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Design of a Water-cooling System for the Inside Roof of 20 t Electric Arc Furnace for Oxygen Blow Decarburization Using CFD Analysis

Chung-Hyok Oh*, Kwang-Hyok Song, Song-Hua Chon, Jong-Mun Rim, Song-Il Ra

Abstract

An electric arc furnace (EAF) roof usually works at high temperature for a long time, undergoes not only heat radiations from electric arc, molten metal, and lining of high temperature, but also is washed and affected by chemical erosion due to high temperature and gas flow. In addition, it might be eroded by slag with high temperature. Inside roof of EAF is more severely affected by heat load than outside roof. Thus, the life of the EAF roof built of refractory materials is not so long. Furthermore, the higher the input power to the EAF is, the larger the thermal load exerted on the roof is. It follows from this that the refractive roof could not be satisfied with the requirements of the EAF. Therefore, a water-cooling system should be installed so that it can endure thermal load of high temperature. The previous water-cooling system had disadvantage that heat load of cooling tube gets so much bigger due to the arc heat of electrode, waste gas heat when decarbonizing and refining, and carbon oxidation reaction heat that with lower safety of inside roof it is often broken, and its life gets lowered. In this study the previous cooling system is first investigated by means of CFD and causes of bad points are considered, because of that, appropriate water-cooling system for 20 t EAF inside roof is designed and a cooling condition is determined. Secondly the safety test of the newly designed water-cooling system is done. After that, comparing to the previous cooling system, with new cooling system outlet the temperature falls from 64 to 43℃ and the inside roof is safe even after smelting 3~15 times. Outlet temperature of inside roof ranges from 43 to 49℃ and it can melt up to 3~15 times.

Keywords: Electric arc furnace (EAF), water-cooling, furnace roof, oxidation refining, outlet temperature, CFD

INTRODUCTION

The electrical arc Furnace (EAF) is the common technology used in industry to make steel [1, 2]. EAFs are used to heat the materials installed in the furnace by an electric arc.

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The temperature of the EAF can be up to 1,800°C. Only 32% of the steel factory in the world used the EAF due to its expensive cost compared to the traditional furnaces.

The EAF is composed of three parts: the shell which includes walls and lower bowl, the main part and the roof part which is well insulated, or water cooled [3].

Assad *et al.* investigated numerical heat transfer of water-cooled roof in an electric arc furnace [4]. The results showed that the decrease in brick material thermal conductivity resulted in a significant decrease in the top surface temperature of the furnace roof. The results showed that rectangular brick material is the best option in the roof to keep it at low temperature. Khodabandeh *et al.* investigated heat transfer of a water-cooled lance for blowing oxidizing gas in an electrical arc furnace in experimental and numerical mode [5]. Lenhard *et al.* investigated numerical modelling of heat flows in the upper blast furnace of the electric arc furnace [6]. The model was developed implementing the finite volume method in ANSYS-Fluent program code.

The AC Furnace equipment development focused on roof cooling panels which are simultaneously optimized for ease of manufacture and operational safety [7–10].

The roof cooling system is divided into the outside roof cooling part and inside roof cooling one, which is also divided along the radial direction. Division of the components is made to keep uniformity of hydraulic resistance and in the principle of controlling cooling strength in line with magnitude of heat load of cooling component. Inlet and outlet temperature of cooling water is one of main factors for water-cooling strength while it has also an influence on the magnitude of heat loss. And it is a main factor for determining the amount of flow rate needed for cooling water. Now the allowable rise temperature of cooling water is 15~20℃ for industrial water and 20~25℃ for soft water in the world. The inlet temperature t_{in}=20℃ is chosen based on the time and the amount of water evaporated from the EAF cooling system, as well as the quantity of new water entering the reservoir. Outlet temperature t_{out}=45~50℃ is the one chosen because of investigation of water used in ironworks and steelworks lest fur should be formed. Outlet temperature is not allowed to exceed 60℃ to the maximum. However, outlet temperature in the previous roof cooling system is about 60~65℃ so that vapor comes out of outlet. In addition, the maximum temperature in local part of inside roof reaches 1,000~1,200℃, so water leaks through the crack in the roof due to oxidation loss of steel plate from 12 to 3 mm, and the life of the roof gets lower.

