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Development of the CLECIM-KSC Type DC Arc Furnace*

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1 Introduction

As illustrated in **Fig. 1**, the DC arc furnace melts scrap and heats molten steel by generating an arc between the upper carbon electrode as cathode and the bottom electrode installed on the hearth as anode. DC arc furnace have the following proven advantages over the conventional AC arc furnaces:[1-3]

(1) Low unit consumption (electrodes, electricity and refractories)
(2) Low flicker
(3) Low noise

In a large DC arc furnace with one upper electrode (100 t/heat scale), however, the phenomenon of high-current arc deflection is conceivable.[4] This phenomenon causes not only an increase in each of the above unit consumptions, but also equipment problems and a decrease in productivity.

Furthermore, when considering the future labor-force situation where the operations around the furnace, which are known to be dirty, dangerous and difficult and call for a realization of a more comfortable working environment,[5] the replacement and repair of the bottom electrodes, which are inevitable with a DC arc furnace, must be conducted safely and easily. Kawasaki Steel, in conjunction with CLECIM in France, has

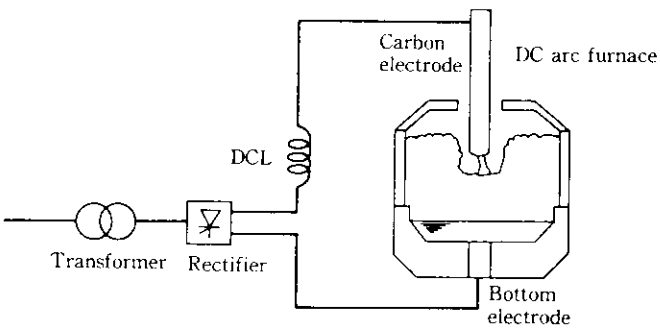

Fig. 1 Schematic diagram of DC arc furnace

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developed the CLECIM-KSC type DC arc furnace to solve these problems with conventional large DC arc furnaces. The newly developed DC arc furnace was supplied to Daiwa Steel's Mizushima Works and has shown good operating results.[6-11] This report describes the concept of the CLECIM-KSC type DC arc furnace and an analysis of the melting mechanism with the water-cooled bottom electrodes, and outlines the automation of operations around the furnace, labor-saving equipment and techniques for making a comfortable working environment.

2 Newly Develped Techniques

The CLECIM-KSC type DC arc furnace employs water-cooled bottom electrodes which were developed by IRSID in France and known for its long service life and advantages in terms of cost. The following new techniques are incorporated to ensure low cost, low unit consumption, high productivity and a comfortable working environment:

(1) A power supply method capable of individually controlling the current to each of the bottom electrodes was developed, which also enables the arc direction to be controlled.
(2) To prevent the phenomenon of arc deflection, the bottom electrodes and bus tubes are arranged in the optimum configuration.
(3) To replace and repair the bottom electrodes safely, easily and in a short time, the bottom electrodes, shell and refractories are structured at the bottom in a single unit. This enables the electrodes to be automatically installed and removed by remote-control, using a dedicated bottom-change device, from outside the furnace.
(4) A large-capacity (120 m^3-norm/min) oxygen blowing and powder injection device for one-man operation was developed and has proved stable in service.
(5) The dust emission from the arc furnace and the flow of dust-containing gas in the building were simulated by a numerical analysis. By considering the results of this simulation and of a 1/10-scale model experiment, the optimum hood shape and arrangement and the specification of the dust collecting equipment were determined.

3 Technique for Uniform Melting (Controlling the Arc Direction)

In a DC arc furnace, a DC magnetic field is generated around each bus tube, and the arc formed involves a DC current. Therefore, when the arrangement of the bus tubes is inappropriate, a horizontal electromagnetic force always acts to the arc and changes its course to a fixed direction. This is called the arc deflection phenomenon. For example, when the bottom electrode and upper carbon electrode are arranged in the center of the furnace and the bus tubes are arranged over the shortest distance as shown in **Fig. 2**, an electromagnetic force acts on the arc in the direction indicated by the arrow in the drawing, i.e., the side opposite to the power supply side. This arc deflection phenomenon makes the heat supply nonuniform in the circumferential direction within the furnace and causes not only an unmelted portion of scrap, but also excessive thermal load on the water-cooled panels of the furnace wall and an increase in each unit consumption, thus offsetting the advantages of a DC arc furnace. Therefore, preventing arc deflection is a problem that must be solved at any cost in constructing a large DC arc furnace.

