Development of Vacuum Decarburization Technologies at Yawata Works, Nippon Steel

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Abstract

Characteristics are described herein of the DH and REDA vacuum decarburization technologies developed at Nippon Steel's Yawata Works for applications to ordinary steels. Their attainable decarburization level and decarburization rate-constant were evaluated regarding their applications to ultra low C steels. The processes were also compared regarding decarburization capacity, focusing especially on steel circulation amounts, reaction boundary area and Ar gas injection amounts. As a result, decarburization capacity of REDA was found to be superior to that of DH and nearly the same as that of RH. Because the amount of the Ar gas injection cannot be increased any more in the operation of REDA and RH, development of a method to generate fine bubbles in molten steel is an important task in the near future for improving the decarburization capacity.

1. Introduction

The DH vacuum degassing technology (hereinafter DH) was introduced to Japan from Germany in the early 1960s and was developed to play a significant role in the improvement of steel quality and productivity as well as in the reduction of production costs[1]. Nippon Steel's Yawata Works, which was the first Japanese steel works to introduce DH, developed Slim DH[2] and then Revolutionary Degassing Activator (REDA)[3-5] based on DH. This report reviews the history of the expansion of decarburization capacity from DH to REDA, comparatively evaluates the DH, REDA and RH degassing technologies, and suggests an orientation of future development for a more powerful decarburization technology.

2. Development and Characteristics of DH and REDA

The history of the development of vacuum decarburization technology at Yawata Works, which started from DH and reached REDA, can be divided into four stages as shown in **Fig. 1**. The key points of technologies developed in each of the stages, decarburization levels therein attained and other aspects are summarized below referring to the figure.

2.1 First stage (1960-67): comprehension of fundamental functions of DH

DH degassing tests started in Yawata Works in 1959 using a 25-t vessel, and 2 units of 70-t DH degassors were introduced in 1962. During this stage, decarburization mechanisms based on CO reactions were clarified, and the operation parameters contributing to decarburization effects (the relationship between liquid steel suction velocity and steel amount, the number of vertical strokes of a vacuum vessel, the amount of steel remaining in the vessel at the top of the vertical strokes, etc.) were quantified. As a result, an ultimate carbon concentration [C] as low as 0.02% was attained. Melting conditions of alloys were investigated using RI(^{198}Au), and the concept of homogeneous mixing time τ was introduced also in this stage.

2.2 Second stage (1968-78): function and size expansion of DH
2.2.1 Function expansion

In 1969, it was made clear that the rate of decarburization tended to decrease with low C steels, and a minimum attainable [C] of 50 -

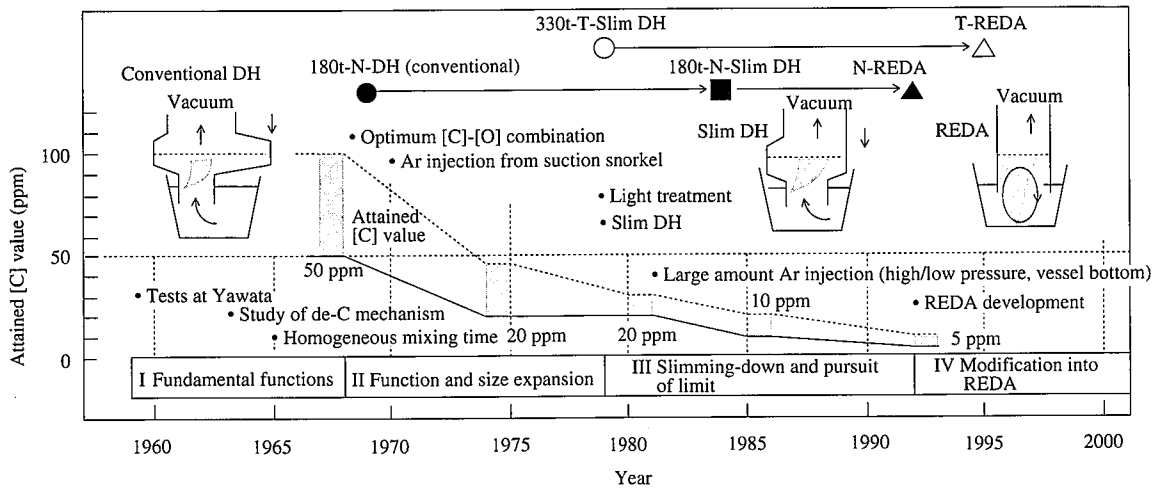[*1] Technical Development Bureau, presently Nippon Steel Technoresearch Corporation

