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Recent Advances in Electric Arc Furnaces for Steelmaking

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Abstract:

In recent years, electric arc furnaces for steelmaking have been shifting from AC to DC furnaces, and there have been mounting demand for improving scrap preheating technology to increase the energy efficiency. This paper introduces features of Nippon Steel's DC electric arc furnaces centering on the bottom electrode, arc behavior control and high-speed scrap melting technology, as well as on the single-power source, twin-vessel system. The operating results of DC electric arc furnaces of the single-power source, twin-vessel type supplied to Kansai Billet Center Co., Ltd. are described with emphasis placed on the effects of scrap preheating and bottom gas-induced bath agitation and the service performance of the bottom electrode. The three scrap preheating systems, namely, the single-power source, twin-vessel system, shaft furnace system, and continuous scrap feeding system, are numerically analyzed for scrap preheating temperature and comparatively evaluated in terms of the scrap preheating effect.

1. Introduction

Electric arc furnaces for steelmaking apply high-current and low-voltage electric energy to steel scrap as raw material, and thereby melt and refine it. Formerly the AC furnace was mainstream type, but recently the DC furnace has been developed, and its many advantages over the AC furnace have been confirmed[1]. As a result, there is a world-wide transition from the AC to DC furnaces.

Nippon Steel anticipated this technological trend several years ago, and started work on the development of a DC electric arc furnace, and succeeded in establishing its DC electric arc furnace technology. It was a joint development work with Daido Steel of Japan and Usinor-Sacilor of France. After completing the project, the Nippon Steel-Daido Steel Group has received a steady flow of orders for DC electric arc furnaces, as shown in **Table 1**.

This article presents the features of Nippon Steel's DC electric arc furnaces, and describes the operation performance and technical assessment of the one supplied to Kansai Billet Center(KBTC).

2. Features of Nippon Steel's Electric Arc Furnaces

2.1 Features of DC electric arc furnaces

In carrying out the development work, we aimed at adding productivity-enhancing technology to the existing technology complex directed towards operational stability and reliability. As a result, a DC electric arc furnace with the following features was completed[2].

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Table 1 Main specifications of Nippon Steel-type DC electric arc furnaces

Customer	Furnace capacity (tons)	Furnace diameter (m)	Transformer capacity (MVA)
Daido Steel/ Hoshizaki, Japan	25	4.0	9
Nakayama Steel Works, Japan	75	6.4	60
Kansai Billet Center, Japan	120	7.0	85
Takunan Steel, Japan	40	5.8	50
HYLSA/ Monterrey, Mexico	135	7.0	150
Feng Hsin Iron & Steel, Taiwan	85	6.1	80
Posco, Korea	130	7.0	100
Sumitomo Metals, Japan	40	4.9	40

(1) Long-life and high-reliability bottom electrode technology
(2) Arc behavior control technology for preventing arc deflection
(3) High-speed scrap melting technology for raising productivity

2.1.1 Bottom electrode technology

The bottom electrode is based on a billet electrode of the water-cooled copper mold type developed by Usinor-Sacilor of France, and Nippon Steel's original technology is added to ensure longer life and higher reliability (see **Fig. 1**). Insulation breakdown by lead dissolving from scrap and settling in the furnace is liable to cause a serious equipment trouble. To cope with this, Nippon Steel has adopted the insulation system structure with insulation monitoring system illustrated in **Fig. 2**. These devices totally eliminate the insulation breakdown trouble.

2.1.2 Arc behavior control technology

As high current flows through a conductor, a strong magnetic field forms and deflects the arc in a particular direction. As the arc deflection increases, there occur operational troubles. This problem of arc deflection was recognized early in the development stage, and an arc deflection analysis program was established after repeated analyses and tests.

The program can determine the static displacement of the arc as well as the force acting on the arc with its direction (see **Fig. 3**).

DC electric arc furnaces that incorporate the above arc behavior control technology have developed no arc deflection trouble, demonstrating their high equipment capability since their startup.

2.1.3 High-speed scrap melting technology

Nippon Steel has various blowing technologies accumulated in the operation of LD converters. In the application of there LD converter blowing technologies to the electric arc furnace, gas is injected through the furnace bottom to stir the molten steel in the furnace, thereby accelerating the melting and shortening the melting time while reducing the electric power consumption. The furnace profile provides a greater bath depth than the conventional type to make more effective use of the bottom gas energy (see **Fig. 4**). **Fig. 5** shows the results of test furnace operation. As indicated the power-on time is shortened by about 5%.

