Numerical investigation of electromagnetic brake effect on macroscopic transport behavior in a given tundish

Feng Zhu¹,a, Jixiang Gao²,b, Liejun Li³,c, Songjun Chen⁴,d, Haibo Sun¹,e,*

¹School of Materials Science and Hydrogen Energy, Foshan University, Foshan 528000, China
²Guangdong Polytechnic Normal University, Guangzhou 510640, China
³Guangdong Key Laboratory for Advanced Metallic Materials Processing, South China University of Technology, Guangzhou, 510640, China
⁴784204871@qq.com, b;gjx205@163.com, c;iliejun@scut.edu.cn, djasonchensj@163.com, esunmyseven@fosu.edu.cn
*Corresponding author: sunmyseven@fosu.edu.cn

Abstract. The macroscopic transport behavior inside the tundish simultaneously adopting electromagnetic weir and dam were investigated via a 3D computational fluid dynamics modeling. Results showed that the flow pattern of molten steel can be effectively controlled by local electromagnetic brake force to replace the conventional weir and dam made of refractory in the given tundish. The increases of magnetic intensities for both the electromagnetic weir and dam within the range of 0.05~0.35 T are conductive to the reduction of dead volume fraction and the increases of plug volume fraction and residence time of molten steel in the tundish. The recommended values of magnetic intensities in both the electromagnetic weir and dam zones are 0.3 T owing to that the changes for all RTD characteristics tend to moderate when further increasing the magnetic intensity. This work will provide a pertinent advice on designing electromagnetic weir and dam for the tundish to gain a desire flow pattern without physical flow control devices.

1. Introduction
Tundish is a key metallurgical vessel that acts as a buffer and distributor to hold and allocate molten steel in a desired steel flow rate to the mould(s)¹², so as to allow sequence casting when a ladle exchange occurs during continuous casting process³⁴. Flow control devices (FCD), including turbulent inhibitor, weir, and dam, etc, were frequently used to control melt flow pattern inside the tundish to promote flotation removal of inclusion by increasing residence time of molten steel in the tundish, and to prevent slag entrapment and re-oxidation of molten steel by reducing the turbulent of incoming stream from ladle shroud⁴⁵. However, they are normally made of refractory, thus resulting in a reduction of effective volume of tundish. Moreover, the continuous corrosion damage of the traditional refractory FCD owing to the combined effects of chemical reactions, thermomechanical stress and molten steel flow erosion⁶⁷ during casting process will cause the increase of large-size inclusion content in molten steel⁸. 

Electromagnetic force is an effective and non-contact mean to control the flow pattern of molten steel in the tundish¹⁰. Wang et al¹¹ investigated the flow characteristic in a centrifugal flow tundish by water modeling and numerical simulation techniques, in which the molten steel is horizontally
rotated by electromagnetic force. Tripathi [12] put forward using electromagnetic dam as a flow modifier in the tundish, and investigated the electromagnetic flow control phenomenon in the tundish different combinations of electromagnetic dams via a magnetohydrodynamics model.

In this work, the macroscopic transport behavior in the tundish using electromagnetic braking zones with different magnetic intensities to replace the physical weir and dam were systematically investigated based on a developed 3D computational fluid dynamics modeling. And then, the reasonable magnitude of magnetic intensity for the electromagnetic braking zone could be obtained by analyzing the residence time distribution (RTD) characteristics of molten steel in the tundish. This work will offer a referable idea for using electromagnetic braking force to gain optimal flow pattern in the tundish.

