Decarburization

and Its Operation Improvement*

Behavior in RHreactor -

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Synopsis
In order to investigate the decarburization behavior in the RH-reactor, the samples of bulk steels and splashed metals were directly taken from the vacuum vessel by the use of a specially designed sampler in addition to the conventional ladle samples.
The analyses of samples have revealed that (i) the carbon content of the bulk steel is uniform throughout the vacuum vessel and (ii) the carbon con-tent of the splashed metal is almost the same as that of the bulk steel. On the basis of the results obtained, several decarburization mechanisms were examined and a new decarburization model has been proposed. In this model, it is assumed that the C-0 reaction in the bulk steel is affected by the static pressure of the vessel and also by the evolution pressure of CO bubbles, therefore the reaction gradually decreases with the progress of decarburization. This mechanism covers the reason of low reaction rate in the final stage of decarburization.
Along with the discussions of the mechanisms, a new method to measure the circulation flow rate of molten steel has been established and also a new equation which is able to make more precise estimation of the flow rate has been derived. A few experiments have been made with the 100 t RH-reactor in Hirohata Works, 1%/SC to accelerate the decarburization rate. It has been found that the use of oval shape snorkels is effective in the early stage, and that argon blowing from the bottom of vacuum vessel is effective in the final stage of decarburization.

cussion, the behavior of carbon content of steel in the
vacuum vessel is estimated on the basis off the informa-
tion actually obtained for the carbon content of steel in the ladle.
In order to investigate the decarburization be-havior in the RH-reactor, the samples of bulk steels and splashed metals were directly taken from the
vacuum vessel by the use of a specially designed sam-

pler in addition to the conventional ladle samples.
On the basis of these findings, the primary reaction sites and the effective factors to promote the reaction were studied. In addition, the circulation flow rate of molten steel was measured by a newly developed method and a modified equation being able to esti-mate the circulation flow rate was derived.
Furthermore, in order to accelerate the decarburi-zation rate, the circulation flow rate was increased by the use of oval shape snorkel and by the application of argon blowing to the 100 t RH-reactor in Hirohata Works.

II. Decarburization Behavior in the RH-reactor
Key words: secondary steelmaking; vacuum degassing; RH-reactor.

I. Introduction

Recently the RH process has been applied to up-grade the steel quality and to produce a new type of steel. Particularly nowadays, the RH serves as a main reactor for decarburization. The range of car-bon content after the RH treatment is of 30 to 40

ppm, except for special kinds of silicon steel. How-ever, in cases of continuous annealing processes newly adopted for cold rolled sheet, a large amount of ultra low carbon steel is required. In the previous studies on the RH decarburization,1,12~ it was found that the rate control stage in the reaction is mass transfer of carbon, and that the apparent reaction rate is expressed by a first order equation when the carbon content of steel in the vacuum vessel is estimated from that of ladle samples2~ with some assumptions. But the overall reaction behavior in the range of high carbon to ultra low carbon can not be explained by these models, especially in the range of ultra low car-bon content which is below 20 ppm, consequently some modifications of the reaction model are required. Many investigators studied on the reaction sites of RH decarburization. However in most of their dis-

1. Experimental Procedure

In most of the previous studies on the decarburiza-
tion behavior in the RH-reactor, the reaction mech-anism is discussed on the basis of the change in carbon
content of steel mixed in the ladle.3-5> In other
words, the decarburization reaction is inferred from indirect information of carbon content under various assumptions.
Needless to say, the decarburization reaction in the RH-reactor proceeds in the vacuum vessel; therefore the direct information from reaction sites is required
to analyze the reaction behavior more precisely. The
molten steel in the up-leg, the bulk steel and the splashed metal in the vacuum vessel are regarded as
three possible reaction sites for decarburization. The
molten steel decarburized at these possible sites is dis-charged into the ladle and mixed with the residual steel in the ladle.
As shown in Fig, 1, the specially designed sampler
is installed to take the samples of the bulk metal or the splashed metal in the vacuum vessel. The sam-pling in the vacuum vessel is made at the positions
both above the up-leg and the down-leg, since the
up- and down-legs are exchanged periodically. Two