2.2 Single-power source, twin-vessel system

Recovery of the waste gas heat during operation is an important technical issue from the point of view of productivity and production cost. In answering this technical challenge, Nippon Steel supplied a DC electric arc furnace of the single-power source, twin-vessel type to KBTC. This type preheats scrap by means of high-temperature furnace off-gas. It registers preheating efficiency and eliminates the problems of white smoke and foul odor that accompany the conventional scrap preheater.

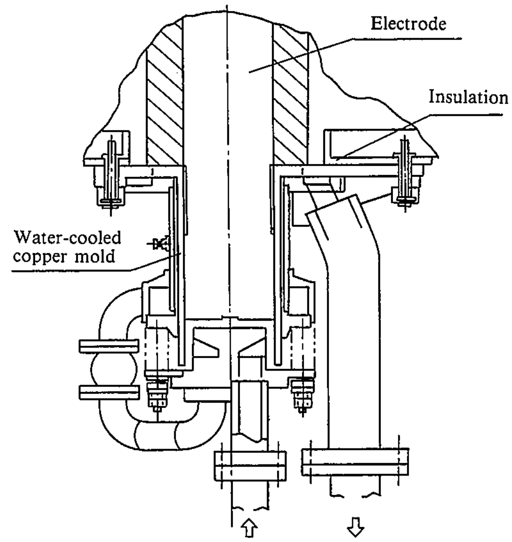


Fig. 1 Electrode of water-cooled copper mold type

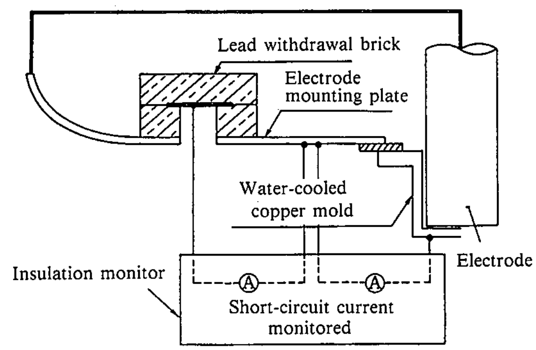


Fig. 2 Insulation structure and monitoring system

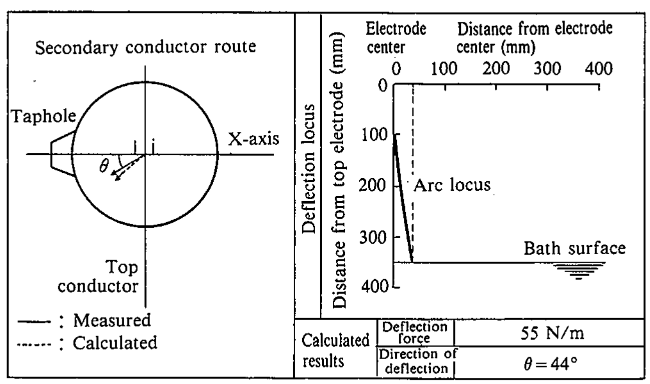


Fig. 3 Results of arc deflection calculation of DC electric arc furnace for Company N

