Simulating the magnetic field/transfer phenomenon of the tundish with channel type inducting heating

B. Yang¹,², A. Y. Deng¹,²* and E. G. Wang¹,²

¹ Key Laboratory of Electromagnetic Processing of Materials (Ministry of Education), Northeastern University, NO. 3-11, Wenhua Road, Heping District, Shenyang, China
² School of Metallurgy, Northeastern University, NO. 3-11, Wenhua Road, Heping District, Shenyang, China

Abstract
The tundish with channel type inducting heating is usually used to stabilize the superheat of molten steel, and remove the non-metallic inclusions. In order to research the transfer characteristics comprehensively, A mathematical model including electromagnetic field, flow and heat transfer is established to investigate the distribution of magnetic flux density, electromagnetic force (EMF), joule heat, flow and temperature field. The results indicate that the effective area of electromagnetic field mainly contains the channels, moreover, the region near the side walls contacting with channels also belongs to it. Therefore, the EMF generated in this area affects the flow pattern in pouring chamber and distribution chamber, and the pinch force produced in the channels also makes the molten steel rotate strongly. A comparison of flow field between the tundishes with and without induction heating implies that compared with the EMF, the thermal buoyancy has little influence on the flow of molten steel. The joule heat mainly distributes in the channels and accounts for 91.68%. Besides, after the induction heating being applied, the thermal drop can be compensated, and the temperature distribution gets more homogeneous.

Key words: numerical simulation, induction heating, tundish

1. Introduction
The inclusions removal and constant temperature casting with low temperature are two essential and tough issues in continuous casting[3]. The channel-type induction heating tundish inspired by the Marty’s research and the application of induction furnace was developed to deal with the problems.[2] Compared with the traditional tundish, the channel-type induction heating tundish can cleanly and effectively compensate the temperature loss of the molten steel, besides, it is confirmed that is can promote the inclusions removal.

The electromagnetic characteristics of a induction heating furnace or tundish was always obtained by solving the Maxwell’s equations using finite element method.[5, 4] It was found that the inductive current formed loops in the channels and chambers, and the magnetic field is rotational, on cross section, the EMF points to the interior of the channels. These basic phenomenon is also observed in the Vives’s experiment.[10] The flow and temperature field was investigated by solving the Navier-Stokes equations using finite volume method. Jamil I. researched the effect of standard k-ε model, standard k-ω model, SST model and Zero Equation model on the flow pattern in induction heating furnace, and the results showed that there was no obvious difference between them.[9] In the channel type induction heating tundish, the inclusions removal was supposed by the absorption of the channel wall or floating to free surface, and the absorption behavior was forced by the electromagnetic pressure force.[1] However, it is reported that the movement of inclusions is most affected by the flow, namely, the influence of EMF on the movement of inclusions is very limited.[8] Besides,The previous works mostly concerned what happened in the channels, the phenomenon occurred in the chambers was ignored. Therefore, in order to promote the inclusions removal, it is essential to figure out the electromagnetic characteristics, flow and temperature distribution in the whole tundish, which have a non-negligible effect on the movement of inclusions.

In present work, based on the commercial software of ANSYS APDL and CFX, a mathematical model containing magnetic field, flow and heat transfer is established to gain a deep insight into the channel type induction heating tundish. The electromagnetic field distribution features, the flow and heat transfer behaviors in the tundish are qualitatively and quantitatively presented.

2. Mathematical model
The following assumptions are made to simplify the numerical model: (1) The molten steel is an incompressible continuous Newton fluid, and the physical properties are constant with temperature; (2) The slag layer is not modeled, thus, the effect of slag on the molten steel is neglected; (3) The displacement current is negligible. The electromagnetic mathematical model is based on the Maxwell’s equations and the constitutive equations.[9, 10] The Navier-Stokes equations and standard k-ε model are employed to obtain the flow and temperature field[11, 12]
Single-phase alternating current of 50Hz is applied on the induction coil, and the magnetic field intensity is regarded as zero at infinity when simulating the magnetic field. In the fluid and heat transfer model, uniform velocity calculated by the steel flux balance is applied at the inlet of the tundish, the temperature here is supposed as constant at 1748K. The surfaces of molten steel and the walls are set as free slip wall and no-slip wall, respectively. A pressure outlet is applied. According to the Sahai’s research\cite{13}, the heat flux at the free surface, the bottom, the longitudinal walls, the transversal walls, and the channel walls are 15 kW/m², 1.8 kW/m², 4.6 kW/m², 4.0 kW/m², and 0.2 kW/m², respectively. Other simulation parameters are listed in Table 1.