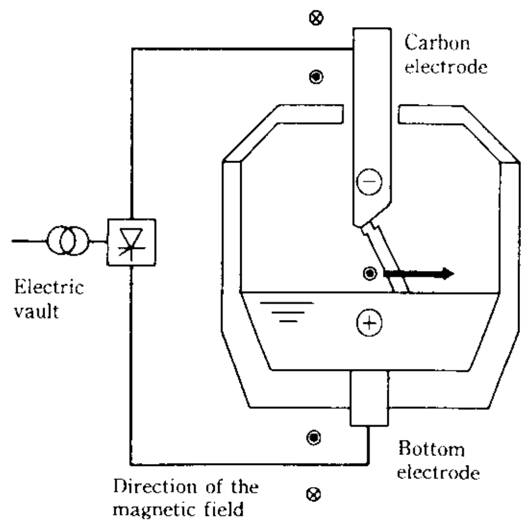


Fig. 2 Schematic diagram of arc deflection phenomenon in DC arc furnace

3.1 Analysis of the Electromagnetic Force Acting on the Arc

The arc deflection phenomenon is due to the DC magnetic field generated around each bus tube, and the intensity and direction of the magnetic fields in the arcing position can be obtained by analysis using electromagnetic theory. In designing the CLECIM-KSC type DC arc furnace, the number of water-cooled bottom electrode and bus tubes, and their installation positions were determined by analyzing the intensity and direction of the magnetic field in the arcing position, including the effect of a shell that provides a magnetic shielding effect.

3.2 Individual Current Control to the Bottom Electrodes

In addition to preventing arc deflection, the power supply method shown in **Fig. 3**, which can individually control the current to each bottom electrode to optimize the arc direction, was developed for use. The arc direction can be controlled in the 100-t furnace of Daiwa Steel by simply increasing or decreasing the cur-

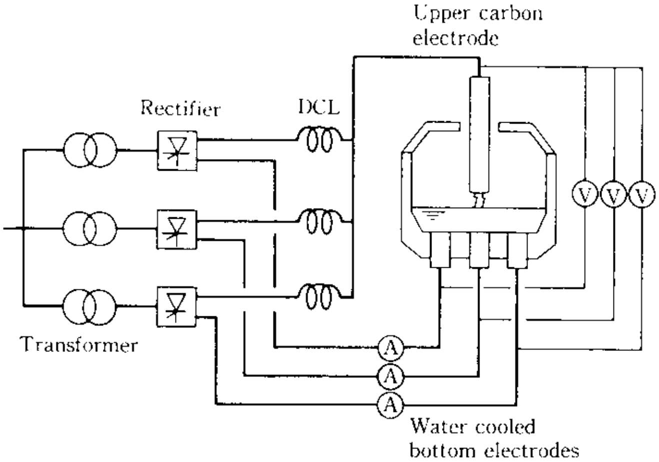


Fig. 3 Skeleton for control of arc direction

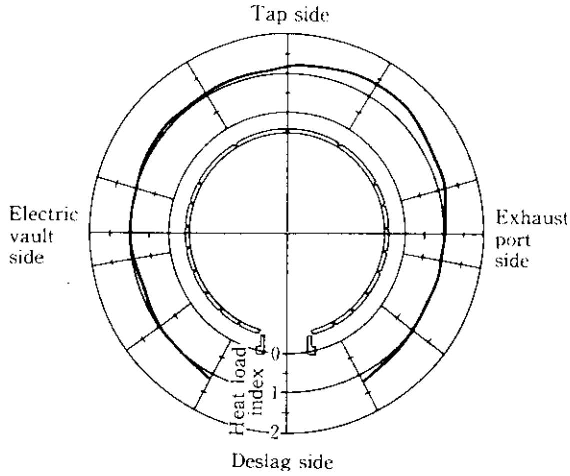


Fig. 4 Distribution of heat load on water cooled panels above hearth line

rent to any one of the three bottom electrodes by several percent, and the electric energy input is little affected by this. Furthermore, the arc direction can be deliberately controlled as required when the optimum current is increased or decreased by about 10%. Moreover, because the current to each bottom electrode can be controlled and monitored, it is possible to detect a non-conducting bottom electrode and adjust the current to the conducting bottom electrodes accordingly. Safety in operation is thus ensured.