Fig. 1 Historical changes of main technologies of DH and REDA

100 ppm was reported as a result of an optimum combination of [C] and [O] before the vacuum treatment. In 1970, an ultra low carbon stainless steel having a [C] of 0.014 - 0.02% after the treatment was produced with an injection of Ar gas from the suction snorkel of the 70-t DH. Since the Ar gas injection proved very effective for decarburization, it was adopted as a normal practice ever since.

2.2.2 Size expansion

Construction of large capacity facilities supported rapid growth of steel production, and DH was no exception in being required to increase capacity through expansion of facility size. In 1969, a large size 180-t DH degassor entered into operation at the Tobata District of Yawata Works, and proved to be effective for further cost cutting in response to the First Oil Crisis of 1973.

2.3 Third stage (1979-90): development of slim DH and pursuit of limit

2.3.1 Development of slim DH

Quality demands grew from intense to severe in the steel industry after the Second Oil Crisis in 1979, and a treatment of ultra low carbon steels in large heat sizes was requested as a consequence to the application of the continuous annealing process to the production of cold rolled sheets. A new melt shop with 330-t/heat converters was built at Yawata Works and a newly developed slim DH degassor (hereinafter 330t-T-Slim DH) was put into commercial operation at the shop in 1979[6]. The degassor featured a vessel having a larger height/diameter ratio than conventional DH degassors and a vessel outer diameter smaller than the ladle inner diameter as shown in **Fig. 2** (a) so that the vacuum vessel may be put inside a ladle. The

degassor also had a larger vertical stroke to increase the amount of liquid steel sucked up per cycle of the vertical stroke. The number of vertical strokes per minute was also raised to increase the amount of liquid steel circulation per minute Q. Agitation energy of molten steel in ladle was increased as a result, and the homogeneous mixing time τ was remarkably reduced. Further, the 180-t DH degassor (hereinafter 180t-N-DH)[7] was modified into the slim type in 1984 (hereinafter 180t-N-Slim DH).

2.3.2 Pursuit of limit of DH through large amount Ar injection

In the slim type DH, an enhancement of decarburization capacity was attempted from 1980 to around 1985 by means of injection of Ar gas in a large quantity from (1) the suction snorkel and (2) the vessel bottom, as shown in Fig. 2 (a). In the case of the Ar gas injection from the suction snorkel (Fig. 2 (a) (1)), a method was worked out to suppress the resistance of the injected gas against steel flow: the Ar gas was injected in a large amount and at a high pressure when the steel was sucked up into the vacuum vessel; and it was injected in a small amount at a low pressure when the steel returned to the ladle[1]. **Fig. 3** shows the progress of decarburization during vacuum treatment in which a large amount of Ar gas is injected by this method[1]. Compared with A where no Ar gas is injected, the decarburization velocity in the [C] range of 50 to 20 ppm increases in B where 2,500 L/min of Ar is injected, and [C] is reduced to 10 to 20 ppm or so in a 20-min treatment. The decarburization velocity constant K (1/min) in this case is 0.15 (where, [C] is carbon concentration in %, t is treatment time in min, t = 0 means the beginning of degassing, and the value K (1/min) is calculated under the condition
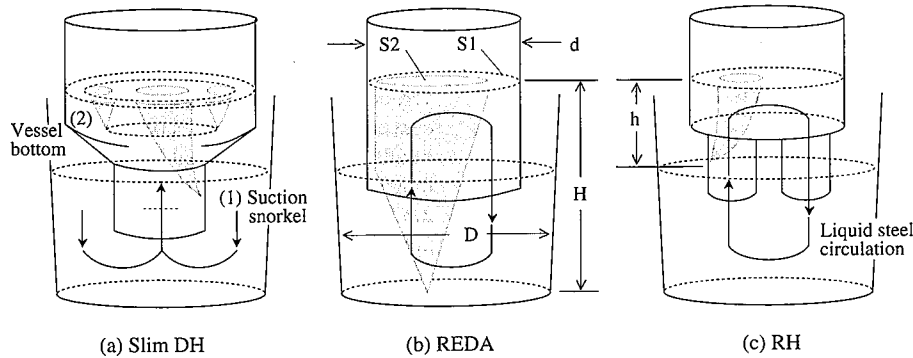

