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STATE OF THE ART IN TUNDISH WITH INDUCTION HEATING (IH) FOR CLEAN STEEL CASTING

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The electrical magnetic field plays an essential role in controlling the molten steel flow, heat transfer and migration of inclusions. Electromagnetic induction heating technology utilizes the force or heat effect of the electromagnetic field or simultaneously uses force and heat effect to control molten metal flow, heat transfer and the movement of non-metallic inclusion in the metallurgical process, to optimize the metallurgical process, improve production efficiency, quality, and performance. In this work, the development of IH in continuous casting tundish was outlined. The current theoretical and experimental research on electromagnetic induction heating for molten steel flow and heat transfer were introduced. Meanwhile, the electromagnetic purification mechanism and research progress of non-metallic inclusions in molten steel were analyzed. Finally, the prospects for the application of electromagnetic IH are proposed.

Key words: steel casting; tundish; induction heating; clean steel

INTRODUCTION

Continuous casting tundish is one of the essential vessels in steel production connected the ladle and continuous casting mold. Channel type induction heating (IH) tundish is a newly developed technology, which applies the electrical magnetic field into the molten steel in the tundish. Compared with the traditional tundish, the molten steel in the channel type electromagnetic IH tundish has a specialized flow field and temperature field. The channel type electromagnetic IH technology can not only heat the molten steel but also purify the molten steel and other metals and alloys, which have good application value and prospect. Thus, the appropriate technology and design of a tundish are vital for increasing the quality of steel productivity.

The flow and temperature distribution of molten steel during electromagnetic IH and the movement behavior of inclusions were simulated [1-5]. The industrial test and research are more expensive and dangerous of high-temperature molten steel than the numerical simulation. Thus, industrial data is less reported [6, 7].

Based on the previous research on continuous casting tundish with electromagnetic IH, this paper systematically summarizes the latest research progress of tundish IH technology, analyzes and discusses the problems existing in the study of tundish steel liquid flow field and temperature field, and puts forward the research direction of further research. The relevant theoretical and experimental research has been extensively reviewed in this field.

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FLOW AND HEAT TRANSFER IN IH

Tundish with IH is a new technology to compensate for the temperature of molten. The schematic diagram of the two-channel IH tundish [6] is shown in Figure 1. Its basic principle is that alternating current produces alternating magnetic, and induced current in molten steel produces Joule heating and improve the temperature of molten steel. When the alternating current passes through the primary coil, an alternating magnetic field is generated around the coil, and the alternating magnetic flux is on the secondary coil. The molten steel generates an induced electromotive force. Due to an alternating current is generated in the molten steel surrounding the core, and the Joule heating generated by the induced current passing through the molten steel that can heat the molten steel.

Industrial experiments for IH tundish studied a 7 t tundish equipped with channel-type IH equipment [7, 8]. Due to the high risk of high-temperature molten steel, the auxiliary conditions required for the experi-

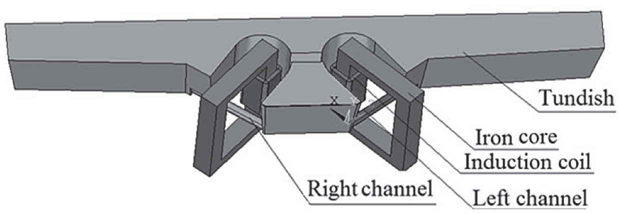

Figure 1 Schematic of channel type IH Tundish [6]

ment are demanding, and the cost is high, so the high-temperature experiment is carried out less. The industrial test and research are less than water modeling and numerical simulation. Water modeling [5, 9] was used to simulate the molten steel flow and optimize the flow control devices and metallurgical vessels process parameters. In the water modeling experiment, the pinching effect of the electromagnetic force was ignored. In order to overcome the difficulties of high-temperature experiments and the simultaneous interaction between electromagnetic force and Joule heat in the water experiment, numerical simulation [6, 8-12] was used to simulate the IH tundish. In the numerical calculation, Yue [6, 8] investigated that the channel type electromagnetic IH tundish, when the electric power reaches 1, 000 kW, the electromagnetic force close to the wall surface of the tundish IH channel is $4,5\times10^5$ N/m^3, and the gravity of the molten steel is $7,0\times10^4$ N/m^3, the electromagnetic volume force is about 6,4 times of gravity, and the Joule heating close to the wall surface of the channel is $1,5\times10^7$ W/m^3. The time-averaged electromagnetic force and Joule heating distribution of the molten steel in the channel cross-section are shown in Figure 2. Therefore, the use of water simulation to study the flow