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sampler guides are also newly equipped in order to take the ladle samples at the positions both just below the up- and the down-legs. By making a series of sampling from the ladle, the up-leg, the vessel bulk steel, the splashed, and the down-leg, the reaction be-havior is investigated.
Since the sampler in the vacuum vessel has five boxes at regular intervals of 290 mm along the height direction, the change in carbon content along the depth direction of molten steel can be measured. The height of molten steel calculated from the pres-sure of vacuum vessel is about 300 mm from the bot-tom of vessel, which is almost the same as that of the 2nd lowest box. However, in the actual operation, the circulating steel swells in the vessel particularly with bursting of the upcoming steel above the up-leg. Therefore it is not possible to identify whether the box contains the bulk steel or the splashed metal. Although some metal splashes to much higher posi-tion, the height of metal splashed can be measured from the position of the steel droplets adhered on the sampler rod.
Dissolved oxygen, which is known to affect decar-burization, is measured by the oxygen probe inserted into the ladle.

2. Experimental Results
Changes in carbon and oxygen contents of steel in the ladle during the RH treatment under various pat-terns are shown in Fig. 2. The variation of pattern is made by changing the starting time of each booster.

The carbon content of steel in the ladle is measured

by the sample taken from just below the up-leg.
As already observed in the previous investiga-tions,6-8~ the initial decarburization reaction appar-ently proceeds as a first order reaction and the rate of reaction decreases sharply at the carbon content of 20'-'40 ppm. The characteristics of decarburization after being treated for 10 min is that both the critical carbon content which reduces the reaction rate and

the final carbon content decrease as the pressure in the vacuum vessel is low and the content of dissolved

oxygen is high. Therefore, to reduce the overall de-carburization time for the treatment of ultra low car-bon steel, the decarburization behavior of the later half have to be fully investigated and the factors af-fecting on the reaction rate should be clarified. Figure 3 shows the results of sampling obtained by five different boxes of the rod sampler. The decar-burization ratio; ([C]1-[C]3)/[C]1 does not change so much by the sampling position as shown in Fig. 3, that is, the sample A taken at the bottom of bulk steel to the sample E partially including the splashed metal.

The relation between the carbon content just be-low the snorkels and those of the vacuum vessel are

shown in Fig. 4. The amount of decarburization is plotted against the carbon content of steel in the ladle. The value of [C]3 is the average of five samples. The carbon contents of the samples just above the up-leg seem to be the same as those of the samples just below the down-leg. Also the carbon contents just below the down-leg are almost the same as the values of [C]4.
Figure 5 shows the change in splashed height against the RH treatment time. Splashed height is the height where metal droplets are adhered on the sampler rod. It is thought that the splashing is vi-gorous in the initial stage, but it becomes gentle with
the lapse of treatment time, if the rate of decarburiza-
tion is taken into account.

Fig. 1. Sampl mg apparatus.

Fig. 2. Changes in carbon content
upper part of vacuum vessel,
molten steel in ladle.

of steel just below
and the dissolved

up-leg,
oxygen

pressure at
content of

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Although it is expected that the site of decarburiza-
tion can be clarified by the adoption of the direct sampling from the vessel, the primary reaction sites are hardly identified as can be seen from the results shown in Figs. 3 to 5.
From the results shown in Fig. 4, it can simply be presumed that the decarburization takes place grad-ually in the period that circulating steel flows into the up-leg snorkel. However, this presumption is con-tradicted by the results of Fig. 3, which does not clear-ly shows the change in carbon content. Furthermore, the change in height of splashed metal shown in Fig.

5 seems to be corresponding to the decarburization behavior shown in Fig. 2, but the sampling results do not show the clear difference in the carbon contents

between the splashed metal and the molten steel.
It is, therefore, not possible to identify the reaction site from the simple analysis of the direct sampling data alone. However, the possible decarburization mechanism is thought to be either of the followings.
(1) The decarburization reaction which is taken place in the steel flowing into the up-leg.
(2) The decarburization reaction which is taken place in the bulk steel of the vacuum vessel, being mixed homogeneously.
(3) The decarburization reaction which is taken place in the metal splashed from the bulk steel, being mixed homogeneously.
Further discussions for the decarburization site and

the mechanism will be given in Chap. IV, together with some decarburization models.