DESIGN OF INSIDE ROOF COOLING SYSTEM

The EAF inside roof is designed in a way which is completely different from the previous. In the previous system, three blocks are combined to form one inside roof structure, but in a new system it is designed in a monolithic mode as shown in Figure 1. Analysis of the proceeding previous furnace cooling system indicates that some failures such as severe difference of pressure in inside roof, occurrence of reverse flow of cooling water, and the presence of locally overheated area can be caused due to defects of roof design and existing structure.

Hence three types of inside roof water cooling systems are analyzed to choose an appropriate one. The result is shown in Table 1.

As shown in Table 1, the 3rd cooling system is the best of them. Based on the type 3 cooling system, two plans are chosen, their analysis was done, and the results are given in Table 2. The structure of each plan is shown in Figure 2.

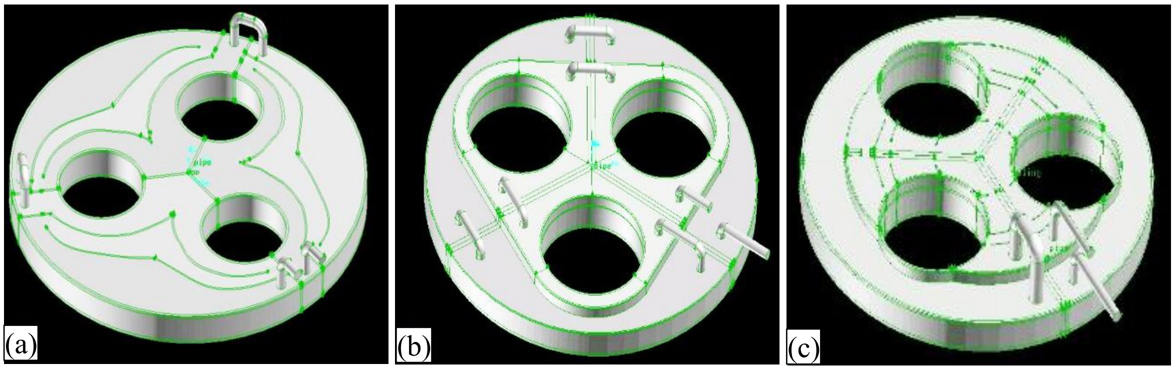


Figure 1. Structure of each type of the inside roof (a: type 1, b: type 2, c: type 3).

As shown in Table 2, plan 1 seems to be better than plan 2. Comparing to the previous cooling system, outlet temperature is reduced from 63.8 to 43.2°C and the maximum temperature on lower plate is fallen from 1,167.2 to 570°C. After its reconstruction, there is no existence of locally overheated area and pressure loss is reduced from 0.27 to 0.13 MPa. As all items for evaluating a cooling capacity are satisfied, a proper inside roof is designed according to the first plan model mentioned above. A cooling water flow distribution, heat distribution, and pressure distribution of plan 1 model are analyzed, whose results are shown in Figures 3–5. As shown in Figure 3, the flow rate of cooling water is very fast for average rate 0.82 m/s and maximum flow rate 13.5 m/s.

The fast flow rate of cooling water is because a reverse flow does not occur due to uniform width of 250 mm and a solid type of flow line. The width of the flow line gets narrower to raise the flow rate in inner block. As there is no stay area of cooling water and flow rate is fast, the outlet temperature is low as 43.2°C, the maximum temperature is also low as 570°C, and local heating area does not exist as in Figure 4. As given in Figure 5, pipes are not used because the inside roof was designed in the monolithic mode, so pressure loss in the pipe gets diminished, and by using φ80 mm pipe connecting inner block to outer block the pressure loss is reduced. It can be said that total loss of 0.13 MPa is low. Therefore, the amount of cooling water flowing into cooling system is 17.97 kg/s, so that outlet temperature of cooling water gets dropped.

Table 1. Comparison of the cooling capacity evaluation items in each type.

Items Kind	**Maximum flow rate (m/s)**	**Average flow rate (m/s)**	**Outlet temperature (°C)**	**Maximum temperature (°C)**	**Flow rate (kg/s)**	**Loss of pressure (MPa)**
Type 1	9.35	0.63	63.8	1 167.2	9.58	0.27
Type 2	9.95	0.72	53.8	1298	12.8	0.21
Type 3	13.5	0.82	43.2	570	17.97	0.13

Table 2. Comparison of the cooling capacity evaluation items in each plan.