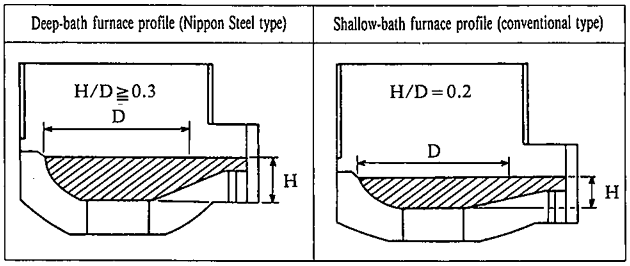


Fig. 4 Comparison of furnace profiles

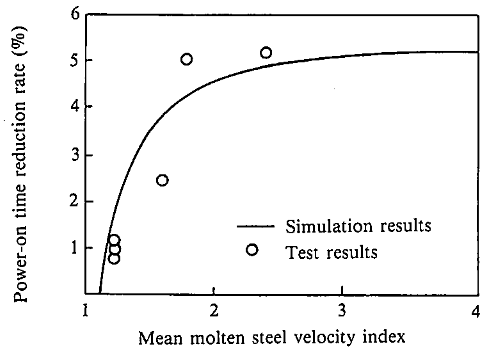


Fig. 5 Power-on time reduction

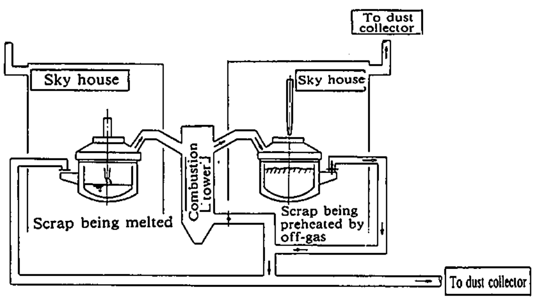


Fig. 6 Equipment configuration of single-power source, twin-vessel system

Fig. 6 shows the equipment configuration of the single-power source, twin-vessel system. Off-gas from the melting vessel is conducted into the preheating vessel. To enhance the preheating efficiency, the two vessels are located closely alongside, and the off-gas exhaust from the preheating vessel is located as low as possible. To stabilize the preheating operation, it is essential to stabilize the dust collection capacity. The duct connecting the two vessels and the gas exhaust part of the preheating vessel are protected against any loss of dust collection capacity due to dust and slag buildup.

3. Operation at KBTC

3.1 Basic concept of equipment plan

KBTC was founded in April 1990, to supply users with billets, slabs and other semifinished steel products. It was put to commercial operation upon the construction of its electric arc furnace plant in January 1992. The basic concept of its equipment plan points to high productivity, minimum labor, and thoroughgoing environmental control.

The pursuit of high productivity took the course of fully utilizing the features of Nippon Steel's electric arc furnaces. First, the tap-to-tap time and preparation time were shortened by the single-power source, twin-vessels system. Second, the power-on time was shortened by high-temperature scrap preheating and by bottom gas stirring. Third, the melting function and refining function were separated from each other through the introduction of an eccentric bottom tapping (EBT) system and ladle furnace (LF) system.

A fine example of labor saving achievement can be seen in the realization of a full-automatic scrap charging system comprising an overhead traveling crane and a charging car. As a result, four operators now operate the two vessels at a time. In July 1993, a water-cooled lance, developed on the basis of Nippon Steel's many years of electric arc furnace operation, was introduced to completely eliminate the furnace-side work during melting.

In respect to environmental control, the white smoke and foul odor generated during scrap preheating were eliminated by high-temperature scrap preheating based on the single-power source, twin-vessel system. Besides the conventional direct fume extraction and plant building dust collection, sky houses, or furnace barrier walls, were introduced as dust and noise control measures to improve the workshop environment.

3.2 Results of startup operation

Production results of the KBTC electric arc furnace plant are shown in **Fig. 7**. The plant entered into commercial operation in January 1992 and started twin-vessel operation in June 1992. The production volume sharply increased with the increase of twin-vessel operation ratio coupled with scrap preheating. Despite some period of operation curtailment forced by a stagnant steel marked, the plant in January 1993 registered a twin-vessel operation ratio of 80%, preparation time of 2 min per heat and scrap preheating ratio of 70%, and produced 60,000 tons per month. **Table 2** shows the plant's production data by operation pattern. The twin-vessel operation system increased the production capacity by about 20% over the single-vessel operation system.

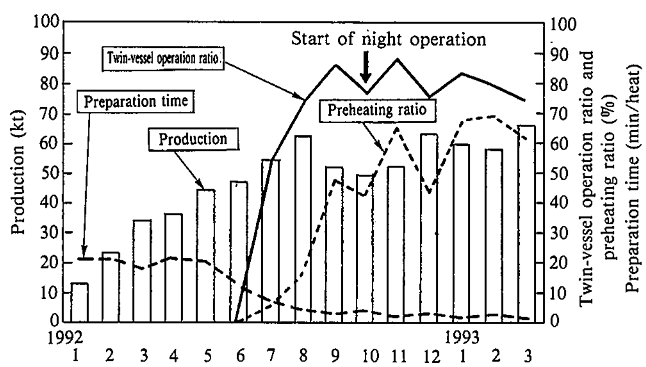


Fig. 7 Changes in production, twin-vessel operation ratio, and preheating ratio

Table 2 Productivity indices by operating pattern

	Single-power source, single-vessel system	Single-power source, twin-vessel system	
Preheating	No	No	Yes
Tap-to-tap time (min/heat)	69.2	62.1	56.7
Productivity	100	110	120

3.3 Results of single-power source, twin-vessel operation

3.3.1 Single-power source, twin-vessel operation pattern

Fig. 8 shows the statuses of the operating and non-operating vessels under the single-power source, twin-vessel operation. While vessel A is melting scrap, vessel B can be charged with scrap or repaired, and its preparation time can be shortened. As soon as the scrap melting is completed in vessel A, the power can be switched to vessel B. Hot off-gas from the operating vessel A is conducted into the vessel B for efficiently preheating the first scrap charge for the next heat.