III. Measurement and Estimation of the Circu-lation Flow Rate

1. Measurement of the Circulation Flow Rate

The precise flow rate of circulating molten steel is required for the analysis of the RH operation data. Generally RI (Radio-active isotope) is used for the measurement, but this method is somewhat trouble-some to use despite the accuracy is not so good as compared with others.
Therefore, a new method of measuring the flow rate by the addition of ferro-alloy has been established in the current work.

As shown in Fig. 6, a specified amount of alloy v(t/min) is continuously added into the vacuum vessel during the RH treatment. The following two equa-tions are derived from the material balance in the vacuum vessel.

wdC~ jdt = Q(CIN - CoUT) +v .... (1)
Cp = CIN+dC (4C = const.) ....(2)

Equation (2) can be derived if it is assumed that there is a steady state circulation flow and a uniform dis-tribution in the vessel for any alloy level. From Eqs.
(1) and (2), Eq. (3) is obtained and Eq. (4) is derived from Eq. (3).

wdCIN/dt = Q(CIN-CoUT) +v ....(3)

Q = 1I(COUT-CIN) X (U-wdCIN/dt) ....(4)

If CoUT and CIN are continuously measured at the positions below the up-leg and the down-leg, respec-tively, the circulation flow rate, Q, can be calculated from Eq. (4).
An example of the measured results is shown in Fig. 7. At the time 2 or more min after the ad-dition of ferro-alloy GIN and GOUT become to show linear relations to the time and the gradients of CIN and GOUT are almost the same. This experimental re-sults reveal that the assumption used in Eq. (2) is reasonable one.

As an example, the circulation flow rate calculated

Fig. 3. Decarburization ratios determined pling positions.

at various sam-

Fig. 4. Amount of decarburization
of steel just below up-leg.

against carbon content

Fig. 5. Change in splashed height.

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from Eq. (4) under the conditions listed in Fig. 7 is 32.4 t/min. In this calculation, the value of w is calculated from the pressure of vacuum vessel, and therefore it is not so accurate due to the circulation of molten steel. However the value of o is much

greater than that of wdGIN/dt in Eq. (4), therefore the effect of w seems to be comparatively small. For example, even if w is twice as many, the difference in the circulation flow rate is no more than 3 %.

2. Estimation Formula of the Circulation Flow Rate

Energy E; the buoyant force of bubble is expressed by Eq. (5)

vz

E1 = nRT/V dV = CRT/(60x22.4)•ln (Pi/P2)
vl

...........................(5)

Dissipation energy E2 of the friction force between the fluid and the pipe wall is given by Eq. (6).

E2 = pqu2/2.(~a+~e+Eb/Ob+e +AL/(OIND)+AL/D) ....(6)

If the efficiency of energy is taken into account, Eq.
(7) is derived.
E2 = iE . ...(7)

From Eqs. (5) to (7), Eqs. (8) and (9) are obtained.

1/3 4/3 2 1/3

K = 60/1000 V~2p2R~I/(60 x 22.4 x 8(ca+~e+eb/Ob

+e +AL/(OIND)+AL/D) (9)

The validity of Eq. (8) is verified by the use of data obtained by the water model experiments over a wide range.
Though the data are cited from three different water model experiments, a linear relation is obtained as shown in Fig. 8. This fact reveals the validity of Eq. (8) and K is known to be constant.
The circulation flow data obtained in several actual

Fig. 6.
Measuring method of the cir-
culation flow rate by the addi-
tion of ferro-alloy

Fig. 7. Changes in silicon content.

Fig. 8. Estimation
model.

of the circulation flow rate in water

Fig. 9. Estimation of the circulation flow rate in the actual RBI operation.

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processes including the above measurement are shown in Fig. 9. Since there exists a clear linear relation-ship, the circulation flow rate in the actual RH pro-cess can be given by Eq. (10).

Q.(t/min) = 1 1 .4G"3D4/3(ln (P,/P2))1/3 (l0)

IV. Discussion of the Decarburization Site and Mechanism

As discussed in Chap. II, the decarburization site can not be identified by the simple analysis of the direct sampling data alone. To examine three pos-sible mechanisms mentioned before, several reaction models have been applied to analyze the sampling results.