| (a) Slim DH | (b) REDA | (c) RH |

Fig. 2 Vessel shapes and Ar gas injection positions

	Suction snorkel	Vessel bottom	Total	K
A	0	0	0	0.10
B	2,500	0	2,500	0.15
C	1,200	[500]	1,700	0.16
D	0	1,000	1,000	0.23
E	0	540	540	0.23

A-B : 330t-T-Slim DH
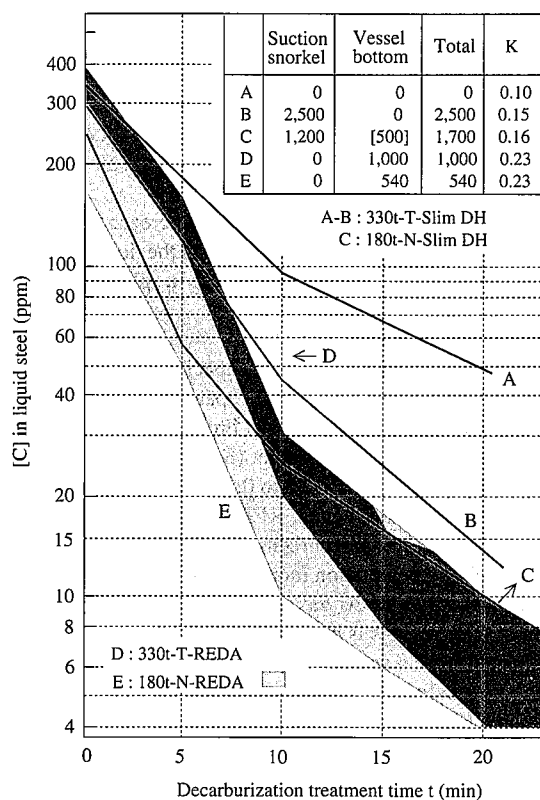C : 180t-N-Slim DH

D : 330t-T-REDA
E : 180t-N-REDA

Fig. 3 Decarburization curves of DH and REDA

of d [C] / dt = –Kt and a decarburization time of 15 to 20 min).

When the gas injection amount was raised to about 3,000 L/min, however, there occurred a delay in the return flow of liquid steel from the vacuum vessel to the ladle, and it became clear that there was a certain limit to the gas injection amount. With regard to the Ar gas injection from the vessel bottom (Fig. 2 (a) (2)), although a decarburization acceleration effect of the method was confirmed[8], the idea of using this method for commercial production was abandoned because of much splash occurring in the vessel, impossibility to inspect erosion of the injection tuyere at the vessel bottom, and residual slag in the vessel bottom burying the tuyere and hindering stable operation. It has to be noted, however, that the 180t-N-Slim DH could reduce [C] to 10 ppm in a 20-min treatment with Ar injection from both the suction snorkel and the vessel bottom[9], as seen in C of Fig. 3.

