

Electromagnetic Devices for Continuous Steel Casting Tundishes

Rajneesh Chaudhary, K. Ravi Kumar, Martin Seden, Bengt Rydholm, Jan-Erik A. Eriksson, Hongliang Yang

▶ **To cite this version:**

Rajneesh Chaudhary, K. Ravi Kumar, Martin Seden, Bengt Rydholm, Jan-Erik A. Eriksson, et al.. Electromagnetic Devices for Continuous Steel Casting Tundishes. 8th International Conference on Electromagnetic Processing of Materials, Oct 2015, Cannes, France. hal-01334849

HAL Id: hal-01334849
https://hal.science/hal-01334849

Submitted on 21 Jun 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Electromagnetic Devices for Continuous Steel Casting Tundishes

Rajneesh Chaudhary[1a], K. Ravi Kumar[1b], Martin Seden[2a], Bengt Rydholm[2b], Jan-Erik A. Eriksson[2c], Hongliang Yang[2d]

[1] ABB Corporate Research Center, Bangalore, India.

[2] CoE Metallurgy Products, Process Automation-Industry Solutions, Sweden.

Corresponding author: ravikumar.kandasamy@in.abb.com

Abstract

Electromagnetic (EM) devices such as electromagnetic stirrer (EMS) and brake (EMBR) are extensively being used in steel industry across various processes in furnaces, ladles and casters. The application of EM devices in tundish is not well known despite the fact that tundish offers huge potential to improve steel cleanliness and overall melt quality, due to the availability of large surface area, before the melt is solidified in the mold. This article focuses on to develop EMS and EMBR for tundishes by way of quantifying their benefits in the process. For slab casting, a "T" shape two strand tundish is considered and for billet casting a "V" shape six strand tundish is considered for the analysis.

Simulations of various combination of EMS and EMBR configurations are carried out for both two and six strand tundish to obtain better fluid flow characteristics, melt thermal homogenization and steel cleanliness. EM devices when used in tundishes influence the melt to reduce the temperature variations from around 15-17K to 5-7K besides avoiding short circuiting, compositional segregation with better control on strand(s) temperature while significantly improving inclusion floatation to produce cleaner steel. A surface heater canbe included in the tundish along with EM device to maintain strand(s) temperature at desired level while achieving optimum superheat to cast better quality steel and avoiding nozzle freezing.

Key words: Electromagnetic stirrer (EMS); Electromagnetic brake (EMBR); Temperature homogenization; inclusion removal; tundish heater

Introduction

Continuous casting of steel is time and energy intensive process and requires precise control to improve the steel quality and cleanliness. In continuous casting process,the melt flows from ladle to tundish and finally to caster loses heat throughout the path and also fromvarious vessels.Tundish gets molten steel (at ~1600^{o}C) from ladle in a batch wise process while supplying the same continuously to the caster. Tundish plays an important role in maintaining desired melt flow pattern and thermal homogenization at required melt temperature with desired steel cleanliness. As a current practice, the flow and temperature distribution in tundish are typically controlled with the help of physical tundish furniture such as dam, weir, turbulence inhibitor and impact pads [1]. Though tundish furniture is beneficial for melt flow and temperature distribution but limited to the extent of their effects on the flow characteristics and overall tundish operation.In order to improve flow characteristics, thermal uniformity, the efficient use of electromagnetic devices such as electromagnetic stirring (EMS) / braking (EMBR) is essential leading to the benefits in terms of steel quality and overall process efficiency. Besides, the number of non-metallic inclusions which are generated along the process have the potential to be efficiently removed in tundish with the help of EMS and EMBR due to the availability of large surface area which is typically missing in the caster. In this article, effect of EMS and EMBR devices on fluid flow and temperature distribution along with the tundish heater for their benefits are analyzed for slab and billet casting applications.

Modeling of Electromagnetic Tundish

Slab and Billet Casting Tundish

The slab and billet casting tundish are modeled to analyze the benefits of EMS, EMBR and tundish heater in terms of temperature homogenization, melt outlet temperature and fluid flow distribution. For slab casting, two strand "T" shaped tundish is considered and for billet casting, six strand "V" shape tundish is considered and are shown in Figure 1 and 2 respectively. More details on dimensions of two and six strand tundish and thermo-physical properties of steel used for the analysis can be found elsewhere [2-3].

Computational Model

The governing equations for the coupled flow-thermal-electromagnetic field are given in the following sub sections. The electromagnetic equations are solved in Opera/ELEKTRA for electromagnetic forces and magnetic fields which are then imported in FLUENT to model their influence on the flow-thermal phenomena in the tundish [4-5].