The reaction in the up-leg is simulated by " the single bubble model " and the reaction in the splashed metal is simulated by the decarburization model of flying spherical particles. The reaction in the bulk steel is analyzed by the simple mass transfer model and then by a more precise model in which the static pressure of the molten steel is taken into consideration.

1. Decarburization in the Up-leg-Application of the Sin-gle Bubble Model
In order to estimate the amount of decarburization

in the up-leg by the single bubble model, it is assumed that many bubbles are formed by the injection of argon into circulating steel.
The floating argon bubbles gradually expand with the decrease in static pressure and the absorption of CO gas. In this model the pressure of bubble is treated by two ways. First the pressure of bubble is assumed to be the same as the static pressure and secondly it is assumed to be the sum of the static pres-sure and the surface tension of steel; 6. The partial pressure of CO in the latter model is expressed as Pco (J) +2 i/R (J), here Pco (J) is the same partial pres-sure of CO as that in the former model.

Since expanding bubbles may combine with each other in the process of floatation, the followings are considered to be the condition for bubble combina-tion.
Two bubbles are combined with each other to form one bubble when the bubbles float in a short

period of time 4t in a certain space and the space can not contain all the floating bubbles. In other words when the diameter of a bubble 2R(J) is larger than the diameter of sphere [2rr2U(J-1) X 60/NK]1/3 which one floating bubble can occupy, two bubbles are combined with each other to form one bubble.

The number of bubbles J'TK changes to NK/2 and its diameter R(J) to R(J) X /2.
The following are also presumed for the calcula-tion.

(1) Each bubble is spherical in shape.
(2) The resistance for mass transfer exists in the liquid boundary film.
(3) The mass transfer coefficient is given as k=
2 .S/DL/7rt, t=2r/Ua.
(4) The rate controlling step is mass transfer of

carbon as the carbon content is very low.
(5) The carbon content is constant even when decarburization is taken place by bubbles.
The assumption (5) generally makes overestimation of the decarburization amount, as the circulating steel is actually decarburized in the up-leg.
The results of calculation based on these presump-tions are shown in Fig. 10.
The relation between the diameter of initial bubble and the amount of decarburization is shown in the

initial decarburization stage ([C]=250 ppm) and the final stage ([C] =30 ppm). Here the solid line re-presents the results obtained by the simple bubble model without consideration of the surface tension

and the bubble combination, which gives the most overestimated value. Even in this case, the bubble diameter is less than 0.2 cm for the occurrence of de-

carburization in the up-leg, both in the initial and the final stages. According to Saeki et al.,"~ the initial diameter of a bubble is about 1 cm and argon bubbles are likely to combine in the actual operation, there-fore the contribution of the up-leg reaction to the total amount of decarburization can be concluded to be

small. This conclusion is in good agreement with the results of the previous studies that the reaction in the up-leg scarcely occurred, especially in the low carbon region.

2. Decarburization of the Splashed Metal
In order to estimate the amount of decarburization

by the splashed metal, it is assumed that the particles of molten steel are spherical in shape and are decar-burized under the condition that the rate controlling step is the diffusion of carbon in the particle.
The basic equation is written as

6C/at = DL(a2C/are+2dC/rar) (11)

Fig. 10. Comparison of the values calculated from the single bubble model with the observed ones.

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The flying time of the splashed metal is calculated to be less than 2.6 s as the vessel height is about 8m.

The relation between the diameter of splashed met-al and the decarburization ratio was calculated and is

shown in Fig. 11. According to the calculation by this model the particle diameter should be less than 1 mm for all steel which is circulating with 39 t/min, if all of decarburization takes place only in the splashed metal. Although some metal splashes to about 2 m high, for many cases no metal is caught in the sampling operation. Therefore it is unlikely that a large amount of small droplets exist in the vacuum vessel. Furthermore, as shown in Fig. 3, the carbon content of steel in the highest sampler box E, by which splashed metal can only be caught, is almost the same as that of the bulk steel. Consequently the splashed metal is not to be the primary reaction site.