3.3.2 Preheating effect

The off-gas flow of the preheating system under the single-power supply, twin-vessel operation pattern is as indicated in **Fig. 6.** Hot off-gas from the operating vessel is conducted into the other vessel via a combustion tower to preheat the scrap. **Fig. 9** shows the relationship between the preheating time and the preheating effect in commercial plant operation. Preheating the first scrap charge (60% of the total scrap charge) for 25 min resulted in reducing the power consumption by about 35 kWh/t.

3.4 Bottom gas stirring effect

KBTC manufactures billets for non-integrated steelmakers and slabs for integrated steelmakers. In the slab manufacture, tramp elements such as Cu and Sn are tightly limited in the material scrap. Heavy scrap that is low in the Cu and Sn contents must therefore be increased, which, however, incurs melting difficulty. This problem was solved by introducing the bottom-blown gas stirring technology based on the equipment and operating know-how of combined-blown LD converters. The effect of bottom gas stirring in reducing the power consumption is as shown in **Fig. 10**. Bottom gas stirring during the melting period has been found to reduce the power consumption by about 15 kWh/t.

Bottom gas stirring was also found to have the effect of lowering the tap temperature by about 5°C, decreasing the tap temperature fluctuation, lessening the thermal load in the ladle furnace, and raising the operational stability.

3.5 Service performance of bottom electrode

3.5.1 Recorded service life of bottom electrode

Fig. 11 shows the transition of the life of bottom electrodes in the KBTC electric arc furnace. Since the startup, the bottom electrodes have been exchanged as scheduled, and their soundness has been confirmed by disassembly inspection after use. The electrode life is extremely stable, with vessel B registering 2,222 heats for the third campaign.

The soundness of bottom electrodes is verified by constant monitoring of a thermocouple embedded in the lower part of each bottom electrode. **Fig. 12** shows the temperature transition in the lower part of the bottom electrode at the end of the third campaign for the vessel B. The electrode temperature is stabilized at 45°C or lower as considered necessary from heat transfer simulation. This result confirmed the soundness of bottom electrodes and established the validity of the bottom electrode design technology.

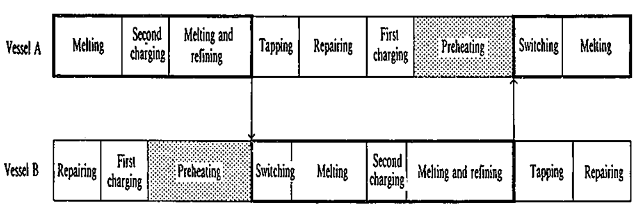


Fig. 8 Operating status of operating furnace and non-operating furnace under single-power source, twin-vessel operation pattern