2.4 Fourth stage (1991-99): modification of DH into REDA
2.4.1 Development and introduction of REDA

Based on the finding that homogeneous mixing of steel could be rapidly achieved by a method to form a circulating flow of liquid steel by a continuous gas injection from the ladle bottom, REDA was developed as a new process in 1991 through a modification of the 180t-N-Slim DH. Then, the 330t-T-Slim DH was also modified into a REDA unit in 1994[3-5] (hereinafter 180t-N-REDA and 330t-T-REDA, respectively). In the design of REDA, the vacuum vessel has a diameter larger than a conventional suction snorkel as shown in Fig. 2 (b), and the vessel does not move vertically. Decarburization proceeds as Ar gas is injected from the ladle bottom to the vessel interior to form a circulation flow of the molten steel between the vessel interior and the ladle. REDA proved to be superior to the slim DH in terms of decarburization capacity.

2.4.2 Enhancement of decarburization capacity by REDA

In the geometry of REDA shown in Fig. 2 (b), the agitation force of gas increases as the liquid steel level H becomes higher, and decarburization becomes stronger as the steel surface area S1 and the steel exposure area to the Ar gas S2 in the vessel become larger. When the vessel diameter d is larger, the steel surface area S1 in the vessel becomes larger and the decarburization becomes stronger, but the liquid steel level H becomes lower and the steel exposure area S2 becomes smaller and, as a result, the decarburization is suppressed. It is therefore necessary to choose an optimum vessel diameter d with which the steel exposure area S2 becomes the largest. The vessel diameter d of the 330t-T-REDA is approximately 2 m, 0.5 times the ladle inner diameter D (d/D = 0.5)[5, 10]. The homogeneous mixing time τ was investigated using water models and it was confirmed that, whereas τ of the slim DH was 80 s or so, that of REDA was around 65 s, a reduction by about 20%[5]. As a consequence, the 330t-T-REDA achieved a steel circulation amount of approximately 200 t/min in commercial operation and the 180t-N-REDA approximately 160 t/min.

Fig. 3 shows the decarburization behaviors of the 330t-T-REDA (D) and the 180t-N-REDA (E), both modified from the slim DH units[3,4]. As is clear from the figure, REDA is capable of obtaining a carbon concentration of 10 ppm or so in a treatment time of approximately 15 min, and 10 to 5 ppm in 20 min, which fact indicates that its decarburization velocity is higher than that of the slim DH. Thus, as seen in Fig. 1, after 35 years of the introduction of the DH technology, it was made possible to easily attain a carbon concentration level of 10 to 5 ppm in commercial production in the form of REDA.

3. Discussion on Decarburization Capacity of Slim DH, REDA and RH

The slim DH and REDA are compared below with regard to the decarburization capacity focusing on the factors to determine it, namely the liquid steel circulation rate Q, the reaction surface area S and the Ar gas injection rate A. The decarburization capacity of the RH degassing process is also studied based on recent literatures and is compared with those of the slim DH and REDA.

3.1 Comparison of slim DH and REDA
3.1.1 Comparison of liquid steel circulation capability

For increasing the decarburization capacity it is imperative to circulate a great amount of liquid steel into the vacuum vessel interior to expose it to the vacuum. The index of circulation capability I (1/min), which is defined as the liquid steel circulation rate Q (t/min) divided by the heat size W (t/heat), was remarkably increased through the modification from the conventional DH to the slim DH, and was further increased by about 20% through the modification into REDA, as seen in **Fig. 4**. (Note. Abbreviations in Figs. 4, 6 and 7 mean as follows: NSC, Nippon Steel; KSC, Kawasaki Steel; NKK, NKK Corporation; and SMI, Sumitomo Metal Industries.)

3.1.2 Comparison of reaction surface area in vacuum vessel

Fig. 5 compares the reaction surface area S in the vacuum vessel (its section area) and the decarburization rate constant K in the course of the development from the conventionally shaped DH to the slim DH, and finally to REDA. Despite the fact that the reaction surface area S of the slim DH is smaller than that of the conventional DH, the decarburization rate constant K increased from K = 0.12 of the conventionally shaped 180t-N-DH to K = 0.15 to 0.16 of the slim DH, and then to K = 0.23 of REDA.