3. Decarburization in the Bulk Steel

From the discussion in the preceding Secs. IV.] and IV. 2, the primary decarburization site is consid-ered to be the bulk steel in the vessel, then the decar-burization mechanism in the bulk steel is discussed in this section.
1. Mass Transfer Controlled Model

Decarburization in the RH-reactor is usually ana-lyzed to be controlled by mass transfer of carbon.1"2~ The equations for the mass transfer model are ex-pressed as follows :
- Wd [C]IN/ dt = Q([C]IN- [C]ouT) .... (12) -wd[C]OUTIdt = -Q([C]IN-[C]OUT)

+pk'A([C]ouT- [C]eq)
........................(13)

where k' is the apparent mass transfer coefficient and is only the parameter of this model. The calculation result of this model applied to Heat 4 is shown in Fig. 12. In this calculation the pressure gap between the vessel and the exhaust gas pipe is assumed to be 2 torr from the pressure measurement.
The result obtained with k'=0.3 m/s shown by a broken line in Fig. 12 agrees quite well with the ob-served values in the initial stage, but deviates largely in the final stage. This fact reveals that the overall reaction mechanism can not be explained only by Eqs. (12) and (13).

2. Reaction Zone Model
In the discussion for the decarburization site, the bulk steel in the vacuum vessel is treated as a unit

without dividing into several regions. Let introduce a new model with the assumption that the bulk steel in the vessel is divided into two regions; the region near the surface of bulk steel where decarburization

occurs and the region of the bulk steel except the surface where no decarburization takes place.
The concept of this model is illustrated in Fig. 13. The decarburization region, which is called the reac-tion zone hereinafter, can be determined if the reac-tion equilibrium is considered under the static pres-sure of Po+pgh at the steel depth h. The depth of reaction zone is denoted by Hm. The reaction zone is deep in the initial stage as the product, [C] x [0], is large, but this zone gradually becomes shallow along with decreasing carbon content. Thus the reaction rate is large in the initial stage, but it becomes small in the final stage. As shown in Fig. 13, the cal-culated depth of reaction zone, Hm is about 7 cm in the beginning, then decreases to a few milimeters and the reaction remains only on the surface.
Equations for this model are written as follows :

Hm -1.48 x (K[C][0]-PV) ....(14)

-Wd[C]IN/dt = Q([C]IN-[C]OUT) ....(15)

Fig. 11. Effect of droplet diameter on the ratio.

decarburization

Fig. 12. Comparison of the curves for the carbon content of steel in the ladle with the observed ones.

Fig. 13. Depth o f reaction zone against the treatment time.

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-wd [C]oUT/dt = - Q([C]IN- [C]oUT)

+pAk'([C]oUT-[C]eq)

Hm +pAka $ o ([CIouT-[C]eq(h))dh

........................(16)

The depth of reaction zone, Hm, is defined by Eq. (14). The factor 1.48 is the height of steel column which gives 1 atmospheric pressure. The term K [C] [O] represents the equilibrium partial pressure of CO, so the term K[C] [0] -PV means the pressure under which CO reaction occurs.
The term k' is the mass transfer coefficient for the

surface reaction of the penetration theory. The term ka is the only one process parameter of this model, and ka x dh has the same dimension as that of mass

transfer coefficient. If ka is large, the reaction becomes more vigorous. The term [C] eq (h) is the equilibrium carbon content which is corresponding to the static pressure of molten steel. The term pAk'([C]oUT-[C]eq) means the surface reaction taken place at the cross-sectional area of the vessel as the reaction interface, and the term

pAka Hm ([C]ouT- [C]eq(h))dh

0 is the volume reaction in the bulk steel. Because the

real interface is much larger than the cross-sectional area, the surface reaction is underestimated in this model. In other words, the slope of decarburization curve is smaller than that of real reaction in the final