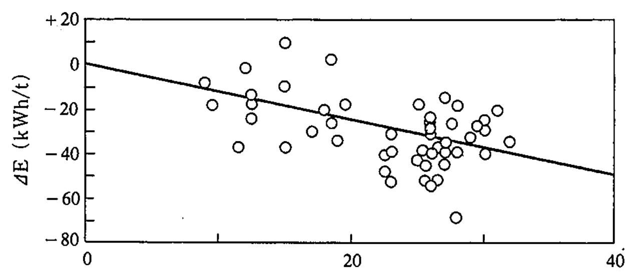


Fig. 9 Preheating time and preheating effect

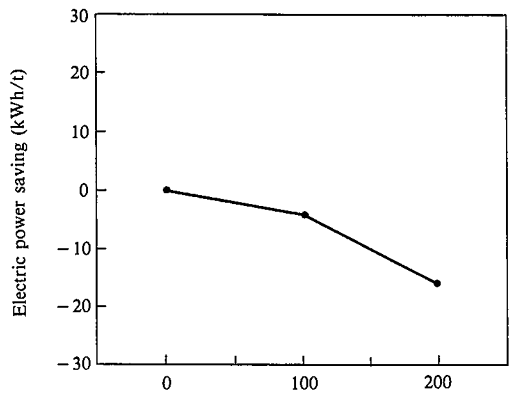


Fig. 10 Effect of bottom gas stirring in reducing electric power consumption

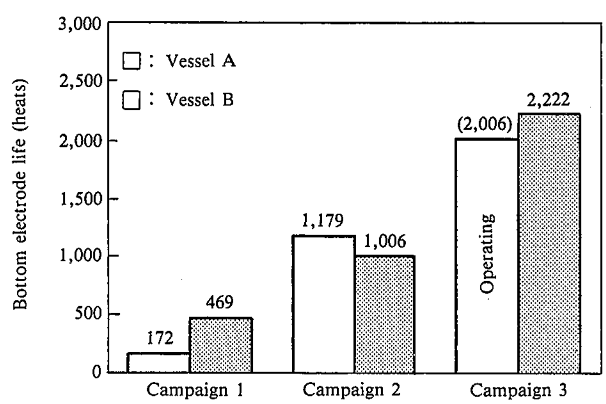


Fig. 11 Change in bottom electrode life

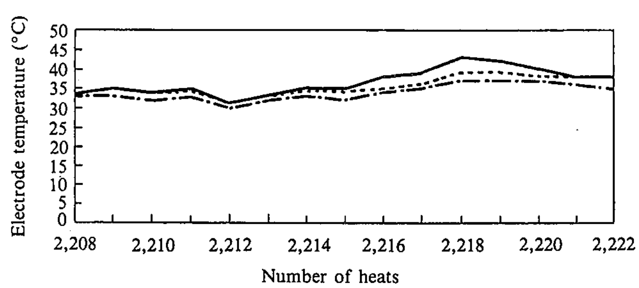


Fig. 12 Transition of bottom electrode temperature

3.5.2 Results of bottom electrode disassembly inspection

A used bottom electrode after disassembly is shown in **Photo 1**. As the power is turned on and off, the upper part of each electrode in contact with the molten steel repeatedly melts and solidifies and increases in diameter, although the electrode itself is not worn. As can be estimated from the in-service temperature change, the lower part of the electrode completely retains the original round rod shape. Judging from this result of disassembly inspection, the bottom electrodes would have been able to last a much longer period of furnace operation.

The reliability of the bottom electrode of the water-cooled copper mold type has been proven by its operating performance since the plant startup. Our next task is to challenge a still longer-lasting bottom electrode.

3.6 Behavior of DC arc

KBTC made its equipment plan according to the result of an arc deflection analysis. As a result, operational troubles attributable to the arc deflection have not occurred at all since the plant startup. **Photo 2** shows the tip of a top electrode after the end of melting operation. As evident from the photo, the tip of the top electrode does not have uneven wear due to arc deflection as observed in AC electric arc furnaces. It exhibits an axisymmetric bowl shape, instead. This is because the arc deflection was properly controlled by the optimum design of the secondary conductor.

As noted above, the DC electric arc furnace of KBTC has been smoothly operating since its startup, fully demonstrating the characteristics and capabilities of Nippon Steel's DC electric arc furnaces.

4. Analysis and Evaluation of Scrap Preheating Technology

Scrap preheating by the single-power source, twin-vessel system saved electric power by about 35 kWh/t at KBTC as reported above. Hereunder, this result is numerically analyzed, and the actual performance of the furnace is evaluated in comparison with other scrap preheating systems recently highlighted, namely, the shaft furnace system and the continuous scrap feeding system.

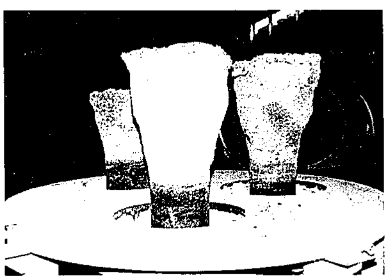


Photo 1 Bottom electrode after disassembly

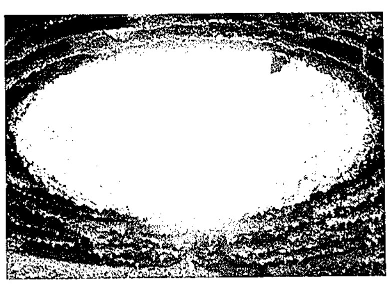


Photo 2 Shape of electrode tip after melting

4.1 Single-power source, twin-vessel system

4.1.1 Concept of analysis

(1) Analysis model

The scrap charged into the electric arc furnace is vertically divided into blocks as shown in **Fig. 13**. Heat transfer is calculated within each block. A half of the blocks below the off-gas exhaust port (that is to say, blocks 9 and 10) are excluded from the range of preheating calculation by assuming that the off-gas does not flow through them.