3.3 Confirmation of Uniform Melting

To confirm the uniform melting of scrap in the actual furnace at Daiwa Steel's Mizushima Works, an investigation was made into the distribution of heat flux under load to the water-cooled panels of the furnace wall and the wear condition of the upper carbon electrode. As a result, no arc deflection was observed, uniform melting of the scrap was obtained, and it was ascertained that the auxiliary heat source used in an AC arc furnace and some DC arc furnaces such as a burner[12] was unnecessary.

3.3.1 Distribution of heat fluxes under load to the water-cooled panels of the furnace wall

The maximum heat flux under load to each of the water-cooled panels of furnace wall above the molten steel bath was determined from the cooling water volume and the difference between the inlet and outlet temperatures. As shown in **Fig. 4**, a distribution almost uniform in the circumferential direction was obtained. A region with a slightly higher heat flux existed between exhaust port side and tap side, and it is thought that this was due to the effect of the post combustion of the CO gas generated from the molten steel bath with oxygen injected through the slag door. **Figure 5** shows the calculated heat flux to the furnace wall made on the assumption that the arc was a point heat source

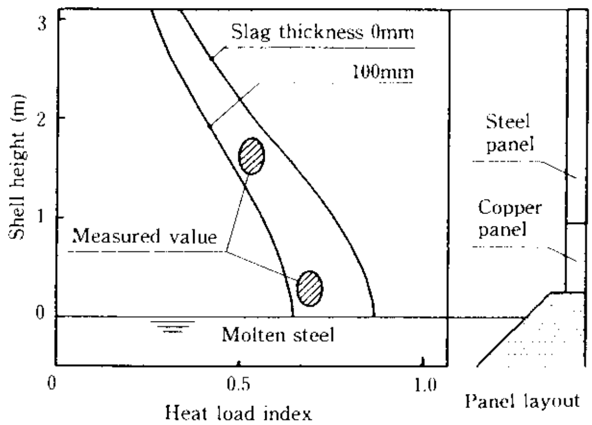


Fig. 5 Results of calculation of heat load on water cooled panels

at the furnace center above the molten steel bath. There is good agreement between the measured and calculated values, and no arc deflection is observed. The aimed good uniform melting condition was confirmed by a visual observation of the interior of the furnace: the boring hole made in the initial period of melting was almost a true circle, no locally unmelted portion of scrap during melt-down nor unmelted large lumps of scrap after tapping were found, and the thickness of metal sticking to the water-cooled panels of the furnace wall was not more than 50 mm across the full wall surface.

3.3.2 Wear condition of the upper carbon electrode

When arc deflection occurs, nonuniform wear occurs at the tip of an electrode, as in an AC arc furnace. However, uniform wear around the electrode was noticed, this being apparent in **Photo 1** which shows the

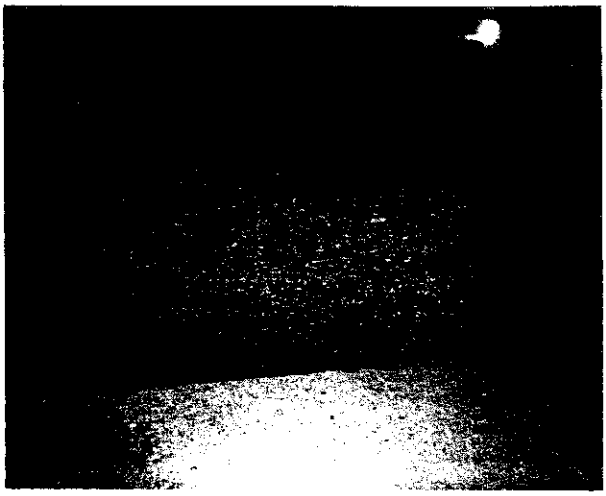


Photo 1 Condition of upper carbon electrode after use

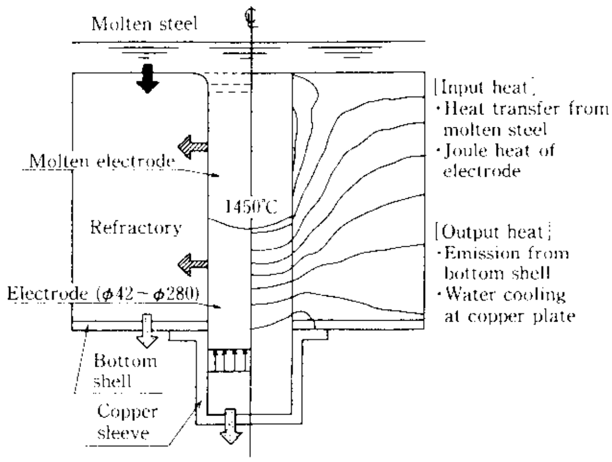


Fig. 6 Model of bottom electrode for heat transfer analysis

wear condition at the tip of the upper carbon electrode.