Items plan	**Maximum flow rate (m/s)**	**Average flow rate (m/s)**	**Outlet temperature (°C)**	**Maximum temperature (°C)**	**Flow rate (kg/s)**	**Loss of pressure (MPa)**
Plan 1	13.5	0.82	43.2	570	17.97	0.13
Plan 2	12.28	0.79	47.04	630	16.31	0.18
Previous	9.35	0.63	63.8	1 167.2	9.58	0.27

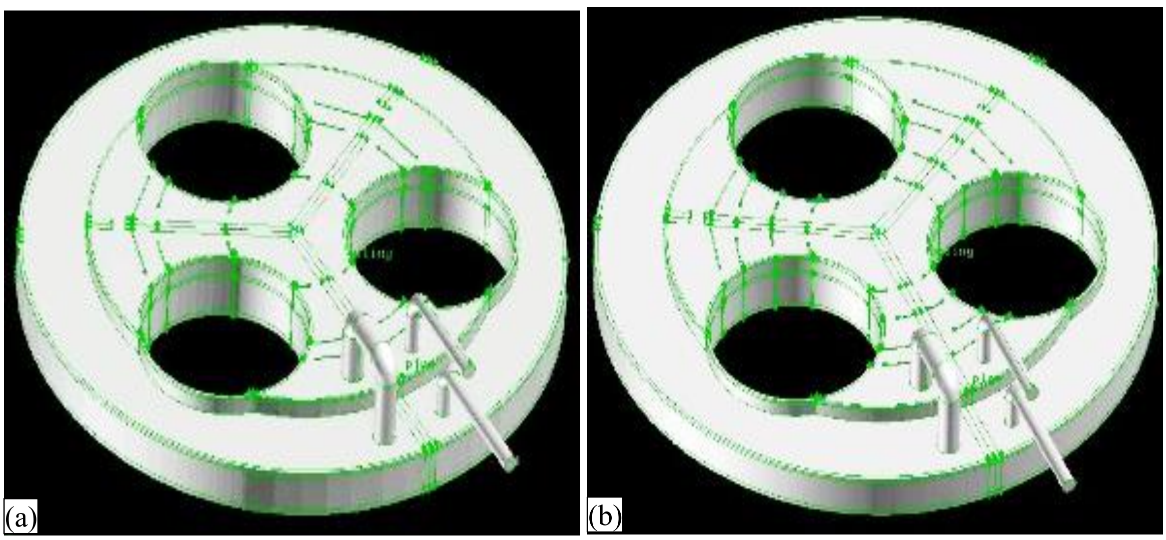


Figure 2. Structure of each plan (a: plan 1, b: plan 2).

THE RESULT AND DISCUSSION

Reasonable Cooling Condition

The inlet minimum pressure and flux of cooling water are determined to maintain the outlet temperature less than 43°C when furnace ambient temperature rises to 1,600, 1,700, and 1,800°C step by step. This result is shown in Table 3.