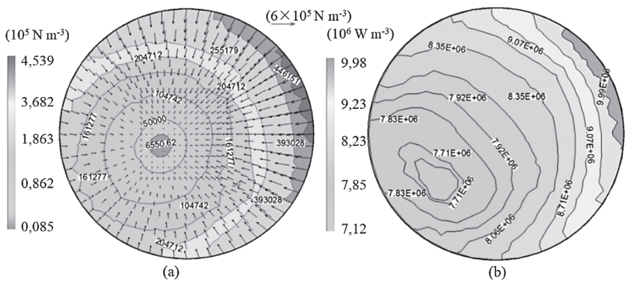

Figure 2 Electromagnetic force (a) and Joule heating (b) distribution in the channel [8]

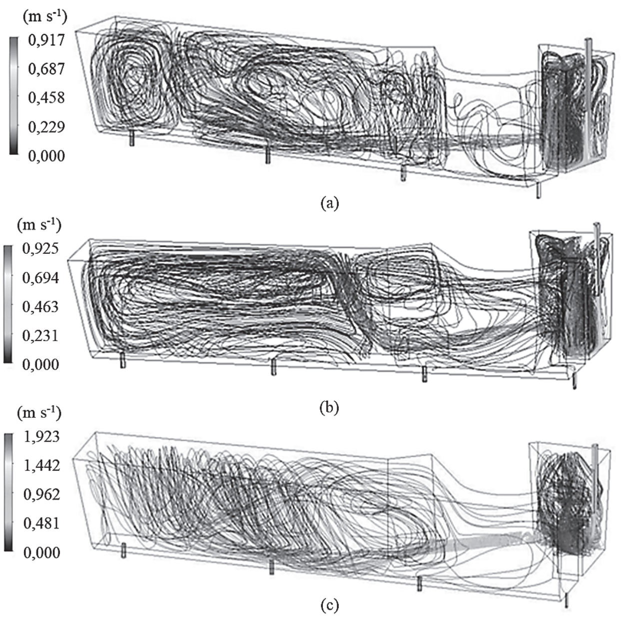

Figure 3 Pathline of molten steel in the tundish (a) without IH, (b) with Joule heating (c) Both electromagnetic force and Joule heating [6]

and heat transfer of molten steel in the channel-type electromagnetic IH tundish is limited.

Figure 3 shows the pathline of molten steel flow through the channels of the tundish with or without induction heating. The induced current in the intermediate channel of the IH and the uneven distribution of the magnetic field causes the Lorentz force of the molten steel to be eccentrically distributed.

The molten steel is subjected to an eccentric Lorentz force, which produces a rotational speed. The molten steel spirals through the channel. When the molten steel flows through the channel, the temperature of the molten steel rises and the floating force generated by the density difference causes the hot molten steel to move upward, prolonging the residence time of the molten steel in the tundish, which is beneficial to the removal of inclusions. Compared with no induction heating, the channel type electromagnetic IH tundish can effectively increase the pathline of molten steel in the tundish, thus improving the average residence time of molten steel.

REMOVAL OF INCLUSION IN IH

The principle of separating inclusions is that the alternating electromagnetic field generates an induced current in the molten metal in the channel, and the induced current interacts with the electromagnetic field to generate an electromagnetic force against the axial center of the metal liquid, thereby generating a pinching effect. A pressure gradient is generated in the fluid to make the force field around the inclusions unbalanced so that the non-metallic inclusion particles in the molten metal move toward the wall of the channels under the action of electromagnetic repulsion and finally adhere to the wall of channel or floatation to remove [13]. The pinch effect schematic diagram is shown in Figure 4. Electromagnetic force has an essential influence on the flow of moving metal liquid. The flow of molten metal has distinct unsteady characteristics [6].