The analysis model assumes that only the initial scrap charge (60% of the total scrap charge) is preheated as done at KBTC.

(2) Off-gas conditions and other data

The off-gas temperature was set at 900°C for the carbon injection period of 13 min according to measured values, and at 400°C for the remaining 12-min period. The total preheating time was set at 25 min. To confirm the effect of preheating time, calculation was also made by extending by 5 min the period for which the off-gas temperature was set at 400°C. The off-gas flow rate was set at the same 1,300 Nm^3/min as actually measured.

4.1.2 Analysis results and evaluation

The results of analysis of scrap preheating temperature are shown in **Figs. 14** and **15**. **Fig. 14** shows how the scrap temperature in each block changes with the preheating time. At the end of the preheating period, the scrap surface temperature is about 550°C. This value agrees well with the scrap surface temperature of 500 to 600°C measured at KBTC.

Fig. 15 shows the effect of the preheating time on the average scrap preheating temperature. It is known that scrap can be preheated to an average temperature of about 350°C at KBTC. This is equivalent to a power saving of 35 to 40 kWh/t and practically agrees with the actual effect of preheating. When the preheating time was extended by 5 min, the scrap temperature rose by 30°C to about 380°C.

The above analysis results indicate that the single-power source, twin-vessel system provides a high scrap preheating temperature, despite the small scrap preheating ratio and short preheating time as compared with conventional scrap preheating systems. Factors in this achievement are relatively long scrap preheating time available and high hot off-gas temperature obtainable toward the end of melting operation.

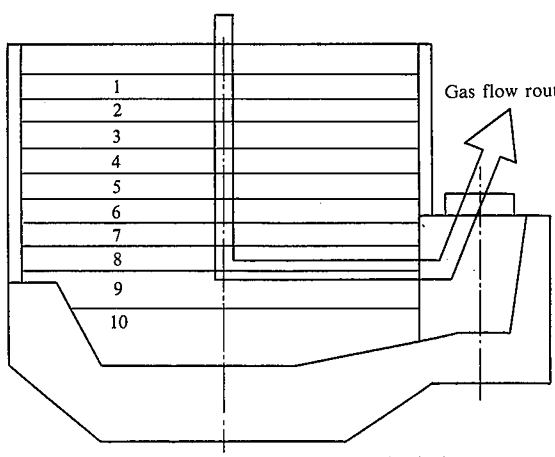


Fig. 13 Model for analysis of scrap preheating in single-power source, twin-vessel system

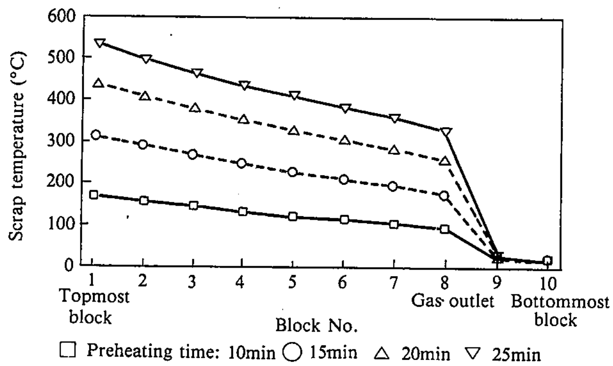


Fig. 14 Scrap temperature in each block

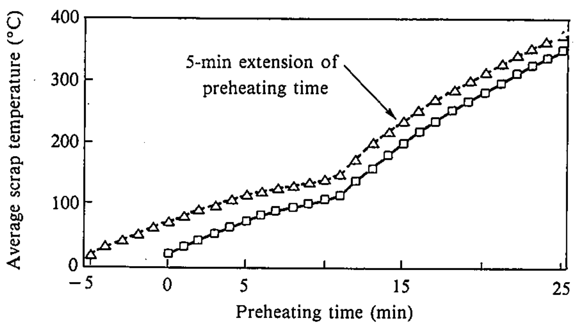


Fig. 15 Effect of preheating time on average scrap temperature

4.2 Shaft furnace system

4.2.1 Concept of analysis

(1) Analysis model

A shaft to be filled with additional scrap charge is provided in the upper part of the furnace, as illustrated in **Fig. 16**. The heat exchange between the off-gas and the scrap takes place in the shaft. The analysis model replaced the shaft with a cylindrical container of the same cross-sectional area. The scrap in the shaft diminishes in volume with the progress of operation. According to literature[3] and **Fig. 17**, the shaft was assumed to be filled completely with a third scrap charge and be empty at the start of the deslagging period. For the purpose of calculation, an approximate method was adopted that changes the degree of filling in five steps.

