1. Introduction

Corresponding to the increasing demand for the mass production of ultra-low carbon steel, technical development to improve the decarburization efficiency in the vacuum degasser is actively reported. Generally, the decarburization rate of RH decreases in the low carbon region of less than about 20 ppm (stagnating region). To meet the demand for ultra-low carbon steel production, the improvement of the reaction rate in this stagnating region is imperative.

In the previous paper, the authors proposed a new decarburization reaction model in which the three reaction sites have been considered. From the calculation result of this model, it was revealed that the bath surface decarburization takes place mainly in the low-carbon region, and the importance of the bath surface reaction enhancement has been stressed.

Also, based on the fundamental experiments, the authors clarified that most of the bath surface reaction have taken place at the bubble rising area at the bath surface (bubble activated surface).

According to these findings, the best design to produce ultra-low carbon steel has been investigated and a novel process in which single large cylindrical snorkel is immersed to the molten steel in the bottom bubbling ladle was invented and named REDA (Revolutionary degassing activator). From the results of the plant tests of 175 and 350 t scale, the high performance of this process has been confirmed.

In this paper, the ruling factors of the decarburization rate by REDA have been analyzed.

2. Best Design of the Vacuum Degassing Process

The best design was considered from the following standpoints:

1) Bath Surface Reaction Rate

To enhance the decarburization rate in the low-carbon region, the increase of the bath surface decarburization rate is important. The fundamental experiments shows the importance of enlarging the bubble activated surface area in addition to increasing the gas flow rate, to enhance the reaction on the bath surface. As the increase of the gas flow rate would cause deterioration of the vacuum pressure and skull formation, increase of the activated surface area with the minimum gas flow rate would be a favorable measure. Concretely, the gas bubbling from the bottom of the deep bath without any small diameter snorkel would be the best process.

2) Perfect Mixing Time

The mixing performance is one of the essential characteristics of the vacuum degasser as it affects not only the decarburization reaction rate but also the uniform distribution of the alloying elements or the floatation of nonmetallic inclusions. Watanabe et al. revealed that the perfect mixing time of the molten steel in the bottom bubbling ladle is short even though the bubbling gas flow rate is
3) Productivity and Cleanliness

To increase the productivity of making the ultra-low carbon steel, high speed evacuation at the early stage of vacuum treatment is imperative. To produce clean steel and to increase the yield of alloying elements, the suppression of the reaction with oxidized top slag should be taken into account. Accordingly, the immersion of snorkel with large freeboard is favorable.

Based on the above considerations, the authors invented a novel vacuum refining process which consists of a large immersion snorkel and a bottom bubbling ladle as shown in Fig. 1. This equipment is named REDA (Revolutionary degassing activator).

3. Industrial Tests of REDA

The industrial tests were carried out using the 175 t DH in No. 1 steelmaking shop and the 350 t DH in No. 3 steel-making shop of Yawata Works. The experimental conditions are summarized in Table 1.

Figure 2 shows the result of the perfect mixing time measurements by Cu addition in each case. Asai et al. proposed Eq. (1) to calculate the perfect mixing time (τ: s) for the bottom bubbling ladle.

\[ \tau = 72 \times e^{-0.337 \times (L/0.2)^{1.16} \times (0.2/H)} \]

where, \( L \) is the diameter of ladle (m), \( H \) is the bath depth of ladle (m) and \( \varepsilon \) is the stirring energy (W/t).

In Fig. 2, sampling time after Cu addition was normalized by the perfect mixing time of the ladle which was calculated by Eq. (1). It can be clarified that the mixing characteristics was not deteriorated by the immersion of the large snorkel. In these cases, the snorkel was immersed shallowly within the limits to keep the vacuum condition in the vacuum vessel.

Figure 3 shows the typical decarburization curves. The carbon content reached about 10 ppm in 15 to 20 min treatment in each case, and after that it decreased to 4ppm without any stagnation. In this figure, the calculated curves by the decarburization model which will be explained later are shown.

4. Ruling Factors of the Decarburization Rate by REDA

Decarburization rate constant can be calculated by Eq. (2).

\[ K = (\ln(C_A/C_B))/(t_B-t_A) \]

where, \( C_A, C_B \) are the carbon content (%) at \( t_A, t_B \) (min) after the start of the treatment, respectively. The carbon concentration range from 150 to 50 ppm is defined as region I and that from 30 to 15 ppm is defined as region II. The decarburization rate constant in regions I and II are named \( K_1 \) and \( K_2 \).

As the ruling factors, specific recirculating rate (\( R; \) min\(^{-1}\)) calculated by Eq. (3), evacuation rate (\( V; \) min\(^{-1}\)) calculated by Eq. (4), surface reaction rate parameter (\( K_S; \) \( \text{m}^2; \text{W}^{1/2};\text{t}^{1/2} \)) calculated by Eq. (5) and the dissolved oxygen content (free O: ppm) were used.

\[ R = 1/(3 \times t/60) \]

\[ V = \log(P_f/P_i)/(t_f-t_i) \]

\[ K_S = (G+6.5 \times S) \times e^{1/2}/W \]
where, \( t \) is time (min), \( P \) is pressure (Pa), \( G \) is the geometrical surface area (m\(^2\)), \( S \) is the bubble activated surface area (m\(^2\)), \( W \) is weight of steel (t) and the subscript of \( I \) and \( F \) stand for the initial and final values of each carbon region.