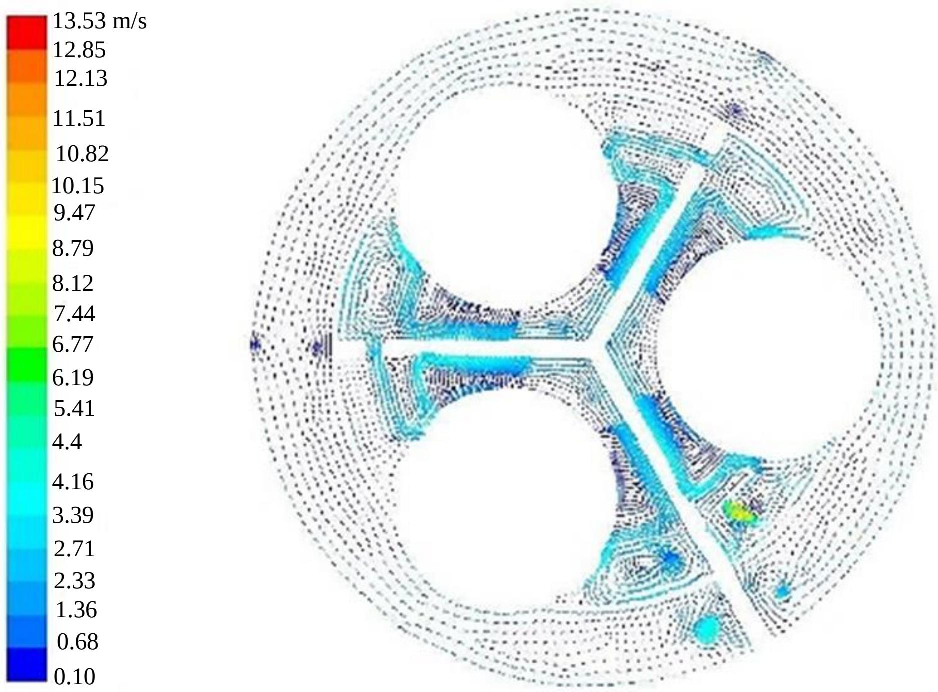
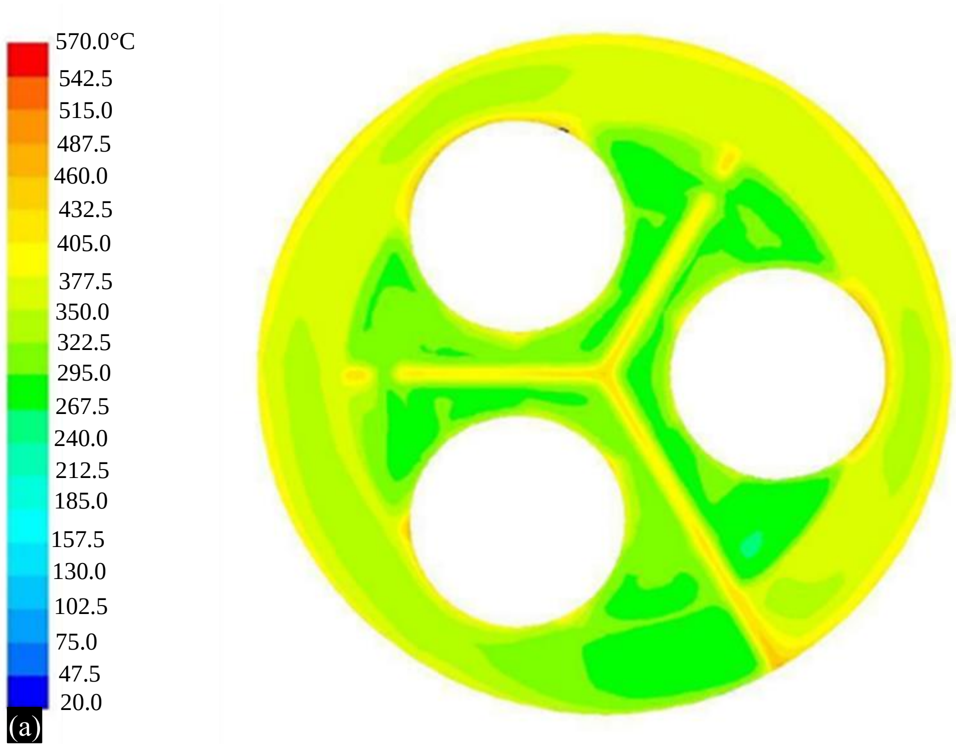


Figure 3. Distribution of the cooling water flow (Average flow rate 0.82 m/s, Maximum flow rate 13.5 m/s).