Modeling of Electromagnetic Field

Under quasi-static limit, Maxwell's equations are solved along with Ohm's law and total Lorentz force (combined EMS and EMBr) may be written as follows:

$$\vec{F}_{Lorentz} = \vec{J} \times \vec{B} \qquad (1)$$

where $\vec{J}$ is the induced electric current and $\vec{B}$ is magnetic flux density.

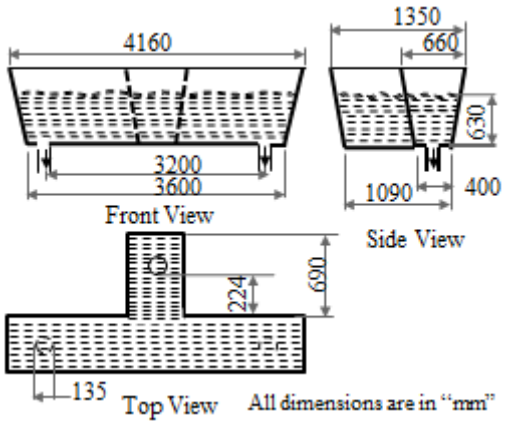


Figure 1 Schematic of two strand tundish

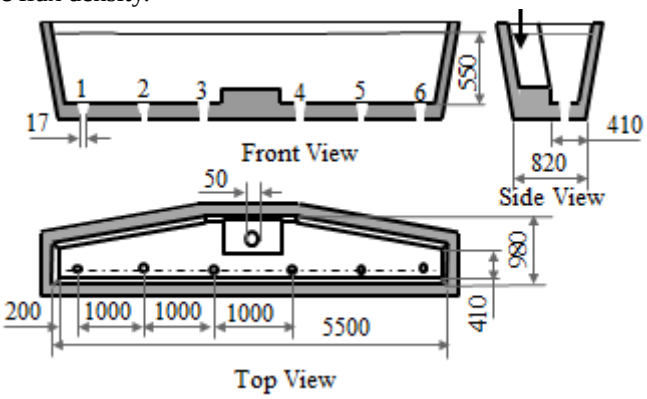


Figure 2 Schematic of six strand tundish

Flow-Thermal Model

The flow-thermal physics is governed by x-, y- and z- momentum, continuity and energy equations [5].
The continuity equation for incompressible flow is given as:

$$\nabla \cdot \vec{V} = 0 \qquad (2)$$

The transient momentum equations (x-, y- and z-) in vector form can be written as:

$$\frac{\partial(\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V}\vec{V}) = -\nabla P + \nabla \cdot (\mu + \mu_t)(\nabla \vec{V} + \nabla \vec{V}^T) + \vec{F_B} + \vec{F}_{Lorentz} \qquad (3)$$

where ρ is the fluid density (kg/m^3), μ is the dynamic viscosity (N-s/m^2), $\vec{V}$ is the velocity vector (m/s), P is the pressure (N/m^2), $\vec{F}_{Lorentz}$ is the total Lorentz force generated by EMS and EMBR, μ_t is the eddy or turbulent viscosity (N-s/m^2). In this model, the density is assumed constant except its variation with temperature whose effect has been incorporated in the momentum equation through Boussinesq approximation as defined via $\vec{F_B}$.

To maintain conservation of energy in the domain, an energy equation is also solved along with continuity and momentum equations to complete the flow-thermal part of the model. The scalar energy equation is given as:

$$\frac{\partial(\rho C_p T)}{\partial t} + \nabla \cdot (\rho C_p \vec{V} T) = \nabla \cdot \lambda(\nabla T) + \dot{q} \qquad (4)$$

where T is the temperature (K), λ is the thermal conductivity (W/m K), C_p is the specific heat (J/kg-K) and $\dot{q}$ is the volumetric heat generation (W/m^3) such as induction heating etc.

Boundary Conditions

The inlet velocity for two and six strand tundish for steady state operation is considered as 0.23 m/s and 2.2 m/s respectively. The inlet temperature of melt for steady operation is considered as 1873 K and 1823 K respectively for two and six strand tundish. A zero pressureoutlet boundary condition (=0 Pa) is used at all the outlets. All the side, bottom and walls are subjected to typical constant heat flux boundary conditions and can be found in elsewhere [3].

Validation

The developed computational model and numerical methodologies are validated to capture various physics in the tundish to make sure model captures the desired physics. The turbulent flow and thermal parts of the model are validated with the work of Damle and Sahai [6]. To validate electromagnetic brake, a Hartmann flow is simulated and compared with the analytical solutions of Bershader and Landshoff [7]. The model predictions for electromagnetic stirring in a box shape domain are compared with the experimental and numerical works of Dubke et al. [8] and Felten et al. [9]. Validation results are not reported here due to restriction ofmanuscript length and these results are report by Kumar and Chaudhary [10]. Overall, the present numerical methodology seems to be very well capturing physics associated with flow, thermal and electromagnetics aspects needed to model the effect of electromagnetic devices in tundishes.