stage wherein the volume reaction is almost com-pleted.
The calculation result obtained by the application of this model to Heat 4 in Fig. 2 is shown by the solid line in Fig. 12. It seems to be impossible to explain thoroughly the observed decarburization be-havior, especially that in the final stage by this model even if the parameter ka is changed from 1(1 /s) to 20(l/s).
To modify this model, the effect of evolution pres-sure of CO has been taken into account. To form CO bubbles the value of [C] x [0] has to be more than the certain value corresponding to the bubble evolution pressure. The decarburization curve was calculated varying the bubble evolution pressure with
an assumption that decarburization in the reaction zone of bulk steel does not occur when [C] x [0] is less than the value corresponding to the bubble evolu-tion pressure. In other words, the term

pAka SHm ([C]oUT-[C]eq(h))dh
0 is taken as zero when [C] x [0] <Kco (bubble evolu-tion pressure). The result shown in Fig. 14 is in a good agreement with the observed value when the bubble evolution pressure is taken as 0.02 atm. Ac-cording to Kraus et a1.,'3~ the bubble evolution pres-sure is reported to be 0.01 atm, which is close to the value obtained in this work. The calculation result

for Heat 2, in which the pressure of vacuum vessel is

large is shown in Fig. 15. The result agrees well with the values obtained for high pressure. Consequently the decarburization behavior in the RH-reactor can

well be explained by this reaction zone model with the bubble evolution pressure.
According to Eq. (16), the first term in the right hand side of the equation, namely the circulation flow rate, contributes to the promotion of the reaction rate in the initial stage. But in the middle or in the final stage, the second and the third terms become more effective compared with the first term, therefore it is necessary to increase k' or ka. To promote the de-carburization, along with an increase in circulation flow rate, it will be effective to increase the reaction interface by stirring, to enlarge the reaction zone by the highly evacuated condition, or to reduce the bub-ble evolution pressure.

V. Improvement in Decarburization Rate
In the preceding section, it is proposed that the decarburization reaction occurs in the domain close to the surface of bulk steel, and that the decarburiza-tion rate can be expressed by Eq. (16).
It is expected from Eq. (16) that the improvement of decarburization rate can be made by the following
means :

1) To increase the circulation flow rate
2) To increase the surface area of molten steel in the

Fig. 14. Comparison of the curves for the carbon content of steel in the ladle obtained by the reaction zone
model under the consideration of bubble evolution
pressure with the observed ones.

Fig. 15. Application of the reaction zone model in
eration of bubble evolution pressure to
served values at high pressure.

consid-
the ob-

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vacuum vessel
In this section, the contribution to decarburization
by the increase in the circulation flow rate by the use of an oval type snorkel and by the increase in the sur-face area by argon blowing into the vacuum vessel are discussed.

1. Oval Type Snorkel

According to Eq. (10), enlargement of the snorkel diameter is most effective way to increase the circula-tion flow rate.

Since it is not possible to simply enlarge the size of round snorkel because of the limitation owing to the vacuum vessel diameter of the 100 t RH in Hirohata

Works, an oval shape snorkel shown in Fig. 16 has been adopted to increase the effective cross-sectional area of circulating flow in the current work. The circulation flow rate of the oval shape snorkel is shown in Fig. 17, compared with that of the conventional round snorkel of which the new measurement method

discussed in the preceding chapter is adopted. As shown in Fig. 17, the circulation flow rate obtained by the use of oval shape snorkel increases to 79 t/min, more than twice as much as that obtained by the use of round snorkel (34 t /min). These figures are very close to the values estimated from Eq. (10) in Chap. III.

The decarburization behavior observed by the use of oval snorkel is shown in Fig. 18 together with that obtained by the round snorkel. The decarburization rate increases remarkably for first 10 min and the carbon content decreases to 20 ppm by the use of oval

snorkel. In about 20 min, the carbon content de-creases below 10 ppm, showing the effect of increased circulation flow rate.

2. Argon Blowing into the Vacuum Vessel
In order to increase the surface area of bulk steel, argon was blown through 7 nozzles from the bottom of vacuum vessel. The equipment is shown in Fig. 19, and the experimental conditions adopted are listed in Table 1.
Experimental results are shown in Fig. 20. The
decarburization rate increases in the period of 5 min
after the beginning to the end of treatment. Espe-cially a remarkable change in decarburization is ob-served at 10 min after the beginning of treatment.
To accelerate the decarburization rate, attempts to
increase the circulation rate by the use of oval snorkel
and to increase the surface area by argon blowing

Fig. 16. Schematic d iagram of round and oval snorkels.