4 Clarification of the Melting Mechanism for the Water-Cooled Bottom Electrodes

DC arc furnace are inferior to AC arc furnaces only in that a bottom electrode is necessary; in general, the service life of the bottom electrode is shorter than that of the hearth refractories, and leakage of metal from the bottom electrode of a steelmaking furnace is a worry.[1,3] However, there is no report on the melting mechanism or safety of the bottom electrode in a steelmaking furnace, and a thorough evaluation of this problem had not previously been made. Therefore, before introducing the water-cooled bottom electrodes from IRSID, the melting mechanism for the these electrodes was clarified by a heat transfer analysis in order to optimize the equipment and operation, and to evaluate and confirm safety.

4.1 Analytical Model

As shown in **Fig. 6**, the area around one steel electrode was defined as a model that is symmetrical with respect to the axis, and a heat transfer analysis and melting simulation were carried out by using parameters related to the phenomena of electrode melting such as the molten steel temperature, electrode diameter, heat transfer coefficient of the cooled surface, and thickness of the hearth refractory.

4.2 Analytical Results

The following information was obtained from the analysis:

(1) As shown in **Fig. 7**, the effect of current density on the melting amount of electrode is greater than that of any other parameter. The effect of the electrode diameter is the next greatest, and the effect of the electrode water-cooling capacity ranks third. In other words, it is most effective to control the current density below an allowable value in order to regulate the melting amount of electrode.

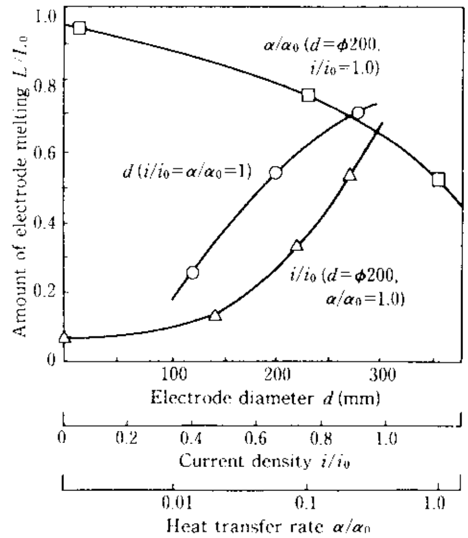


Fig. 7 Effect of each parameter on melting of bottom electrode

(2) The effect of the refractory thickness is shown in **Fig. 8**. When the refractory thickness is above a certain value, the position of the electrode surface does not change. When the refractory thickness is below this value, however, the melting amount of electrode increases rapidly and the position of the electrode surface drops. In order to extend the service life of electrodes, therefore, it is necessary to suppress the erosion of the refractory material near the electrode and to maintain adequate refractory thickness.

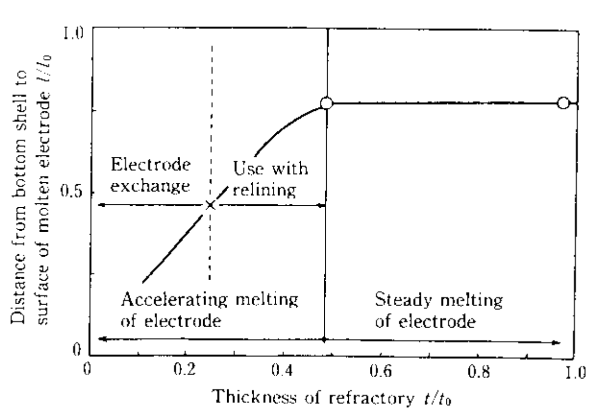


Fig. 8 Effect of refractory thickness on the melting amount of bottom electrode

(3) Even when the maximum current density among all analytical cases was given with an electrode diameter of 280 mm, the surface of the electrode was more than 200 mm above the bottom shell surface. Therefore, complete safety from molten electrode leakage is ensured.