Results and Discussion

In this section, effect of EM devices on flow and temperature distributions and inclusions removal are compared for with and without EM devices for two and six strand tundish. The benefits of plasma heater are also quantified for the two strand tundish. A special configuration of EMS is used for tundish modeling. In case of two strand tundish, EMS is

placed along the longer arm of the tundish and in case of six strand tundish, EMS is placed along the straight side of the tundish.EMBR is considered at the inlet, outlets and between inlet and longer arm side of the tundish (EMBR dam/weir) for two strand tundish. In case of six strand tundish, EMBR is considered only at the inletwith magnetic field parallel to the flow.

Flow and Temperature Distribution

For a T-shape two strand tundish, it is found that with 100% EMS intensity the maximum surface velocity below the top molten metal layer is very high (0.554 m/s) and may pose danger in terms of steel shearing off slag layer leading to emulsification with small surface waves. When the intensity is reduced, the surface velocity reduced almost linearly reaching less than 0.3 m/s at around 20% EMS intensity, which is less than safe range (0.2-0.3m/s) of maximum velocity suggested to avoid slag entrainment [1]. The similar trend for EMS intensity is observed in six strand tundish as well. Therefore, 20% EMS intensity is considered for the further investigations along with the EMBR for both two and six strand tundish.The maximum and minimum temperature difference across the two strand tundish is found as 14.87 K and 4.88 K for No EM and 20% EMS configuration respectively (Figure 3). The temperature variation is more at slag surface (top wall) due to stagnation regions and stronger cooling effects in that area. Interestingly, adding EMBR at inlet, outlet(s) and EMBR as tundish furniture, slows down flow field leading to stagnation and cold pockets around. The effect of EMS and EMBR is analyzed in six strand tundish as well and similar behavior like two strand tundish is observed. As can be seen in Figure 4, the maximum temperature difference is observed in No EM configuration (16.66 K) and minimum temperature difference is observed in 20% EMS (7.74 K), i.e. 20% EMS showing maximum thermal homogenization.

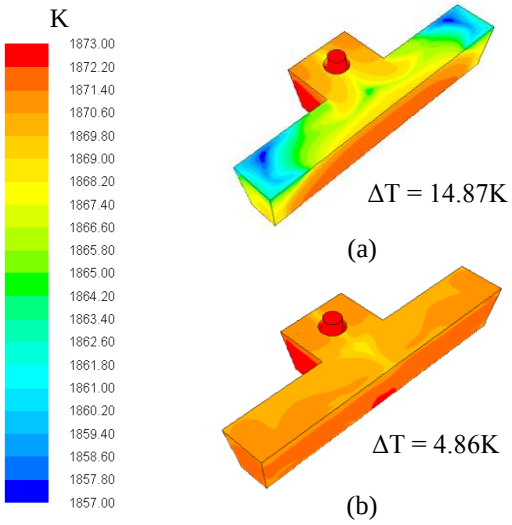


Figure 3 Temperature distribution in two strand tundish (a) without EMS (b) with 20% EMS

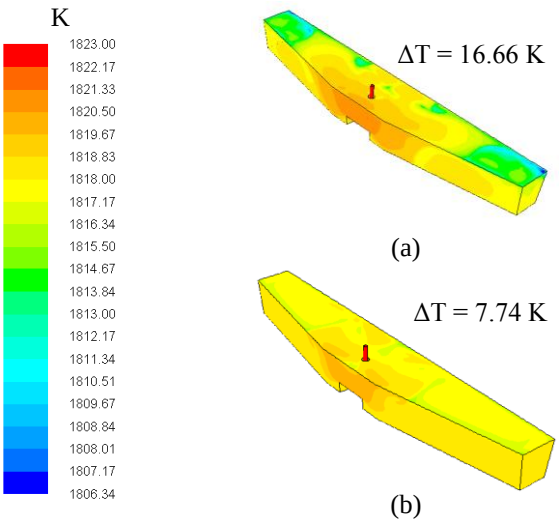


Figure 4 Temperature distribution in six strand tundish (a) without EMS (b) with 20% EMS

Inclusions Removal

The analysis is carried out for various particle sizes ranging from 5 µm to 300 µm viz. 5 µm, 10 µm, 25 µm, 50 µm, 100 µm, 200 µm and 300 µm. The separation rate is less at lower inclusion particle sizes and increases with particle diameter. Most of the particles bigger than 200 µm are removed at the steel-slag surface. The separation rate is higher for all the EM configurations compared to that of No EM configuration for lower particle sizes (up to 50 µm). This shows that EM configuration contributes significantly to encourage non-metallic inclusion floatation, particularly smaller sizes which are most critical to be removed, in the tundish. The EM device extends the residence time of particle in the domain by mixing the flow thus leading to higher chances of its removal from the tundish domain. The separation rate for EM configurations at larger particles is more or less similar as in No EM case. Among all the EM configuration, 20% EMS configuration shows better inclusion separation rate compared to No EM and 20% EMS with all possible EMBR configurations (Figure 5). In case of six strand tundish, 20% EMS configuration encourages the inclusion floatation by 6% compared to the No EM configuration at particle size of 5 µm. The 20% EMS with EMBR performs poor compared to 20% EMS and No EM configuration (Figure 6). This is due to the EMBR at inlet which directs the flow towards other end of the longer arm of the tundish instead of directing flow upwards or towards side.