In Eq. (4), to characterize the evacuation rate, the rate of pressure decrease in logarithmic scale was calculated. The bubble activated surface area was geometrically calculated assuming that the plume area is spread to an angle of 12 degree on each side from the injection nozzle.\(^9\)

For comparison, the results of the large scale RH degasser of about 300 t capacity\(^1,2\) and the calculated curves by the decarburization model which will be explained later are shown in the following figures. The specific recirculating rate of RH was calculated by the equation proposed by Kuwabara et al.\(^10\)

Figures 4, 5, and 6 show the influences of the evacuation rate, the specific recirculating rate and the dissolved oxygen content on the decarburization rate constant of the region I, respectively. The dependence on each factor can be seen.

Figures 7, 8, and 9 show the influences of the specific recirculating rate, the dissolved oxygen content and the surface reaction rate parameter on the decarburization rate constant of the region II, respectively. Also, the dependence on each factor can be seen.

In each figure, the difference between the 175 t with the 350 t scale experiments of REDA is not seen.

5. Discussion

In the previous report,\(^2\) the authors clarified that the decarburization rate of RH in region I was mainly influenced by the specific recirculating rate and the evacuation rate, and that in region II was influenced by the specific recirculating rate and the reaction rate on the bath surface. The similar dependency for the decarburization rate of REDA on each parameter was found in each figure from Figs. 4 to 9.
The decarburization model for RH\textsuperscript{2} was applied to REDA. Based on the original model, mass transfer of carbon and oxygen in the molten steel, the mass transfer of CO in gas phase and the chemical reaction were considered as the rate controlling steps. Also, the bath surface reaction, the Ar bubble surface reaction and the bulk steel decarburization reaction were taken into account. The bulk steel decarburization rate can be calculated by the difference between the hydrostatic pressure and the equilibrium partial pressure of CO for each site in bath depth. The hydrostatic pressure depends on the vacuum degree and the depth from the bath surface, and the equilibrium partial pressure of CO was calculated by the carbon and oxygen contents. In the case of REDA, the steel which is sucked into the large snorkel by evacuation is considered to correspond with the steel in the vacuum vessel in the case of RH. The specific recirculating rate is calculated by Eq. (3).

The results of the calculations for 350 t REDA are drawn in each figure from Figs. 2 to 9. The calculated curves well meet the experimental results for 175 t and 350 t scale REDA. It can be said that various capacities of REDA can be designed by the use of this model.

Figure 10 shows the relation between the carbon content and the amount of decarburization per minute for each reaction site. As indicated, the bulk steel decarburization reaction predominates in region I, while in region II, the bath surface reaction and the bulk steel decarburization reaction occur mainly. Based on the bulk steel decarburization mechanism, in region I, the evacuation rate which affects the hydrostatic pressure, and the dissolved oxygen content which affects the equilibrium partial pressure of CO have influences on the decarburization rate. On the other hand, the dissolved oxygen content affect the carbon content at which the bulk steel decarburization reaction comes to an end. The decarburization rate in region II is influenced not only by the surface reaction rate parameter ($K_S$) but also by the dissolved oxygen content. These dependencies are the general phenomena for the vacuum decarburization reaction and there are no differences with REDA and RH. For each process, the specific recirculating rate is the important factor. By this research, it was clarified that the specific recirculating rate of REDA can be calculated by Eq. (3) to compare with that of RH.

Figure 11 shows the calculation results of the specific recirculating rate ($R$) for REDA and RH. In REDA, only low flow rate of Ar is necessary to obtain the large specific recirculating rate equal to that in RH, because the stirring gas is injected from a deep portion of the bath and the buoyancy energy of gas bubbles can directly attribute to the bath agitation.

In Fig. 12, contour lines which indicates the same value of $K_S$ for various values of injection gas flow rate, bubble activated surface area and injection depth.

5. Conclusions

(1) A novel vacuum degassing process consisting of a large immersion snorkel and a bottom bubbling ladle has been invented for the efficient production of ultra-low carbon steel. This process has been confirmed by industrial scale test using 175 and 350 t scale DH and named REDA (Revolutionary degassing activator).

(2) The carbon content reaches 10 ppm in 15 to 20 min treatment, and decreases to 4 ppm without any stagnation.

(3) The observed perfect mixing time meets the calcu-
lated value using the equation for the bottom bubbling ladle and no deterioration was found by the immersion of the large snorkel.

(4) The decarburization rate in region I was mainly influenced by the specific recirculating rate and the evacuation rate, and that in region I was influenced by the specific recirculating rate and the reaction rate on the bath surface. These tendencies were almost the same as those for RH.

(5) As REDA has a wide bubble activated surface area and a deep injection position, relatively low gas flow rate is necessary to produce ultra-low carbon steel efficiently.

REFERENCES