2. Model description

The melt flow, heat transfer and electromagnetic force in the tundish were simulated by solving the continuity, momentum, heat transfer, and Maxwell equations under turbulent conditions. To obtain the RTD characteristics of molten steel in the tundish, the real-time tracer concentration in mass-fraction units is solved by the species transport equation. The details of the model equation are given by previous studies of authors [2,13]. Based on the computed results, the RTD characteristics can be calculated according to the Table 1, wherein \( C_t \) is average concentration of tracer from outlet at time \( t \).

| RTD characteristics | Symbols | Expressions |
|---------------------|---------|-------------|
| Theoretical residence time, s | \( t_r \) | Tundish capacity / volumetric flow rate = 961.34 s |
| Actual mean residence time, s | \( t_m \) | \( t_m = \frac{\sum C_t \cdot t \cdot \Delta t}{\sum C_t \cdot \Delta t} \) |
| Minimum residence time, s | \( t_{\min} \) | Time of the first appearance concentration of tracer |
| Peak time, s | \( t_{\text{peak}} \) | Time of attain peak concentration of tracer |
| Fraction of plug volume | \( V_{\text{PV}} \) | \( V_{\text{PV}} = \frac{t_{\min} + t_{\text{peak}}}{2t_r} \) |
| Fraction of dead volume | \( V_{\text{DV}} \) | \( V_{\text{DV}} = 1 - \frac{t_r}{t_r} \) |
| Fraction of mixed volume | \( V_{\text{MV}} \) | \( V_{\text{MV}} = 1 - V_{\text{PV}} - V_{\text{DV}} \) |
| Dimensionless time | / | Real time \((t)/t_r\) |
| Dimensionless concentration | / | Real-time monitoring concentration / actual mean concentration |

Fig.1 displays the geometrical dimension for the given tundish with the flow control devices including a turbulence inhibitor, a weir, a dam and a stopper rod. To replace the weir and dam made of refractory, the regions of applied static magnetic fields are set with the same position and size as these of the weir and dam in the tundish. Fig.2 shows the mesh for the computational domain for the tundish with normal refractory and electromagnetic flow control devices, respectively. Hereinto, only a half of the full tundish was simulated in the model due to its symmetrical feature. Table 2 lists the physical properties of the molten steel and operation conditions employed in the numerical models.

For the boundary conditions for this model, a fixed temperature of 1786 K and a constant velocity \( (v_{in}) \) of 1.458 m/s were set at the inlet, wherein the corresponding turbulent parameters \( k \) and \( \varepsilon \) were calculated by the formula \( k = 0.01 v_{in}^2 \) and \( \varepsilon = 2 \times 10^{3}/D_{\text{nozzle}} \), and the \( D_{\text{nozzle}} \) was the inner diameter of the shroud. Frictionless condition at the free surface and a pressure of 1 atm at the outlet were used. Non-slip and standard wall function was employed for all walls in the tundish. Zero normal gradients of all variables normal to plane was set at the symmetry plane. For the heat transfer models, the
recommended values of 15, 1.4, 3.2, and 3.8 kW·m⁻² were employed for the free surface, bottom, vertical walls, and transverse walls in the tundish respectively.

Based on the conditions above, the numerical investigation in this work was carried out on the basis of a computational fluid dynamics code ANSYS Fluent 17.0. Hereinto, the PISO algorithm was chosen for the velocity iterations and the PRESTO for pressure during iterative calculation of the coupled model by Fluent code. The criterion for convergence was established when the calculated enthalpy residual should be less than 10⁻⁶ and the other item convergence limit is 10⁻⁴.