The foregoing results indicate that the water-cooled bottom electrodes would be completely free from the danger of metal leakage and assure safety. In addition, it is relatively easy to increase the diameter of a bottom electrode and the construction of the furnace bottom can be made simple. Furthermore, refractory bricks with high wear resistance and long service life can be used near the electrodes, making the water-cooled bottom electrodes as good as any others for a DC arc furnace.

5 Replacement of the Bottom Electrodes

A DC arc furnace is operated under what is called the hot heel condition, i.e., some molten steel from the previous charge is left in the furnace to maintain a good conduction between the bottom electrodes and fresh scrap. For this reason, the wear rate of the bottom refractories is higher than that of the refractories in other parts of the furnace, making complete replacement of these refractories and bottom electrodes necessary. The CLECIM-KSC type of DC arc furnace uses water-cooled bottom electrodes of a relatively simple construction, so that repairment of the bottom refractories is easy to ensure a long furnace life. A method for complete bottom-refractory and bottom-electrode replacement was developed to minimize the furnace shutdown time and ensure safety for this replacement work.

5.1 Method for Furnace Bottom Exchange

As is apparent from the outline of the method for bottom exchange shown in **Fig. 9**, the existing for Kawasaki Steel's converters with the bottom blowing function (Q-BOP and K-BOP) was modified and applied

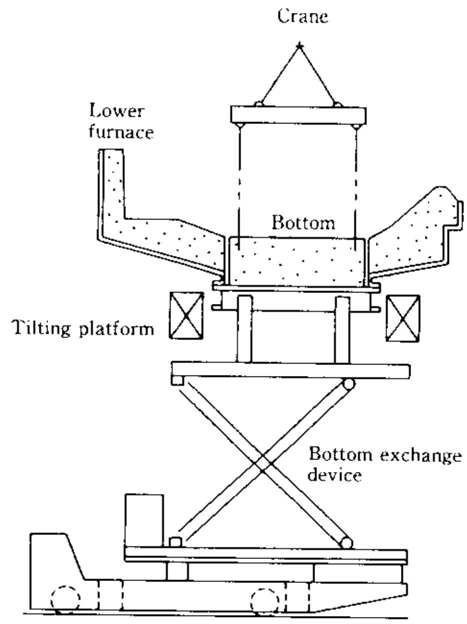


Fig. 9 Schematic diagram of bottom electrode exchange method

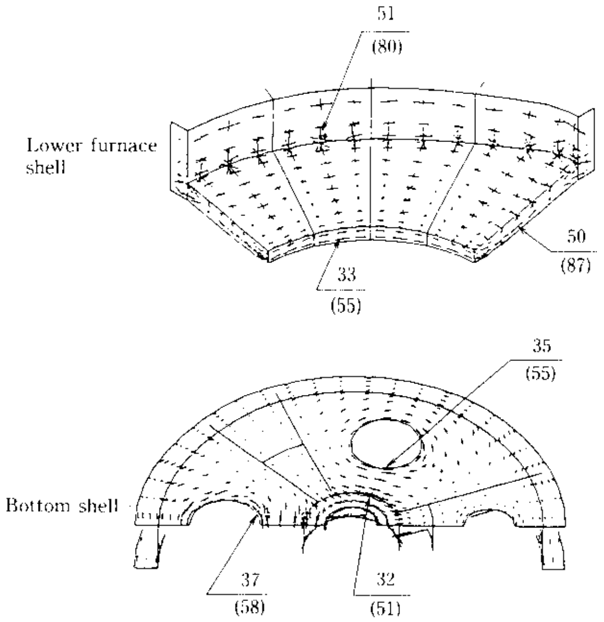
to the DC arc funace. The bottom electrodes, the refractories around them and the shell are constructed in a single unit as the furnace bottom. This bottom is transferred, installed and removed from outside the furnace, and then exchanged by a dedicated bottom-exchange device placed on a steel ladle car. This method has the following advantages:

(1) The amount of work in the furnace at high temperature is small.
(2) The time required to cool the furnace body is short because the work inside the furnace is possible when the refractory surface is cooled.
(3) The transfer, installation and removal of the bottom are carried out by remote operation.
(4) The lifting capacity of the crane must be more than 200 t when the whole of the lower furnace body is to be exchanged by a different method, while the crane capacity is only about 50 t with the present method. Therefore, equipment costs for the crane and building are less.

This method is safe and easy to carry out, bottom replacement can be accomplished in a short time, and operations around the furnace, which are dirty, dangerous, and difficult, are all improved.

