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The New Channel Loop for the Improvement of Operation Characteristics in Single Loop Channel Induction Furnace

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Abstract **Original Research Article**

Channel induction furnace (CIF) and channel type induction heating tundish (IHT) are widely utilized to melting, refining, maintenance, overheating and continuous casting of metals. But due to failures of inductor and other causes, high overheating temperature occurred premature erosion of refractory, so it has short-operating life. This paper proposes a new type channel of single loop CIF for steel melting, and determined optimum design parameters of channel loop using Taguchi method and simulation of the commercial software COMSOL Multiphysics to extend the operating life of CIF. The results of simulation and field test data demonstrate full possibilities of intermittent operation and life extension of channel loop over 140 cycles, so the proposed new structure of channel loop can be satisfactorily applied for steel melting and superheating using channel type induction heating technology.

Keywords: channel induction furnace, Multiphysics software, Taguchi method, tundish, channel loop.

1. Introduction

The industrial channel induction furnace is well-known metallurgical equipment for melting, holding, casting and refining in the metallurgical industry.[1,2,5]

The continuous casting and melting technology using channel type induction heater is significant for improving the quality of metal by removing inclusions in molten metal. Non-metallic inclusions are removed by the electromagnetic separation caused by the electromagnetic force generated by the inductor and rise upward. [3]

The Joule heat is occurred in channel loop and transported to a molten metal pot. The temperature of channel loop is relatively higher than one of the molten metal pot, so the refractory erosion of channel loop is performed faster than the chamber of furnace. This is an +important factor in the reduction of lifetime.[4,5]

Compared with the channel induction heating technique and other heating techniques, the heat efficiency is more than 90% and the heating rate is fast due to the generation of Joule heat by the induction current flowing through the channel loop.[6,7]

Alferenok and Kuvaldin[8] proposed 2-phase induction unit of a channel furnace for making cast iron and simulated the effect of the channel shape and size to improve heat-and-mass transfer and determined the optimum sizes of central channel to decrease temperature gradient of channel.

Xiqing Chen et al.[9,10] discussed the reasonable structure with double-channel and four-channel in IHT and improved overheating rate of molten steel from 1750K to 1850K, provided theoretical basis theoretical basis for improving the refining efficiency of molten steel in a double-channel induction-heating technology.

Xiqing Chen et.al[11] proposed a tundish with double-channel, three-channel and four-channel by applying different current direction for the case of single inductor and two inductors, and found the optimum conditions based on the numerical simulation.

Andris Jakovis et.al[12-15] suggested that damage such as corrosion, deposition and penetration of refractory materials in the channel as well as local overheating in the channel loop can reduce the cleanliness of the treated melt and the effectiveness and safety of the CIF operation. In single loop CIF, the asymmetry of the cross-sectional area of the channel loop and the analysis of the temperature distribution and heat flux with time in various structures depending on the angle of placement of the inductor were simulated.

A butterfly tundish model with two inductors is proposed, and the inductive current density distribution in the cross section of the channel connecting the molten metal pots is higher due to the skin effect and the proximity effect near the inductor, and the centre of the electromagnetic force in the channel section is not the geometric center.[16,17]

The thermodynamic behaviour of the monolithic lining of the furnace body for volume optimization in the channel induction furnace was analysed and the problem of determining the thickness of the lining material was determined using orthogonal array table (Taguchi method). When the furnace is newly installed or repaired, A 9-day preheating process and a 3-day holding period are needed for reducing the thermal stress of the refractories, decreasing the moisture content and hardening of the refractory.[18]

Previous scholars prevented channel failure by building a dual power system using an emergency generator and inserting metal strips into a short circuit, but they are difficult to operate and require high initial investment.

This paper proposes a novel non-disconnecting channel configuration and the temperature field distribution and the shrinkage stress induced hot cracking with commercial softwar COMSOL Multiphysics process modelling based on the orthogonal table-based simulation scheme are discussed.

2. Simulation project and analysis plan

2.1. Geometric model for simulation

The single loop CIF consists of an iron core, an inductor winding, a channel loop and molten metal pot connected to the channel.

The conventional structure with a vertical channel loop[1, 4] is repaired by separating the inductor. The proposed horizontal structure channel loop is suitable for the maintenance of the furnace because it fixes the inductor and separates only the yoke of the iron core.