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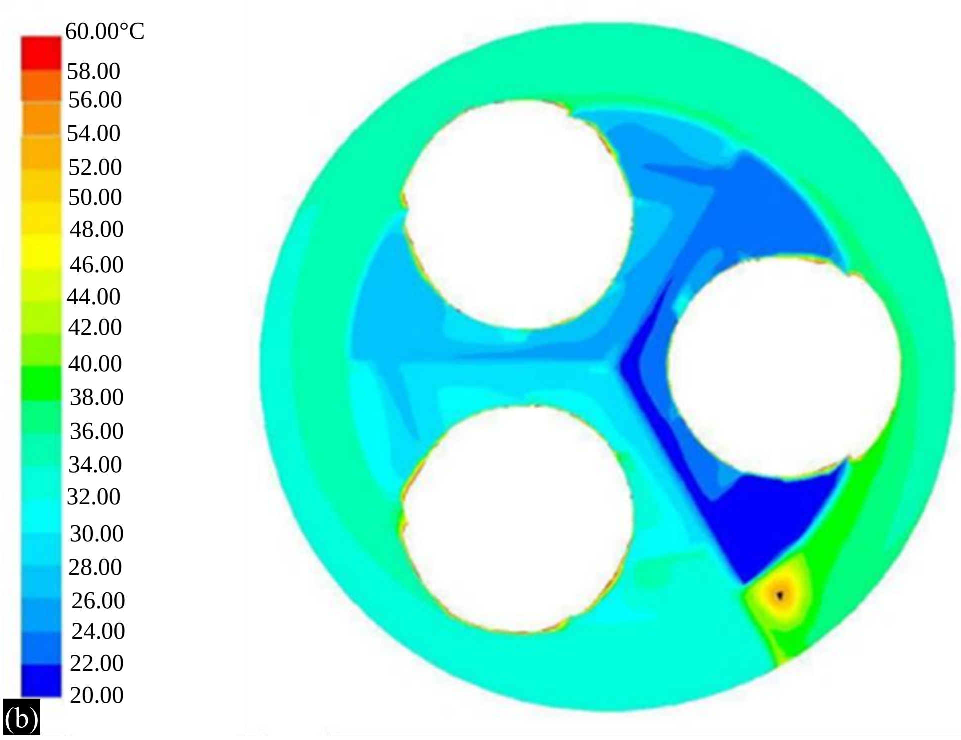

Figure 4. Heat distribution. a: Outlet temperature: 43.2℃, b: Maximum temperature: 570℃.

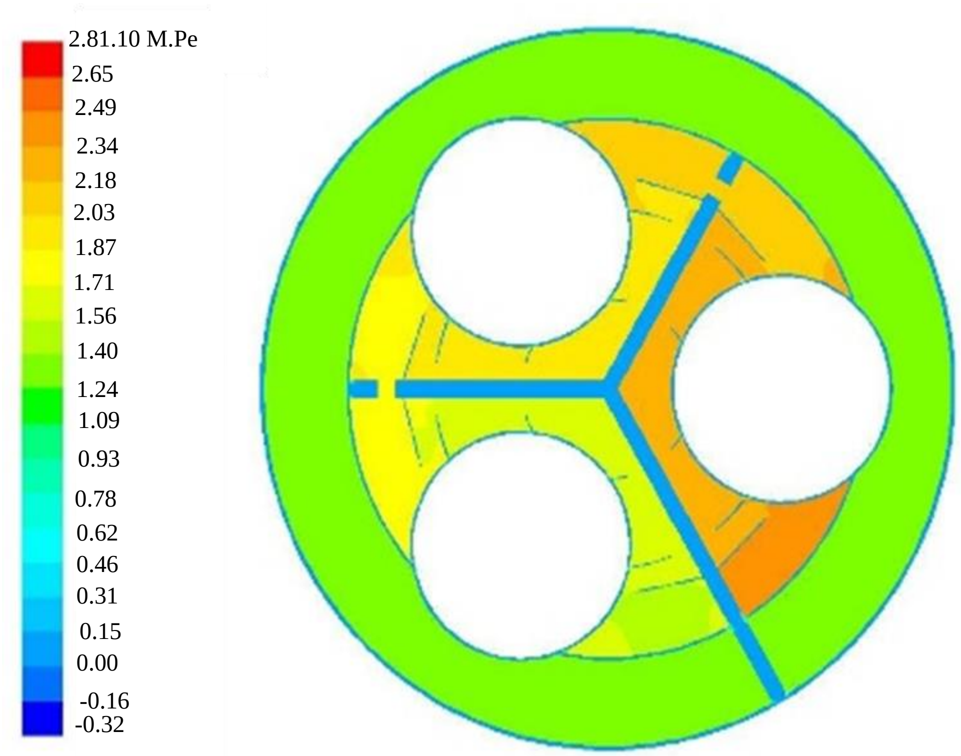

Figure 5. Pressure distribution (Flow rate 17.97 kg/s, Loss of pressure 0.13 MPa).

As shown in Table 3, to keep outlet temperature of 43.2℃ and maximum temperature of 570℃ at 1,600℃, the inlet minimum pressure of cooling water is 0.281 MPa and flow rate is 65 m^3/h. If oxygen inlet is increased, then ambient temperature of furnace is raised furthermore. In case of ambient temperature of furnace of 1,700℃, the inlet minimum pressure of cooling water should be 0.379 MPa and flux is 74 m^3/h, while in case of 1,800℃ the inlet minimum pressure of 0.538 MPa and flux of 89 m^3/h should be ensured.