3. Results and discussion
To replace the given weir made of refractory by electromagnetic weir and generate a desired flow pattern in the tundish, a reasonable magnitude of magnetic intensity (Bw) for the electromagnetic weir should be investigated first. Fig.3 shows the simulated flow patterns and temperature fields of molten steel at the symmetrical vertical planes of the tundish using electromagnetic weir with magnetic intensity in the range of 0.05~0.35T. When the Bw is only 0.05T, the horizontal flow at the tundish upper part can easily cross the area of electromagnetic weir owing to the relatively small electromagnetic braking force of 5.85N/m³, which may cause the occurrence of short circuit flow in the tundish. As the Bw increase up to 0.20T, a vortex flow within clockwise direction begins to appear at upstream side of the electromagnetic weir, however, part of surface horizontal flow can still cross the area of electromagnetic weir. Under these situations above, as shown in Fig.3(a~c), the upwelling with relatively small momentum at the downstream of the electromagnetic weir will preferentially flow to the outlet of tundish after climbing the refractory dam, thus causing that a low-temperature region appears at the downstream of stopper rod. With the further raising Bw larger than 0.3T, as seen from Fig.3(e~f), the electromagnetic weir with the maximum magnetic braking force greater than 26.68N/m³ can cut off the local horizontal flow near free surface. Instead, two vortex flows within...
opposite directions separately present at upstream and downstream sides of the electromagnetic weir. Moreover, the upwelling with relatively high momentum at the downstream of the electromagnetic weir can contribute to the generation of horizontal flow near free surface after climbing the refractory dam. And then, a large-scale vortex flow forms at the downstream side of refractory dam under the restrictions from the combinations of stopper rod, dam, and bottom wall of the tundish.

Fig. 3 Flow patterns and temperature fields of molten steel at symmetrical vertical planes of tundish using electromagnetic weir with different magnetic intensities ($B_w$), a) $B_w=0.05$ T, b) $B_w=0.15$ T, c) $B_w=0.20$ T, d) $B_w=0.25$ T, e) $B_w=0.30$ T, f) $B_w=0.35$ T

Fig.4 gives the predicted RTD curves, $V_{pv}$, and $V_{dv}$ for the tundish using electromagnetic weir under different magnetic intensities. As seen from Fig.4(a), the shift in peak concentration towards to the center, while the dimensionless concentration for the peak of RTD curve gradually fall back with the elevating $B_w$. Hereinto, the dimensionless time for the peak concentration increases from 0.268 to 0.478, while the corresponding dimensionless concentration decreases from 1.48 to 0.99 as the $B_w$ increases from 0.05 T to 0.35 T. These results in RTD curves indicate that the increase in $B_w$ is beneficial to the decrease of $V_{dv}$ [14]. It is seen from Fig.4(b) that the value of $V_{dv}$ reduces from 29.55% to 16.12% when the $B_w$ increases from 0.05 T to 0.35 T, while the corresponding $V_{pv}$ increases from 21.24% to 34.45%. The detailed RTD characteristics and the maximum applied electromagnetic braking forces ($F_{em}$) in the weir region for all the cases in Fig.4 can be seen from Table 3. Moreover, it is also observed that, when the $B_w$ is greater than 0.3 T, the changes for all the RTD characteristics tend to moderate. Based on the discussion above, it is concluded that the recommended magnitude of $B_w$ for the electromagnetic weir is 0.3 T.

Fig. 4 Predicted RTD curves (a), plug and dead flow fractions (b) for the tundish using electromagnetic weir with different magnitudes of $B_w$. 
Table 3 RTD characteristics and the maximum applied electromagnetic braking forces for the tundish using electromagnetic weir with different magnetic intensities

| Case | $B_w$, T | $t_{mv}$, s | $t_{min}$, s | $t_{peak}$, s | $V_{pv}$, % | $V_{mv}$, % | $V_{dv}$, % | $F_{em}$, N/m³ |
|------|----------|-------------|-------------|-------------|------------|------------|------------|-------------|
| 1    | 0.05     | 677.24      | 150.83      | 257.45      | 21.24      | 49.21      | 29.55      | 5.85        |
| 2    | 0.15     | 699.35      | 172.08      | 328.78      | 26.05      | 46.70      | 27.25      | 13.22       |
| 3    | 0.2      | 731.59      | 175.35      | 377.81      | 28.77      | 47.33      | 23.90      | 17.52       |
| 4    | 0.25     | 738.95      | 186.50      | 380.69      | 29.50      | 47.37      | 23.13      | 21.18       |
| 5    | 0.3      | 802.57      | 191.98      | 455.68      | 33.69      | 49.80      | 16.52      | 26.68       |
| 6    | 0.35     | 806.36      | 202.84      | 459.52      | 34.45      | 49.43      | 16.12      | 30.37       |