5.2 Design of the Bottom and Furnace Shell

The bottom and lower part of the furnace shell with openings are connected by flange joints, and were analyzed for strength by the NASTRAN general-purpose structural analysis program. The loading conditions were defined by examining and evaluating the static load from molten steel and scrap, and the impact load during



Upper figure : Stress generated by static load (MPa)
(Lower figure) : Stress generated by impact load (MPa)

Fig. 10 Results of stress analysis of lower furnace shell and bottom shell

scrap charging. The results of the analysis are shown in **Fig. 10**. An evaluation was also made of the thermal stress and low-cycle fatigue, and a maximum stress value for the principal components was set as low as about 90 MPa (during scrap charging) to ensure a high level of safety.

6 Automation and Labor-Saving Equipment

It has not been easy to automate operations around an arc furnace, and human effort has usually been relied upon under severe working conditions of high temperature and high dust concentration. As shown in **Table 1**, however, almost all the auxiliary devices for the arc furnaces at Kawasaki Steel are automated. Among other things, the oxygen blowing and powder injection device, an outline of which is shown in **Fig. 11**, permits one man to remotely operate four oxygen-blowing pipes and one powder injection pipe, and high-speed oxygen blowing at 120 m^3-norm/min has been attained.

7 Control System Concept

The configuration of the control system provides automatic control of each individual device such as that for automatic melting, as well as automation and labor-saving in the whole process for the arc furnace. The features of the control system are as follows:

(1) Each of the devices, including that for automatic melting, has an independent control system, and fully automatic control and operation can be conducted by merely depressing operation buttons on a central control panel.

(2) The whole process is connected by a communication network, and a monitoring system with a central operation desk and CRTs are used. An example of a CRT screen for operation is shown in **Fig. 12**.

This system provides automatic arc-furnace operation, and the operator only has to monitor the process.

Table 1 Automatic devices

Item	Features
Oxygen blowing and powder injection device	· One man operation · Oxygen flow rate 120 m^3-norm./min · Lance pipes Oxygen blowing 40A × 4 Powder injection 40A × 1
Additive feed system	· Storage capacity 6 brands · Orientation Furnace, ladle
Upper electrode conection device	· IHI type · Electrode dia. 28 in · Cycle time 3 min
Tap hole sand fill device	· Swing and cut gate type
Refractory gunning device	· Gunning rate 150 kg/min · Swing and rotary type
Sampling and temperature measurement device	· Cycle time 1 min · Swing type