### Table 1 The simulation parameters

| Parameter                        | Value  | Parameter                        | Value  |
|----------------------------------|--------|----------------------------------|--------|
| Conductivity of molten steel (S m⁻¹) | 7.14×10⁴ | Thermal expansivity (K⁻¹) | 1×10⁻⁴ |
| Relative permeability of molten steel | 1      | Length of tundish (m)             | 5      |
| Density of molten steel (kg m⁻³) | 7100   | Width of tundish (m)              | 1.5    |
| Viscosity of molten steel (Pa s)  | 6.2×10⁻⁴ | Depth of melt (m)                | 1      |
| Specific heat of molten steel (J kg⁻¹ K⁻¹) | 680 | Diameter of the channel (m)      | 0.115  |
| Thermal conductivity (W m⁻¹ K⁻¹) | 30     | Outlet diameter (m)              | 0.07   |

The electromagnetic characteristics and hydrodynamic problem are individually calculated by using the software ANSYS APDL and CFX. The coordinate system and geometric model are illustrated in Fig. 1, and the parameters of the tundish are also listed in Table 1.

3. Results and discussion

In this section, the distribution of magnetic induction intensity, EMF, joule heat, flow and temperature field is depicted in details at the heating power of 800 kW. The results are mainly revealed on some specific planes, for showing results in 3-D is too complicated to be understood clearly. Fig. 2 displays the planes where we will show the results. Plane 1 lies in the plane where the central axes of the two channels lie. Plane 2 is located on the center vertical section of the left channel. Plane 3 and Plane 4 are located on the center cross section and outlet of the channels, respectively.

The distribution of magnetic induction intensity is shown in Fig. 3. It can be seen that the magnetic induction intensity mainly distributes in the channels, in the two chambers, its value near the wall connected with the channels is significantly larger than that within other region. We also obtain the effective region of the magnetic field through two dimensionless numbers $H_a$ and $N$, which can reflect the influence of EMF on the flow of molten steel with respect to shear and inertia force, respectively. In general, when the values of the two dimensionless numbers are smaller than 0.01, the influence of EMF can be omitted. When they reach the value of 1, the driving effect of EMF will be equivalent to that of the other two forces, and the EMF will significantly affect the molten steel on condition that the dimensionless numbers reach the value of 0.1. Consequently, compared with the shear force, the EMF has a significant impact on the flow over the entire tundish; compared with the inertial force, the EMF will show notably effect on the molten steel as long as the electromagnetic induction intensity reaches the value of 0.01T. Therefore, it can be seen in Fig. 3 that the effective area of magnetic field consists of the channels and the area near the walls connected with the
channels.
The spatial EMF distribution should be consistent with that of the magnetic field, for it is generated by the interaction of the induced current and the magnetic field. Now, we focus on the EMF distribution within the marked regions in Fig. 3. It can be seen in Fig.4 that compared with the force near the joints of the channels and chambers, the force near the wall is smaller and points to the interior of the chambers, moreover, its direction is almost perpendicular to the Y-Z plane, which will push the molten steel there away from the walls. The force around the inlet and outlet of the channels is almost equivalent to that in the channels, and it also points to the inside of the chambers from the mouth of the channels, moreover, there is also some pinch effect to some extent. This complicated situation will strongly change the flow pattern and we will reveal it in later segments. It also can be seen that the EMF next to the upper edge is larger than that close by the lower edge. This phenomenon can be illustrated by Fig. 5 clearly. Compared with the EMF distribution on the center cross section (see Fig.5(a)), it is no longer symmetrical with regard to the Z direction at the exit of the channels (see Fig. 5(b)), and the force within the upper region is significantly larger, which will force the molten steel to flow downwards.

![Fig. 5 The EMF distribution on different planes](image)

As can be seen in Fig. 6, the joule heat mainly distributes in the channels, and the proportion in the receiving chamber, channels, and distributing chamber is 4.47%, 91.68%, and 3.85%, respectively. The joule heat is evenly distributed along the axis of the channel, and it decreases gradually from the side near by the coil to the other side, which may give out implications for optimizing the channel structure to increase heating efficiency.