Fig.1 shows the schematic 3D model of the inductor-clamped single loop CIF with horizontal channel loop used in the simulation.

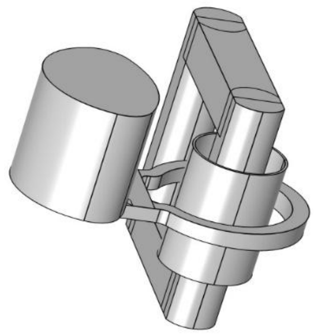

Figure 1. 3D model of single loop channel induction furnace

In order to extend the furnace lifetime in the operation of the channel induction furnace for steel melting, the objective function was to select the temperature difference in the channel.

In the simulation using a Multiphysics software, the simulation results of temperature field distribution up to 0.5 h at the point steel is completely melted are considered to research the local overheating of the channel and premature erosion of refractories by the flow of molten metal.

In the modelling simulation by commercial software, the stress state of the channel was considered at a time point after the end of solidification of the channel, where the maximum stress in the boundary region of the channel and the molten metal pot, which is the region where the break occurs frequently, was taken into account.

2.2. Design of a simulation scheme based on orthogonal table

In this paper, three-level design parameters for four parameters determining the end-ring and boundary sub-structure of the molten steel yarn in a single loop channel induction furnace based on the $(OA)L_9(3^4)$ orthogonal table are presented by simulating the heating and flow processes in Multiphysics software and analysis of the solidification and shrinkage stress in the commercial modelling software.

The structure of the channel for the optimization of the boundary substructure of the channel and the molten metal pot is shown in Fig. 2, and the control factors and levels are given in Table 1.

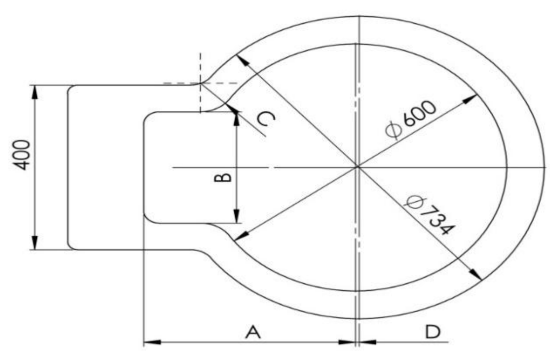

Figure 2. Design parameters of the channel and the representation of each factor

Table 1. Factors and levels of simulation

Level	Control factors			
	A, mm	B, mm	C, mm	D, mm
1	360	210	50	7
2	390	240	70	0
3	420	270	100	-7

The first row (A) is the distance from the centre of channel to the end of the projecting part, the second row (B) the width of the projecting part, the third row (C) the radius of the projecting part, and the fourth row (D) the centre deviation of the outer diameter and inner diameter of the channel.

3. Result and Discussion

3.1 Results and Discussion of Simulation

The heating process of the channel was simulated for heating and flow up to 0.5 h in the presence of the entire molten metal of the channel and molten metal pot using the method of multi-physics field coupling of induction heating, heat transfer and fluid flow modules of the commercial software COMSOL Multiphysics.

Fig. 3 shows the simulated images of the heating process of the channel and the molten metal pot by Multiphysics software for the first experimental scenario.