To simultaneously replace the dam and weir made of refractory by electromagnetic braking region in the tundish, based the case 5 above, Fig.5 presents the simulated flow patterns and temperature fields of molten steel at the symmetrical vertical planes of the tundish using electromagnetic dam with magnetic intensity ($B_d$) in the range of 0.20~0.35T under a fixed intensity of 0.30T for electromagnetic weir. As the $B_d$ is less than 0.25T, part of the horizontal flow at tundish bottom climbs up the electromagnetic dam zone to form an upwelling pointing to the free surface under the electromagnetic braking effect. Meanwhile, however, part of the horizontal flow at tundish bottom can flow through the electromagnetic dam zone due to the relatively low electromagnetic braking force of 21.04N/m³. With further elevating the $B_d$ greater than 0.3T, all the horizontal flow at tundish bottom can climb over the electromagnetic dam zone. And then, two backflows in opposite directions appear at the downstream side of electromagnetic dam, which is conductive to further prolonging the residence time of molten steel in the tundish, thus promoting the growth and floatation removal of inclusions as compared to the single backflow when adopting the normal refractory dam as shown in Fig.3.

Fig. 5 Melt flow patterns and temperature fields at the symmetrical vertical planes of tundish using electromagnetic dam with different magnetic intensities under $B_w = 0.30$ T

Fig.6 gives the predicted RTD curves, $V_{pv}$, and $V_{dv}$ for the tundish using electromagnetic dam with different magnetic intensities ($B_d$) under a fixed intensity of 0.30T for electromagnetic weir. Table 4 lists the detailed RTD characteristics for all the cases in Fig.5. When the $B_d$ increases from 0.20 T to 0.35 T, the dimensionless time for the peak concentration increases from 0.367 to 0.479, while the corresponding dimensionless concentration decreases from 1.14 to 0.97. Combined with the results in Table 4, it is seen that the increase in $B_d$ is beneficial to the decrease of $V_{dv}$ under $B_w =0.3$ T. As seen from Fig. 6(b), the value of $V_{dv}$ reduces from 25.14% to 16.12% when the $B_d$ increases from 0.20 T to 0.35 T, while the corresponding $V_{pv}$ increases from 26.25% to 34.55%. Moreover, it is also seen that, as compared to the case 5, a relatively lower $V_{dv}$ of 16.12% with a higher $V_{pv}$ of 32.70% can be obtained under the case 9, which should be attributed to the two backflows in opposite directions at the downstream side of electromagnetic dam. Moreover, when the $B_d$ is greater than 0.3 T under $B_w =0.3$ T, the changes for all the RTD characteristics tend to moderate. Therefore, the recommended values of magnetic intensities in both the electromagnetic weir and dam zones are 0.3 T for the given tundish.
4. Conclusion
The influence of electromagnetic brake effect on the fluid flow and heat transfer of molten steel in the tundish has been investigated through numerical modelling. The main conclusions are summarized as follows.

1) As the magnetic intensity is larger than 0.3 T, the electromagnetic brake area with relatively high electromagnetic force greater than 26.68 N/m² can cut off the local horizontal flow, which is similar to the flow control role of refractory weir and dam in the tundish.

2) For the tundish only using electromagnetic weir, as the $B_w$ increases from 0.05 T to 0.35 T, the value of $V_{dv}$ reduces from 29.55% to 16.12%, while the corresponding $V_{pv}$ and $t_m$ increase from 21.24% to 34.45% and from 677.24 to 806.36 s owing to the increase of the $F_{ew}$ in the electromagnetic weir region from 5.85 to 30.37 N/m³.