Fig. 17. Relationship between the
the circulation flow rate.

flow rate of argon and

Fig. 18. Effect
havior.

of oval snorkel on the decarburization be'

Fig. 19. Schematic illustration
rangement.

Table 1. Experimental

of the injection nozzle ar-

conditions adopted.

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from the bottom of vacuum vessel have been made

and remarkable effects were observed. This implies that the decarburization mechanism discussed in

Chap. I V is acceptable one.

VI, Conclusion
The reaction mechanism has been discussed on the

basis of the information obtained by the direct sam-pling of molten steel in the RH vacuum vessel, and the results obtained are summarized as follows :
(1) Molten steel in the vacuum vessel is mixed almost homogeneously.
(2) Molten steel in the up-leg or the splashed metal can not be the primary reaction site. Decar-burization occurs mainly in the bulk steel and on the surface of bulk steel in the vacuum vessel, especially in the low carbon range.
(3) The overall decarburization behavior can be explained by a newly proposed mechanism with two reaction zones on the surface and in the bulk steel in

consideration of the static pressure and the evolution pressure of CO bubble.
(4) The rate of reaction is rather fast in the high carbon range because the reaction domain in the bulk steel is large, but in the low carbon range, the reac-tion domain is limited to only near the surface and the rate of reaction becomes small.
As for the circulation flow rate which has a remark-able effect on the reactions in the vacuum vessel, a new measurement method by the addition of ferro-alloy has been developed and a modified estimation equation has been derived.
On the basis of these results, the decarburization rate has been improved (i) by the use of oval shape snorkel, which increases the circulation flow rate and

promotes the reaction rate in the high carbon range, and (ii) by the application of argon blowing from the bottom of vacuum vessel, which increases the surface area and promotes the reaction rate in the low carbon range.

Nomenclature

A : Cross-sectional area of vacuum vessel (m2)
C: Alloy content (%)
[C] : Carbon content (%)
CI: Carbon content at the interface of bubble (%) D : Inner diameter of snorkel (m)

DL : Diffusion coefficient of carbon in molten steel

(m/s2)
E: Dissipation energy (J)
G: Flow rate of blowing gas (NI/min)
H: Depth of injection nozzle (m)
Hm : Depth of reaction zone (m)
h : Depth of steel (m)
J: Ordinal number of space from the blowing point (-)
K: Equilibrium constant of CO reaction (-)
IC : Mass transfer coefficient by the penetration theory (m/s)
A:' : Apparent mass transfer coefficient (m/s)
ha : Reaction rate constant of the reaction zone model (l/s)
L : Length of snorkel (m)
JVK: Number of bubbles (-)
n : Molar number (-)
P: Pressure (atm)
Pco : Partial pressure of CO gas (atm) Q: Circulation flow rate (t/min)
R : Gas constant (-)
r: Radius of a bubble (m)
S: Surface area of a bubble (m2)
T: Temperature of molten steel (K)
t : Time (min)
Z: Time (s)
U: Floating rate of bubble (m Js)
UG : Relative floating rate of bubble to molten steel (mis)
U : Flow rate of molten steel (m/s)
V: Volume of a bubble (m3)
V : Adding rate of ferro-alloy (t/min)
W: Amount of steel in ladle (t)
w : Amount of steel in vacuum vessel (t)
: Contraction flow coefficient (-)
7) : Available ratio of dissipation energy (-) A : Pipe friction factor (-)
e : Enlargement flow coefficient (-)
p : Density of molten steel (kg/m3)
a : Surface tension (N/m2)
~b : Void fraction (-)

Subscripts
IN : Up-leg
OUT: Down-leg
V : In vessel

eq : Equilibrium
1: Just below up-leg
2: Just below down-leg
3: Just above up-leg
4: Just above down-leg
1 : Blowing point
2: Vacuum vessel

a, b : Inlet of up-leg, Outlet of up-leg, respectively c, d : Inlet of down-leg, Outlet of down-leg, respec-tively

Fig. 20. Effect of argon blown into
decarburization behavior.

vacuum vessel on the

1)

2)

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