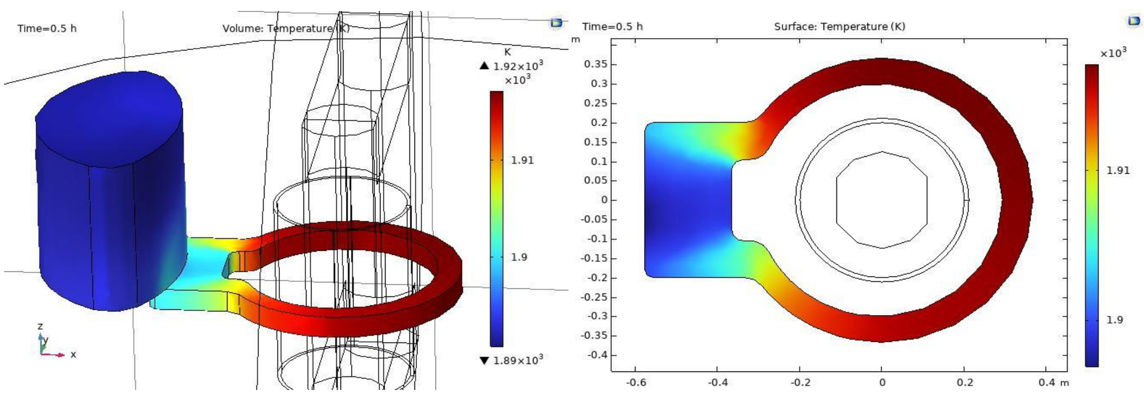

Figure. 3. Temperature field analysis results.

To analyse the simulation results, the SN ratio was calculated for the results of the temperature field analysis and the results of the stress analysis.

The SN ratio was calculated by the SN ratio formula of the network characteristics, because the smaller the target values of the experimental scheme, local overheat temperature and stress values, the better network characteristics.

The SN ratio calculation equation is as follows;

$$SNRi = -10\lg\left(\frac{1}{n}\sum_{k=1}^{n}\delta_{ik}^{2}\right) \quad (9)$$

Table 2 shows the results of the temperature field analysis and the SN ratio with the melting time.

Table 2. Temperature field analysis results and SN ratio

Trail number	ABCD	time, h	Maximum	Minimum	Absolute local	Relative local	SN ratio,

			temperature T_{max}, K	temperature T_{min}, K	overheating temperature Δt, K	overheating temperature $\Delta t/T_{max}$, %	dB
1	1111	0.1	1859.4	1825.4	34	1.8285	-4.1154
		0.2	1876	1843.8	32.2	1.7164	
		0.3	1890.9	1860.8	30.1	1.5918	
		0.4	1904.7	1876.5	28.2	1.4805	
		0.5	1917.1	1890.8	26.3	1.3718	
2	1222	0.1	1869.9	1822.2	47.7	2.5509	-7.2568
		0.2	1885.4	1839	46.4	2.461	
		0.3	1898.8	1855	43.8	2.3067	
		0.4	1911.1	1869.9	41.2	2.1558	
		0.5	1922.2	1883.5	38.7	2.0133	
3	1333	0.1	1865.7	1821.9	43.8	2.3476	-6.5503
		0.2	1880.6	1838	42.6	2.2652	
		0.3	1893.6	1853.4	40.2	2.1229	
		0.4	1905.6	1867.7	37.9	1.9889	
		0.5	1916.5	1880.7	35.8	1.868	
4	2123	0.1	1854.4	1823.6	30.8	1.6609	-3.3473
		0.2	1869.9	1840.5	29.4	1.5722	
		0.3	1883.8	1856.3	27.5	1.4598	
		0.4	1896.7	1870.9	25.8	1.3602	
		0.5	1908.3	1884.2	24.1	1.2629	
5	2231	0.1	1852.8	1823.9	28.9	1.5598	-2.7448
		0.2	1868.5	1841	27.5	1.4718	
		0.3	1882.6	1856.9	25.7	1.3651	
		0.4	1895.6	1871.7	23.9	1.2608	
		0.5	1907.4	1885.2	22.2	1.1639	
6	2312	0.1	1845.2	1824.8	20.4	1.1056	0.4201
		0.2	1861.4	1842.3	19.1	1.0261	
		0.3	1876.3	1858.6	17.7	0.9433	
		0.4	1889.9	1873.6	16.3	0.8625	

		0.5	1902.3	1887.2	15.1	0.7938	
7	3132	0.1	1843.8	1825.7	18.1	0.9817	1.4058
		0.2	1859.9	1843	16.9	0.9087	
		0.3	1874.9	1859.1	15.8	0.8427	
		0.4	1888.5	1873.8	14.7	0.7784	
		0.5	1900.8	1887.2	13.6	0.7155	
8	3213	0.1	1842.4	1824.7	17.7	0.9607	1.5952
		0.2	1858.2	1841.6	16.6	0.8933	
		0.3	1872.8	1857.4	15.4	0.8223	
		0.4	1886.1	1871.8	14.3	0.7582	
		0.5	1898.2	1884.9	13.3	0.7007	
9	3321	0.1	1840	1826.4	13.6	0.7391	3.996
		0.2	1855.9	1843.3	12.6	0.6789	
		0.3	1870.6	1859	11.6	0.6201	
		0.4	1884.1	1873.4	10.7	0.5679	
		0.5	1896.4	1886.4	10	0.5273	

where $\delta_{ik} = dT_{ik}/T_{ikmax} \cdot 100$ is the relative overheat temperature at the kth time in the ith experiment.