3.1.3 Comparison of Ar gas injection flow rate

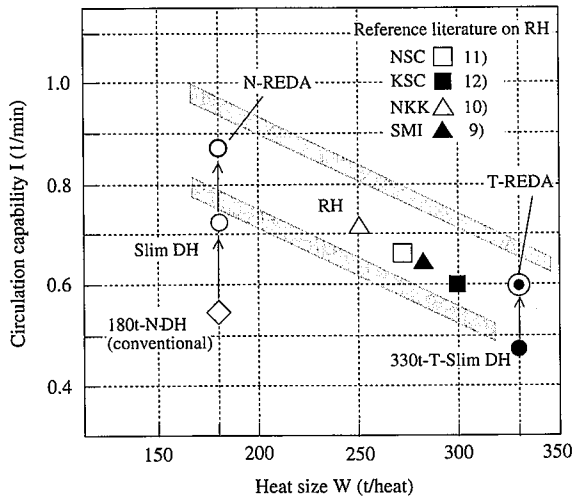**Fig. 6** shows the relationship between the decarburization rate

Fig. 4 Relationship between heat size and circulation capability
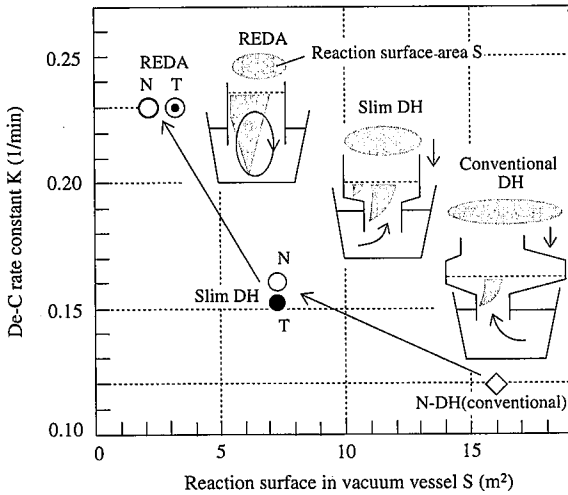

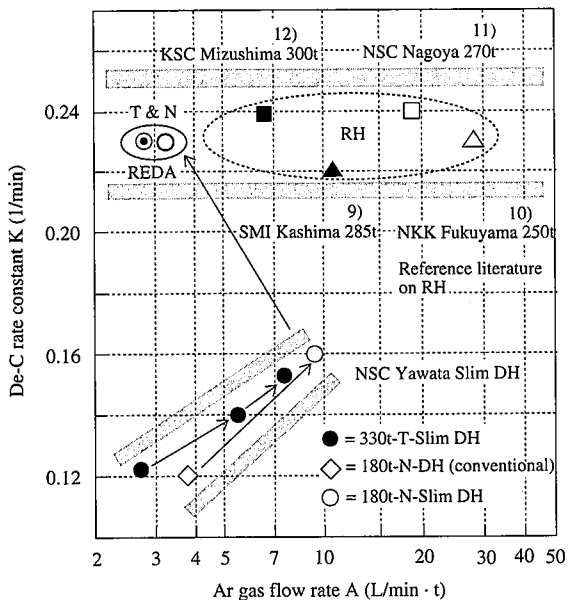**Fig. 5 Relationship between reaction surface and de-C rate constant**

Fig. 6 Relationship between Ar gas flow rate and de-C rate constant

constant K and the Ar gas injection flow rate A (L/min · t). In the slim DH, although the rate constant K increases in proportion to the increase in the Ar gas injection, it hits an upper limit at K = 0.15 to 0.16. In the modification from the slim DH into REDA, on the other hand, while the Ar gas flow rate decreased to 2 to 4 L/min · t [5], less than a half of that of the slim DH, the rate constant increased remarkably to K = 0.23.