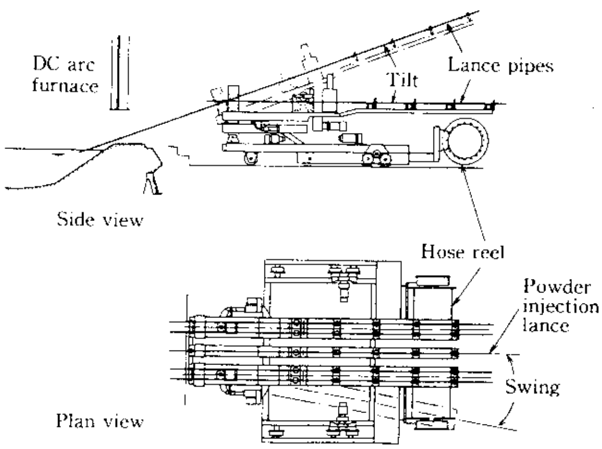


Fig. 11 Schematic diagram of oxygen blowing and powder injection device

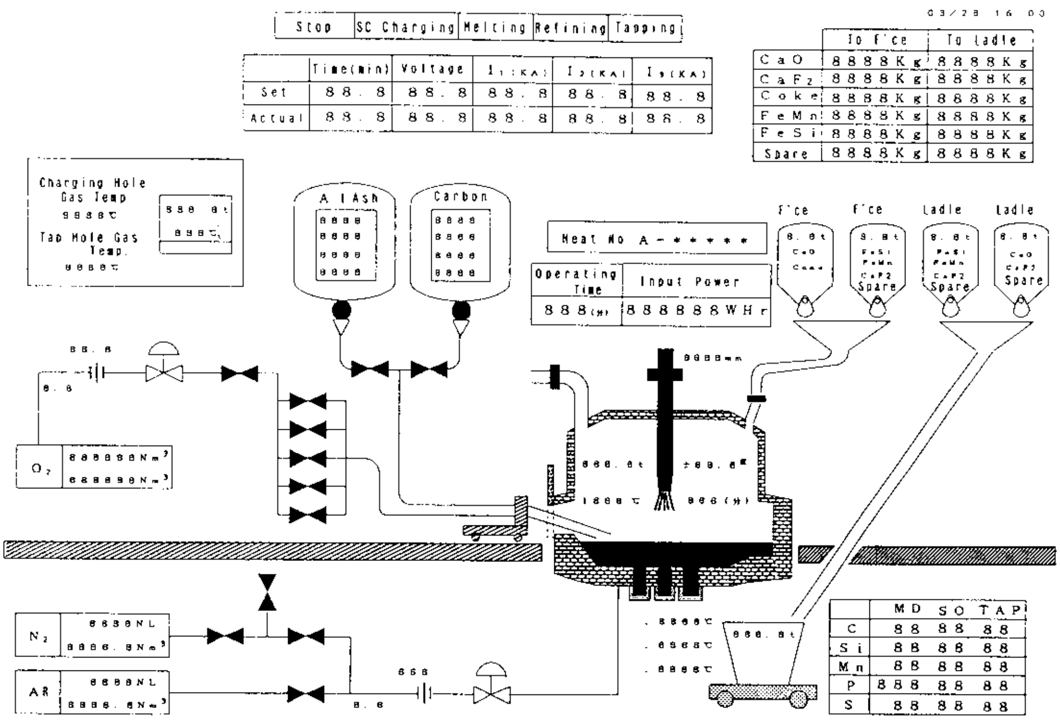


Fig. 12 Example of CRT monitor for operation

8 Techniques for Creating a Comfortable Working Environment

A comfortable working environment in arc furnace plants is essential nowadays by efficiently collecting the dust generated during scrap charging and tapping. The circumstances under which dust is generated and its flow in the building were clarified by simulation and model experiments, and the type of dust collector and its capacity to maintain a comfortable environment were determined.

8.1 Dust Collection

The dust-collecting equipment for the arc furnace comprises a direct suction type of dust collector for the high-temperature gas from the furnace and a conventional type of dust collector for the dust generated in the building during scrap charging and tapping. The combined direct suction system and building collection system is shown in **Fig. 13**. This combination of equipment is advantageous for both running cost and equipment cost, and provides a high level of safety against fire by diluting and cooling the high-temperature gas at the same time.

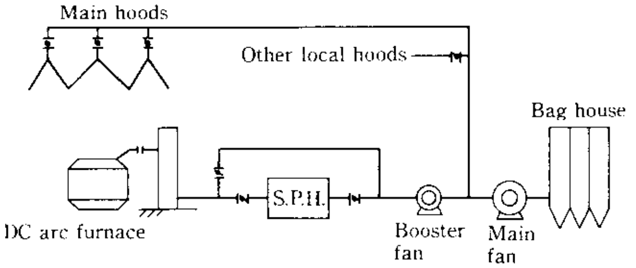


Fig. 13 Schematic diagram of dust collection equipment

8.2 Building Dust Collection System

While a quantitative evaluation of dust collection is difficult, the effects of the shape and arrangement of the main hoods and the collected air volume on the dust collection efficiency were quantitatively evaluated by simulating the flow of the dust-containing gas in the building with the general-purpose PHOENICS flow analysis program and by experiments with a 1/10-scale model. The three shapes of main hood shown in **Fig. 14** were each analyzed, and the dust collection efficiency of these different shapes was determined by considering the collected air volume. **Figure 15** shows the streamlines and dust collection efficiency (capture rate of dust-containing gas in a certain time after starting dust collection) resulting from the analysis. It is apparent with case 1 that the pyramid hoods installed above the arc furnace offerred the best performance. The relationship between the inclination angle of the main hood and the dust collection efficiency was found from the model experiments, and the best method for building dust collection was formulated from this relationship. Multi-point pyramid-suction hoods were installed at Daiwa Steel's Mizushima Works with a collected air volume of