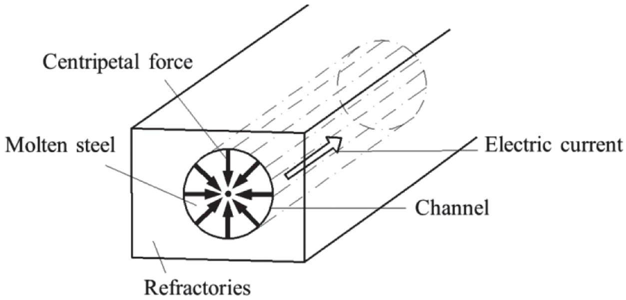

Figure 4 Schematic of the pinch effect of electromagnetic force

Based on the effect of the pinch effect of inclusions in the channel and the separation rate of inclusions, Taniguchi calculated the inclusion removal effect of an IH tundish and found that it was higher than 60 μm. The inclusion separation efficiency is over 95 % [13]. The probability of three collision growth modes of inclusions was investigated in different regions of the tundish under different IH frequencies. It is concluded that the highest probability is turbulent collision modes [10]. Molten steel flow heat transfer and inclusion in the furnace are investigated under the external electromagnetic field. So far, most of the researches have focused on the separation of the molten metal under static conditions of molten steel, and have not considered the influence of Joule heating on the movement and growth of inclusions. The molten metal is static. Actually, the electromagnetic force in the electromagnetic induction tundish channel acts on the flowing molten metal.

Compared with the traditional tundish, the molten steel in the channel type electromagnetic IH tundish has a particular flow and temperature field distribution. Besides, the molten steel which is inductively heated in the channel has a rising flow after the outlet of the channels is ejected, which promotes the inclusions to rise and float to the liquid surface and removed. The industrial application shows that the channel type IH tundish and refining technology can not only adequately compensate the temperature distribution of the molten steel in the tundish to homogenize the temperature distribution, but also significantly reduce the content of inclusions in the steel, especially small particles. The inclusions in molten steel go through the path, increasing the cleanliness of the molten steel [5, 10, 13, 14].

The flow field of molten steel mainly controls the movement of inclusions in the tundish, and heat transfer has an essential influence on the convection of molten steel. It is unreasonable to study the separation behavior of inclusions without considering the molten steel flowing. Most investigation on the separation of inclusions in flowing metal liquids ignores the coupling effect of electromagnetic Joule heating or electromagnetic force. It is not comprehensive to disregard the electromagnetic force or Joule heating in the research process of electromagnetic IH of the molten steel flow field, temperature field, and non-metallic inclusion removal. Therefore, it is necessary to systematically study the influence of the electromagnetic field, Joule heating, and electromagnetic force distribution in the continuous casting tundish and electromagnetic field on the flow of molten steel under the action of IH electromagnetic field.

SUMMARY

Electromagnetic IH tundish is a secondary refining technology developed with continuous casting. It is significant to improve continuous casting productivity and improving the quality of slabs. However, the research on the flow of liquid metal under the action of the electromagnetic field and the migration behavior of non-metallic inclusions in liquid metal still have the following to be considered:

(1) The flow characteristic of molten steel in the channel changes at different flow time, the transient flow feature should be further focused under the action of the electromagnetic field.

(2) Most high-temperature experimental studies usually use molten metal in a high-temperature furnace and then apply an external electromagnetic field to the molten metal and the inclusion particles. The molten metal is quasi-stationary. The effects of the electromagnetic force on the flowing molten metal could not be considered.

(3) The coupling effect of electromagnetic force and Joule heating is still have not demonstrated in the study of liquid metal flow behavior and inclusion migration characteristics.

(4) Due to the lack of experimental data, it is difficult to accurately describe the aggregation and migration characteristics of non-metallic inclusions in the molten metal even by the computational fluid dynamics method in the inclusion removal process. The mechanism of aggregation of inclusions in the IH and adhesion to the wall surface remains to be studied in high-temperature experiments.

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Note: The responsible translator for the English language is Q. Yue, China