(2) Off-gas conditions

The off-gas temperature was assumed to be 500°C during the melting of the initial scrap charge and 1,000°C after the additional scrap charge. The off-gas flow rate was set at a direct fume extraction rate of 1,000 Nm^3/min.

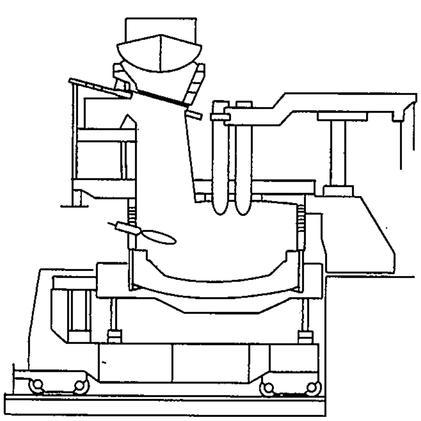


Fig. 16 Vertical cross-sectional view of shaft furnace

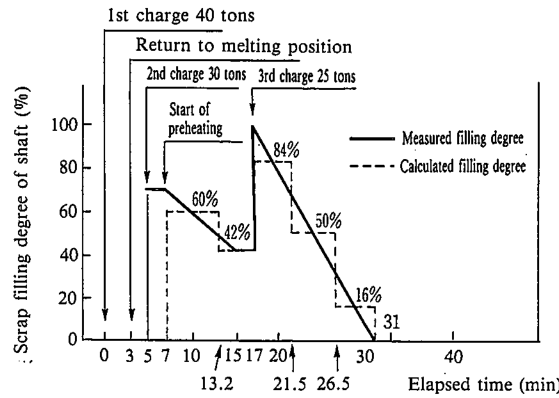


Fig. 17 Change in scrap filling degree of shaft

Table 3 Results of preheating calculation for shaft furnace

Step	Amount of preheated scrap (tons)		Amount of melted scrap (tons)		Preheating temperature of melted scrap (°C)	
	Charge 2	Charge 3	Charge2	Charge 3	Charge 2	Charge 3
I	25.8	—	7.7	—	146	—
II	18.1	—	6.9	—	214	—
III	11.2	25.0	11.2	3.4	410	179
IV	—	21.6	—	14.7	—	363
V	—	6.9	—	6.9	—	520
Total			25.8	25.0		

4.2.2 Analysis results and evaluation

The results of analysis are given in **Table 3**, where the scrap quantity and scrap preheating temperature are shown in five steps. The average scrap temperature is about 325°C. This translates into an electric power saving of 28 to 33 kWh/t, which differs from the 70 kWh/t reported in literature[3]. The probably reason for this difference is a rise of off-gas temperature due to the abundant use of LNG resulting in increasing the scrap preheating effect.

4.3 Continuous scrap feeding system

4.3.1 Concept of analysis

(1) Analysis model

An example of the continuous scrap feeding system is the CONSTEEL process[4] in which the scrap being fed is preheated with hot off-gas from the furnace in a scrap preheating zone connected directly to the furnace (see **Fig. 18**).

The analysis model divides the scrap feeding system in the longitudinal (travel) and bed depth directions, and considers heat transfer in each block as shown in **Fig. 19**.

(2) Off-gas conditions

The model assumes the following off-gas conditions reported as the operating data of the CONSTEEL process[5]:

Off-gas temperature (at inlet of preheating zone): 900°C

Off-gas flow rate (at inlet of preheating zone): 930 Nm^3/min

The preheating zone is 24 m long, and the scrap travels at the speed of 1 m/min through the preheating zone.

4.3.2 Analysis results and evaluation

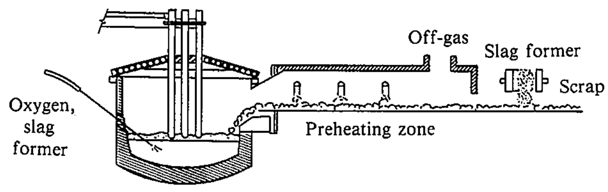
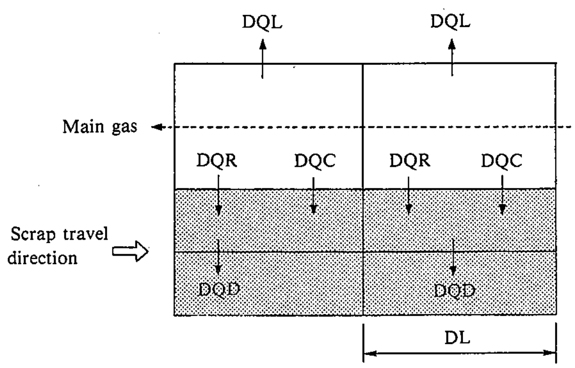