For each objective function, the average of SN ratio and the average range for each objective function with respect to the factor and level have been calculated, and the results are given in Tables 3.

Table 3. Average values and their ranges of the SN ratios of the factors at each level in the temperature field analysis.

level	A	B	C	D
1	-5.9742	-2.019	**-0.7**	**-0.9547**
2	-1.8907	-2.8021	-2.2027	-1.8103
3	**2.3324**	**-0.7114**	-2.6298	-2.7675
Range of the SN ratio	8.3066	2.0907	1.9297	1.8127
3311	420	270	50	7

The bold values in the table indicate the maximum average value of the SN ratio for each factor. In Taguchi method, the optimum condition consists of a factor with the maximum average of the SN ratio for each factor.

From Table 3, the results of heating of the channel show that the average value of the SN ratio has a maximum at the third level of factors A and B, the first level of factors C and D, i.e. the optimum condition for reducing the local overheating in the channel and extending the life of the refractories is $A_3B_3C_1D_1$.

It can also be seen that factor A has a very significant effect because the range of SN ratio is much larger than other factors, followed by factor B and factor C and factor D are not significant.

From the above analysis, we choose the condition of the third level of factor A and B, and the first levels of factors C and D as the optimum of the channel to improve the furnace performance by increasing the life of refractories while preventing the channel breakdown in emergency situations.

Thus, the chosen optimum condition is $A_3B_3C_1D_1$.

The distance from the centre of the channel to the projecting part is 420 mm.

The width of the projecting part is 270 mm

The radius fillet of projecting part is 50 mm

The centre deviation of the outer diameter and inner diameter of the channel is +7 mm

The simulation results for the optimum $A_3B_3C_1D_1$ are shown in Fig. 4 and Table 4.

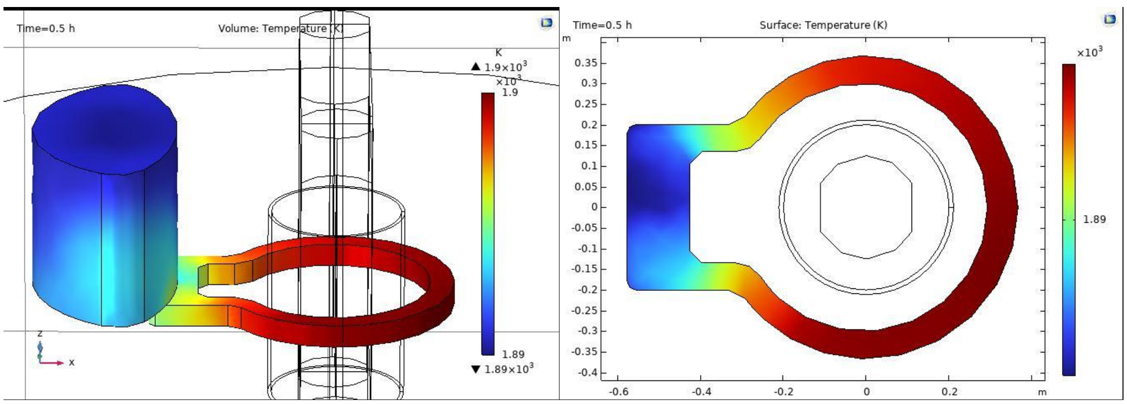

Figure 4. Simulation results of $A_3B_3C_1D_1$ experimental plan

Table 4. Simulation results under $A_3B_3C_1D_1$ condition

ABCD	Maximum temperature T_{max}, K	Minimum temperature T_{min}, K	Absolute local overheating temperature Δt, K	Relative local overheating temperature $\Delta t/T_{max}$, %
3311	1919.3	1905.8	13.5	0.7034

Fig. 4 and Table 4 shows that the absolute local overheating temperature of the channel is 13.5 K, which reduces the local overheating in the channel, thus providing the life of the refractories. Since the conditions of minimizing the local overheating temperature have opposite metallurgical properties, a large intertwining relationship exists between the factors affecting this.