As the inlet pressure from factory is 0.3 MPa and flux is 50 m^3/h, oxygen blowing strength must not be increased excessively to enhance the safety of furnace. And when refining by means of oxygen blowing at factories, the oxygen blow strength should be set by considering the amounts of oxygen and cooling water.

Next, the maximum temperature of inside roof lower plate is determined based on outlet temperature. In the process of real operation, only the outlet temperature can be measured. So, the inside roof lower plate maximum temperature has been determined based on the measured temperature.

As can be seen in Table 4, outlet temperature should be kept less than 41℃ to keep inside roof maximum temperature below 500℃. In the newly reconstructed inside roof, roof maximum temperature is about 570℃ when inlet pressure is 0.281 MPa, and flux is 72 m^3/h. When determining the roof maximum temperature depending on outlet temperature, the maximum temperature is set approximately by measuring only the outlet temperature. So, the safety of furnace can be guaranteed by controlling oxygen blow strength. The previous inside roof has a local overheated area and temperature as high as 1,167℃ to the maximum, so that steel plate tends to be oxidized and cracked.

Experimental Verification

A new 20 t EAF inside roof water-cooling system has undergone a safety test. The result of which is given in Table 5.

Table 3. The cooling water minimum pressure and flow rate at the ambient temperature.

Ambient temperature (℃)	Minimum pressure of the cooling water inlet (MPa)	Flow rate (kg/s(m^3/h)
1,600	0.281	17.97(65)
1,700	0.379	20.54(74)
1,800	0.538	24.85(89)

Table 4. Maximum temperature of the EAF inside roof bottom by outlet temperature.

Outlet temperature	Maximum temperature of the inside roof lower plate	Outlet temperature	Maximum temperature of the inside roof lower plate	Outlet temperature	Maximum temperature of the inside roof lower plate (℃)
38	370	46	655	54	930
40	430	48	720	56	1,020
42	510	50	790	58	1,070
44	575	52	860	60	1,160

Table 5. Results of operation test of 20 t EAF inside roof cooling system.

D_{limit} (mm)	Gage pressure (MPa)	Oxygen flow rate (Nm^3/h)	Oxygen blowing strength (Nm^3/(min.t)	Inside roof			
				Outlet temperature (℃)		Life (charges)	
				previous	*new*	*previous*	*new*
16	0.40	900	0.75	64	43	3	15
	0.50	980	0.82	67	45	3	14
20	0.40	1,106	0.92	69	48	3	13
	0.50	1,328	1.11	71	49	2	13
22	0.40	886.8	0.74	63	43	3	15
	0.50	1,108	0.92	69	48	3	14

As indicated in Table 5, the test has been done in the way of comparing the previous outlet temperature with the latter one and evaluating the roof's life. Oxygen blowing strength is tested while changing burner D_{limit} with oxygen blowing pressure fixed at 0.4~0.5 MPa. Here the inlet pressure is 0.3 MPa.

When D_{limit}=16 mm, and oxygen blowing strength varies from 0.75 to 0.82 Nm^3/(min.t), the outlet temperature gets increased as much as 3℃ and the life is reduced from 15 to 14 charges. Comparing with the previous cooling system, outlet temperature is decreased from 64 to 43℃ and the inside roof is safe even after smelting from 3 to 15 charges.

The outlet temperature of the inside roof ranges from 43 to 49℃, at which 13–15 charges can melt. When D_{limit}=20 mm, the outlet temperature is not easy to be less than 45℃. But if oxygen blow strength is high, oxidation refining time is short. In this case the inlet pressure of the cooling system should be raised.

CONCLUSION

The cooling system of the EAF inside roof was designed and cooling condition is determined. Moreover, the width of the pipeline outer block is uniformed and by building a sidewall between inner blocks cooling water was made to flow into the next block via seven paths. Pressure loss in pipe was reduced by reforming the inside roof as an integral whole to remove connection pipes and connecting the inner block to the outer one with the 80 mm pipe and therefore flux was increased. The minimum inlet pressure of cooling water and the flux are determined according to furnace ambient temperature. And maximum temperature of furnace lower plate is determined in accordance with outlet temperature.

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