The temperature and flow variation against time in the tundish without the use of induction heating is shown in the Fig. 7 and Fig. 8. It can be seen that the temperature field in the receiving chamber is steady, and it gradually drops in the distributing chamber. The temperature drops to 1742K-1745K, and part of the molten steel rushing out from the channels directly flows to the outlet of the tundish at the time of 150s and 300s. The reason for this phenomenon is that the thermal buoyancy force associated with the temperature gradient is too small to conquer the effect of inertia force on the flow. From the time of 300s to 1500s, the temperature in the distributing chamber declines to 1739K-1744K, and the short-circuit flow is gently replaced by an upstream flow because of the improvement of the temperature difference.

![Fig. 7 The change of temperature field against time in the tundish without induction heating](image)

The Fig. 9 and Fig. 10 shows the temperature and flow variation against time in the tundish with the use of induction heating. It can be clearly seen that the molten steel is continuously heated from 1749K to 1781K in the channels at the power of 800kW, and an adequate mixture between the heated molten steel and that in the distributing chamber promotes the temperature there from 1752K to 1777K. The flow field in the distributing chamber consists of a huge swirl and a small one located below the exit of the channels, and it does not change with time. Besides, several changes are notable. The molten steel forms dramatically secondary flow near the inlet of the channels in the receiving chamber, which means that part of the molten steel near the inlet of the channels is pushed away from there and generates two huge vortices on both sides of the receiving chamber. The molten steel can not timely ascend in the distributing chamber and it appears a downward trend compared with the situation that the induction heating is not
applied. This is an undesirable situation for boosting the removal of the inclusions in general. There are two reasons account for this phenomenon. One of them is that the velocity of the molten steel is accelerated when it flows through the channels; another one is that the EMF pointing downwards near the exit of the channels is larger than that pointing upwards, which forces the molten steel to flow downwards at the outlet of the channels. This circumstance implies that the EMF and inertia force dominate the flow of the molten steel. Stable flow and homogeneous temperature field in the distributing chamber are the key element to maintain the quality of steel. After the induction heating is applied, the flow field is significantly stabilized and the temperature difference in the distributing chamber is reduced from 5K to 1K.

Fig. 9 The change of temperature field against time in the tundish with induction heating
(a) 150s (b) 300s (c) 780s (d) 1500s

Fig. 10 The change of flow field against time in the tundish without induction heating
(a) 150s (b) 300s (c) 780s (d) 1500s

4. Conclusions
This work lays a foundation for researching the inclusions removal and optimizing the structure of channel type induction heating tundish in future by investigating the electromagnetic features, flow and temperature field in details. The important conclusions are summarized as follows: The magnetic field mainly distributes in the channels and the areas near the walls connected with the channels. The EMF located in the chambers is directed from the wall connected with the channels to the interior, which stabilizes the flow in the two chambers as a huge swirl flow. Compared with the EMF and inertia force, the thermal buoyancy force has a limited effect on the flow.

Acknowledgment
This work was supported by National Natural Science Foundation of China (51474065, 51574083), the Doctoral Scientific Research Foundation of Liaoning Province of China (20141008), and the Program of Introducing Talents of Discipline to Universities of China (B07015).

References
1. Y. Sahai, Metallurgical and Materials Transactions B. 47 (2016), 2095-2106.
2. P. Marty and A. Alemany, Metallurgical Applications of Magnetohydrodynamics. (1982), 245-259.
3. A.A. Alferenok and A.B. Kuvaldin, Russian Metallurgy (Metally). (2009), 741-747.
4. Q. Wang, B.K. Li and F. Tsukihashi, ISIJ International. 54 (2014), 311-320.
5. C. Vives and R. Ricou, Metallurgical and Materials Transactions B. 22 (1991), 193-209.
6. J.I. Ghojel, Progress in Computational Fluid Dynamics, an International Journal. 6 (2006), 435-445.
7. Q. Wang, F.S. Qu, B.K. Li and F. Tsukihashi, ISIJ International. 54 (2014), 2796-2805.
8. S. Pavlovs, A. Jakovics, E. Baake and B. Nacke, Proceeding of international conference on clean steel, City, 2012.
9. Y. Li, A.Y. Deng, H. Li, B. Yang and E.G. Wang, Metals. 8 (2018), 76-95.
10. F. Felten, Y. Fautrelle, Y. Du Terrail and O. Metais, Applied Mathematic Modelling. 28 (2004), 15-27.
11. B. E. Launder and D. B. Spalding, Computer Methods in Applied Mechanics and Engineering. 3 (1974), 269-289.
12. K. Hanjalić and S. Kenjereš, Flow, turbulence and combustion. 66 (2001), 427-451.
13. S. Chakraborty and Y. Sahai, ISIJ International. 31 (1991), 960-967.