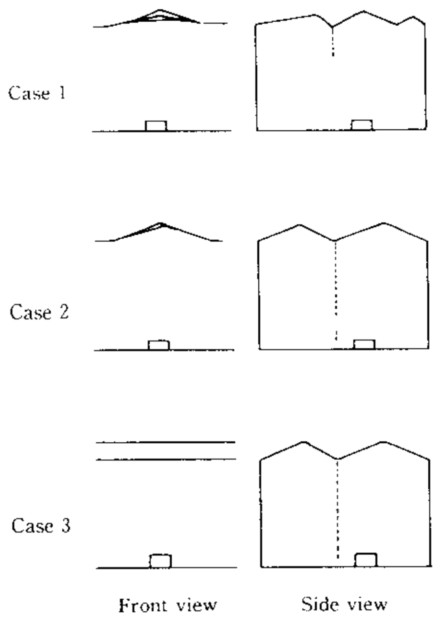


Fig. 14 Shapes of dust collection hood used in flow analysis

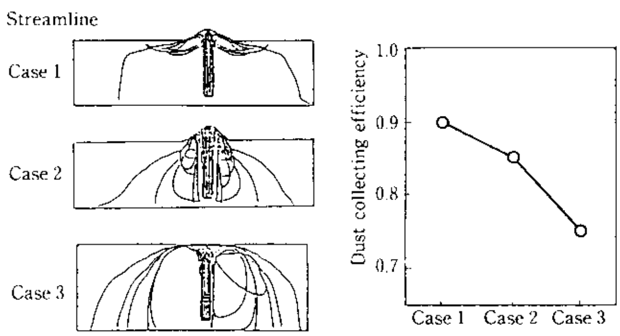


Fig. 15 Effect of shape of hood on dust collection efficiency

not less than 12 000 m^3-norm/min, and a comfortable working environment has been maintained since the installation.

9 Operational Results

The main specifications of the 100-t DC arc furnace supplied to Daiwa Steel's Mizushima Works are shown in **Table 2**, and the operational results there are shown in **Table 3**. Each unit consumption is sufficiently low and results that back up the excellency of DC arc furnace were obtained. At the same time, the effect of the uniform melting of scrap—one of the features of the CLECIM-KSC type DC arc furnace—is reflected in the good operational results. The on-line life of the bottom electrodes has exceeded 1 200 heats, and replace is completed within 24 h, including the time necessary for cooling and heating the furnace body. The initial aims have thus been achieved and are contributing greatly to high productivity.

Table 2 Main specifications of 100 t DC arc furnace of Daiwa Steel at Mizushima

Item		Main specifications
Transformer capacity		100 MVA
Arc voltage, arc current		800 V, 100 kA
Electrode	Upper	28 in × 1
	Bottom	Water cooled billet × 3
Furnace shell (dia. × height)		ϕ 6 700 mm × 3 100 mm
Tapping system		LVT and ladle car
Scrap charging		1 or 2 buckets

Table 3 Operational results of 100 t DC arc furnace of Daiwa Steel at Mizushima

Item		Result
Productivity	Tap to tap time	57 min (average) 46 min (record)
Unit consumption	Carbon electrode	1.1 kg/t
	Electric power	300 kWh/t
	Oxygen	25 m^3-norm./min
Life	Bottom electrode	1 500 heats

10 Conclusions

The CLECIM-KSC type large DC arc furnace superior in the uniform melting of scrap, maintenability of bottom electrodes, and safety was developed. The design concepts of the arc furnace were reported using actual results of furnace operation and their evaluation.

(1) Arc deflection was prevented by the optimum configuration of the bottom electrodes and bus tubes, thus achieving the uniform melting of scrap in this large DC arc furnace. Furthermore, the arc direction was controlled by forming a power supply control system for individual current for each of the bottom electrodes. In actual furnaces, furnace wall thermal load was almost uniform in circumference, and so was the consumption of top graphite electrodes, thus confirming the uniform melting property of the furnace.

(2) By clarifying the melting mechanism of the water-cooled bottom electrodes, the effects of each factor

on the melting amount of the electrodes were grasped and safety was verified. As a result, it was found that the suppression of the wear of the refractories near the bottom electrodes is effective in extending furnace life. The water-cooled bottom electrodes, because of their simple structure, were found superior for DC furnace use because of the usability of brick for refractories around the electrodes.

(3) As a rapid and safe method of replacing bottom electrodes, the bottom replacing method known for its established practice with the company's basic oxygen converters was improved and adopted for electric furnace use, including shell strength analysis.

(4) Almost all the operations around the furnace, including oxygen blowing and powder injection, were automated. Furthermore, a technique was developed whereby to determine specifications for building-type dust collectors using a flow analysis of in-building dust-generating gas as an environment-improving technique.

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