The reason for the improved operating life of the channel induction furnace in this paper can be analyzed as follows.

First, it is possible to reduce the temperature of channel opposite the molten metal pot by changing the cross-section of the conventional uniform channel. That is, by increasing the cross-section of the back side, the electrical resistivity distribution of the channel has become different. The temperature distribution of the channel is directed forward to obtain a uniform temperature gradient.

Second, a new structure for the boundary region of the molten metal pot and channel, which is the main factor of the life degradation, is proposed to reduce the stress caused by the solidification shrinkage in this region.

3.2. Practical verification of the newly developed technology

In order to verify the experimental results for the optimum $A_3B_3C_1D_1$, a field-based test was carried out.

In Fig. 5, the photographs of the newly proposed channel and the industrial application of the single loop channel induction furnace are shown.

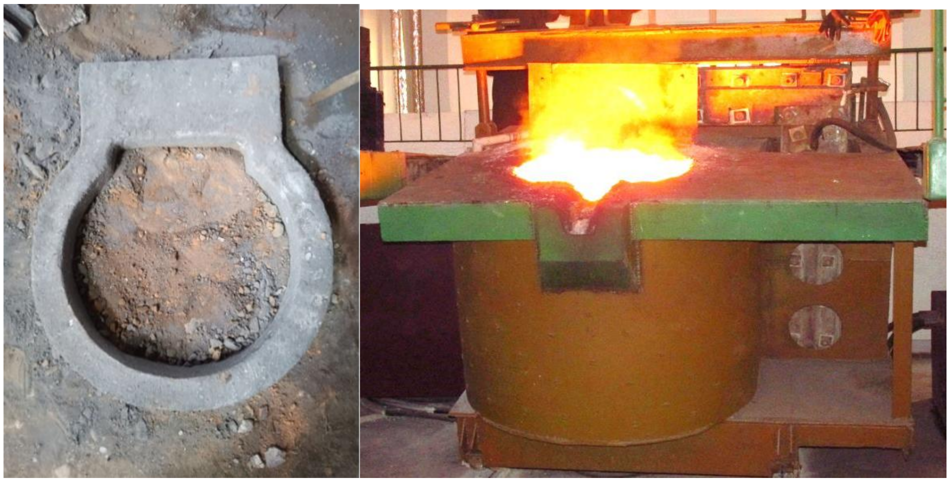

Figure. 5. Industrial application photograph of the new channel loop and single loop channel induction furnace proposed in the paper.

During the three years of industrial application of the furnace, the lifetime of the furnace was extended by 140% compared with the previous one.

Table 5 shows the characteristics of the single loop channel induction furnace using the channel configuration proposed in this paper.

Table 5. Comparison of the characteristics of the proposed single loop channel induction furnace

Item	Unit	New channel	Conventional channel
Charging capacity of furnace	t	1	1
Power of furnace	kW	300	300
Time per charge	h	3~4	3~4
Life of furnace	Time	**140**	100
Frequency	Hz	50	50
Power factor of furnace		0.7	0.72
Power consumption	kWh/t	650	650

Production cost	$/t	65	80
Intermittent operability		Yes	No

Conclusions

In this paper, the multi-physics analysis tool COMSOL Multiphysics have been used to simulate the heating of the channel in a single loop channel induction furnace to determine the optimum channel structural parameters to improve the lifetime of the channel refractories.

The temperature difference between the hot side and the opposite side of the molten metal pot in the channel is less than 20 K so that premature corrosion of the channel refractories by local overheating and the resulting life degradation are avoided and the service life of the furnace has been increased 1.4 times.

Intermittent operation is possible in the channel induction furnace using a new channel, i.e. the reactor can restart after the power supply has been interrupted for a long time during the operation.

The proposed topology modification method of the channel in our paper is considered to be a new technique that can be used not only for the channel induction furnace but also for the tundish which uses the channel type induction heating technique.

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Author contribution

Won-Chol Hong: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing-original draft; Hak-Myong Song: Data curation, Methodology, Validation, Formal analysis, Investigation, Writing-original draft.

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