Fig. 18 CONSTEEL process



DQC: Convective heat transfer from main gas fluid to scrap (turbulent heat transfer through pipe)
DQR: Radiative heat transfer from main gas fluid to scrap
DQL: Convective and radiative heat transfer from main gas fluid to conveyor cover
DQD: Conductive heat transfer in scrap bed

Fig. 19 Scrap preheating analysis model for continuous scrap feeding system

Figs. 20 and **21** show the results of analysis conducted by assuming that the off-gas flows over the scrap bed. **Fig. 20** shows the average scrap preheating temperature at different positions along the feeding system. The average scrap temperature just before being charged into the furnace is about 160°C and agrees well with the reported value[5]. **Fig. 21** shows the scrap temperature in the bed depth direction just before being charged into the furnace. The scrap in the top of the bed is preheated nearly to the off-gas temperature, but the bottom scrap is hardly preheated. This is probably because no gas flow occurs through the scrap bed and the scrap is heated mainly by heat conduction with poor heat transfer efficiency. As a result, the preheating effect translates into a power saving of only about 20 to 25 kWh/t.

4.4 Summary of analysis results

The results of analysis of the preheating effect may be summarized as follows:

Single-power source, twin-vessel system: 35 to 40 kWh/t
Shaft furnace system: 28 to 33 kWh/t
CONSTEEL system: 20 to 25 kWh/t

Each preheating system seems to have some room for future technological improvement, but at present, the single-power source, twin-vessel system surpasses the others in terms of the efficiency of heat recovery from the furnace off-gas. Since the CONSTEEL system preheats all the scrap, its preheating efficiency is lower than that of the other two systems. The shaft furnace system features a high off-gas temperature but marks a lower preheating effect than the single-power source, twin-vessel system, presumably because the scrap volume in the shaft diminishes with the progress of melting and thereby reduces the scrap preheating ratio.

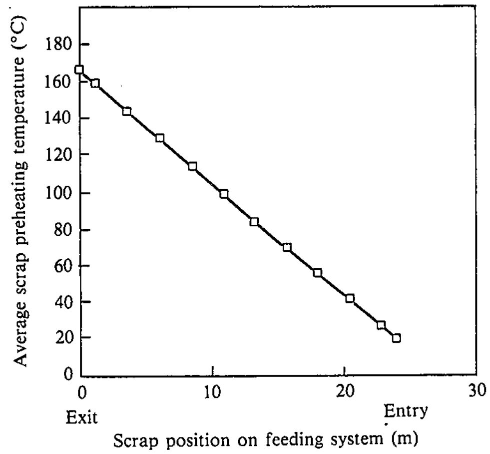


Fig. 20 Average scrap preheating temperature at different positions in scrap feeding system

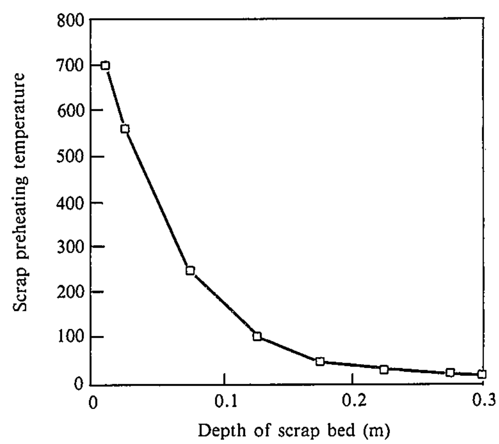


Fig. 21 Scrap temperature distribution in depth direction of scrap bed

5. Conclusions

The durable bottom electrode, arc deflection control technology, high-speed scrap melting technology, and single-power source, twin-vessel system that feature Nippon Steel's DC electric arc furnaces, have been demonstrating their effectiveness in the operation of the DC electric arc furnace at KBTC. The single-power source, twin-vessel system has been numerically analyzed in comparison with other two scrap preheating systems. The numerical analysis has quantitatively established the advantage of the single-power source, twin-vessel system over the other two.

Nippon Steel, along with KBTC, looks forward to still higher productivity in electric are furnace steelmaking achieved through the furtherence of automation and mechanization.

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