3) For the tundish adopting both the electromagnetic weir and dam, the value of $V_{dv}$ reduces from 25.14% to 16.12%, while the corresponding $V_{pv}$ and $t_m$ increase from 26.25% to 34.55% and from 719.69 to 807.42 s, when the $B_d$ increases from 0.20 T to 0.35 T under the $B_w = 0.30$ T.

4) As compared to the tundish equipped with refractory weir and dam, a relatively lower $V_{dv}$ of 16.12% with a higher $V_{pv}$ of 32.70% can be obtained under the case of the tundish using electromagnetic weir and dam with $B_w = B_d = 0.30$ T, which is attributed to the two backflows in opposite directions at the downstream side of electromagnetic dam.

Acknowledgements
This research was funded by the Natural Science Fund of Guangdong Province (Grant No. 2021A1515011796), Guangdong Province Key Project of Foundation and Application Foundation Research Joint Fund (Grant No. 2019B1515120020), Guangzhou Science and Technology Planning Project (Grant No. 202103000013) and Foshan Key Technology Tackling Program (Grant No. 1920001001392).
References
[1] Cwudziński A., Jowsa J., Gajda B. (2020) Physical simulations of macromixing conditions in one strand tundish during unsteady period of continuous slab casting sequence. Steel Res. Inter., 91: 2000027.
[2] Sun H.B., Zhang J.Q. (2014) Effect of actual cooling rate of ladle stream on the persistent metallurgical performance of a given tundish. J. Iron. Steel. Res. Int., 21: 915-922.
[3] Zhang H., Fang Q., Luo R., Liu C., Wang Y., Ni H. (2019) Effect of ladle changeover condition on transient three-phase flow in a five-strand bloom casting tundish. Metall. Mater. Trans. B, 50:1461-1475.
[4] Dipak M. (2019) Review, analysis, and modeling of continuous casting tundish systems. Steel Res. Inter., 90:1800279.
[5] Jrdsr A., Eebds A., Fm A., Jade B. (2019) Modeling and computational simulation of fluid flow, heat transfer and inclusions trajectories in a tundish of a steel continuous casting machine. J. Mater. Res. Technol., 8: 4209-4220.
[6] Andreev K., Harmuth H. (2003) FEM simulation of the thermo-mechanical behaviour and failure of refractories-a case study. J. Mater. Process. Tech., 143: 72-77.
[7] Singh V., Pal A.R., Panigrahi P. (2008) Numerical simulation of flow-induced wall shear stress to study a curved shape billet caster tundish design. ISIJ Inter., 48: 430-437.
[8] Yang B., Hong L., Qian B., Xiao Y., Yan Z. (2018) Numerical simulation of collision-coalescence and removal of inclusions in a tundish. JOM, 70: 2950-2957.
[9] Wang Q., Tan C., Huang A., Yan W., Gu H. (2021) Numerical simulation on refractory wear and inclusion formation in continuous casting tundish. Metall. Mater. Trans. B, 52:1-13.
[10] Xing F., Zheng S., Zhu M. (2018) Motion and removal of inclusions in new induction heating tundish. Steel Res. Inter., 89: 1700542.
[11] Wang Y., Zhong Y., Wang B., Lei Z., Ren W., Ren Z. (2009) Numerical and experimental analysis of flow phenomenon in centrifugal flow tundish. ISIJ Inter., 49:1542-1550.
[12] Tripathi A. (2012) Numerical investigation of electro-magnetic flow control phenomenon in a tundish. ISIJ Inter., 52: 447-456.
[13] Sun H.B., Zhang J.Q. (2014) Macrosegregation improvement by swirling flow nozzle for bloom continuous casting[J]. Metall. Mater. Trans. B, 45: 936-946.
[14] Chakraborty S., Sahai Y. (1991) Effect of varying ladle stream temperature on the melt flow and heat transfer in continuous casting tundishes, ISIJ Int., 31: 960-967.