The value of K of REDA was greatly increased, as described above, thanks to the effects of the increase in the liquid steel circulation rate Q explained before and an increase in splash exposed to the vacuum [5].

3.2 Comparison of REDA and RH

3.2.1 Comparison of decarburization capacity

As seen in Fig. 4, the circulation capability I of the RH process falls within the same band as REDA. From Fig. 6, it is appreciated that the decarburization rate constant (K = 0.23) of REDA is nearly the same as that of RH (K = 0.22 to 0.24) reported in recently published literatures [9-15] and, hence, REDA and DH are considered to have the same level of decarburization capacity.

3.2.2 Limit of Ar gas injection increase

Fig. 6 shows that the Ar gas injection rate A of RH is far larger than that of REDA. This is because, in the RH process the agitation gas is injected from a snorkel at a shallow depth beneath the liquid steel surface (h in Fig. 2 (c)) and thus RH requires a far larger amount of gas than REDA, in which the gas is injected from a large depth beneath the liquid steel surface (H in Fig. 2 (b)). The rate constant K of RH does not increase even when the Ar gas injection rate is increased. In REDA, on the other hand, more injection of Ar gas than in the present practice is not considered effective since it will only cause turbulence in the liquid steel circulation flow.

3.3 Future challenge (fine bubble formation)

The decarburization rate constant K (1/min) is expressed as K = (Q' × ak) / (V × (Q' + ak)) [16] in relation to the circulation velocity of the liquid steel Q' (m³/min), the amount of steel in ladle V (m³) and decarburization reaction volume coefficient ak (m³/min). **Fig. 7** shows plotting of the relationship between the circulation rate Q (t/min) and the decarburization reaction volume coefficient ak. Here, in the
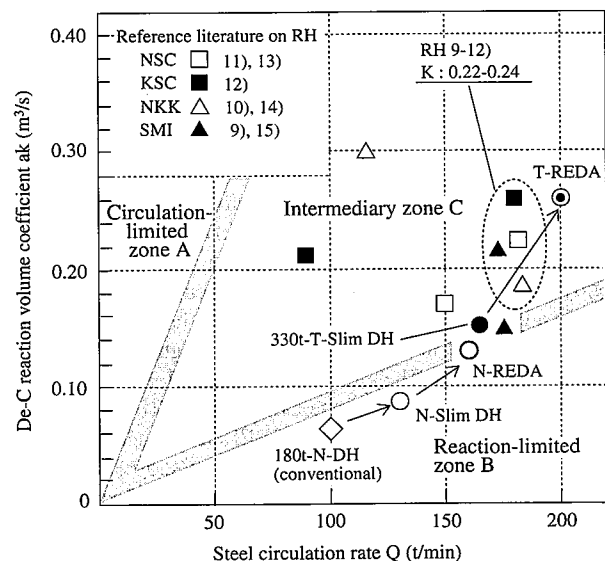

Fig. 7 Relationship between steel circulation rate and de-C reaction capacity coefficient

intermediary area C between the circulation-controlled area A (the area where the value of ak is determined by the steel circulation amount) and the reaction-controlled area B (the area where the value of ak is determined by chemical reactions in steel), we see increases in the circulation rate Q and the reaction volume coefficient ak from the conventional DH to the slim DH and, then, to REDA as indicated by arrows. With large-size units, however, an upper limit of the circulation rate Q is seen to exist near the 200-t/min line, either for REDA or RH. In the future, therefore, it is important to further increase the reaction volume coefficient ak. A possible solution is, for example, to introduce some mechanism to form finer bubbles in the large steel circulation flow of REDA so as to increase yet further the bubble surface area exposed to the vacuum.

4. Closing

The DH process introduced at Yawata Works has developed, through expansion of functions and size, into REDA in which steel circulates continuously. The review of this report from the standpoint of technological history emphasizes the importance especially of development of a technology to form fine bubbles aiming at increasing the reaction volume coefficient ak.

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