Dynamic Simulation of Tundish with Plasma Heater

The dynamic simulation of tundish is carried out in order to understand the improvements and benefits in typical transient tundish operation during ladle changes by way of adding EMS and heaters. Heater in this case, when combined with EMS, helps in maintaining desired melt superheat which is a significant requirement at the steel plants.

In this work, simulation of 20% EMS configuration has been performed for two strand tundish with typical process variables. The target is to maintain bulk temperature of 1890 K with outlet flow rates of 32.5 kg/s from each outlets.Figure 7 and 8 shows the melt temperature (inlet, bulk and outlets) and flow rate (inlet and outlets) respectively. As can be seen from Figure 7, there is a ramp-up period on the bulk and outlet temperatures in the beginning afterwards the bulk temperature of 1890 K is maintained throughout the casting time. Since, bulk temperature is controlled very closely at 1890 K, there are some variations on the tundish outlet temperatures giving peaks at ladle openings, mainly due to heat losses and some variations in the tundish. Outlet flow rate is targeted at 32.5 kg/s (same from both outlets) by changing pressure drop at the outlets and due to transient free surface dynamics, the flow rate fluctuates around 30kg/s.

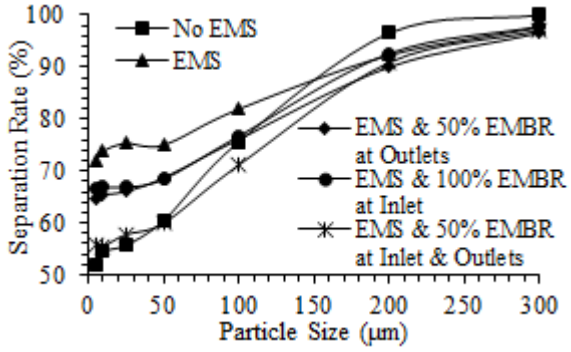


Figure 5 Inclusions separation rate in two strand tundish

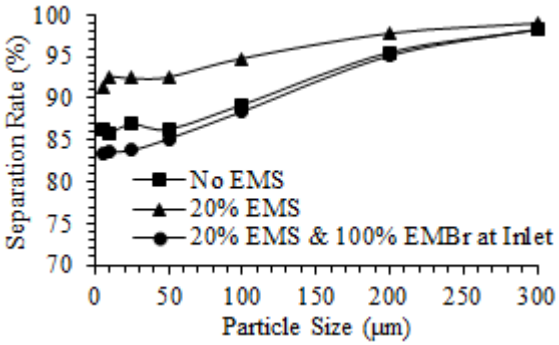


Figure 6 Inclusions separation rate in six strand tundish

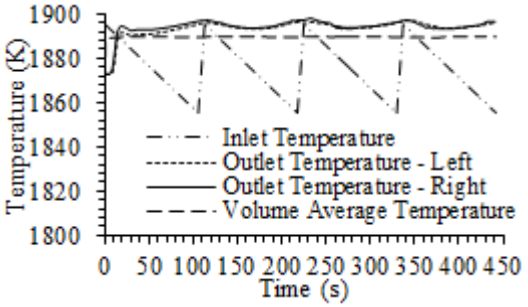


Figure 7 Variation of inlet, outlets and bulk melt temperature with time for two strand tundish

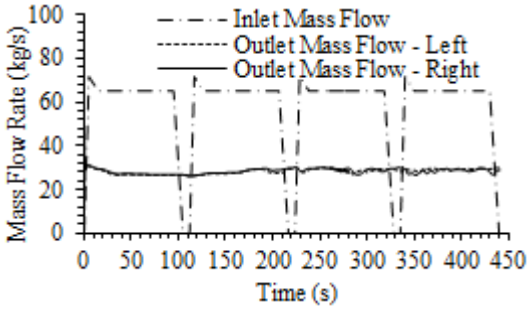


Figure 8 Variation of inlet, outlets mass flow rate with time for two strand tundish

Conclusions

In this article, multi-physics modeling of slab and billet casting tundish were carried out to study the effect of electromagnetic devices on fluid flow distribution, temperature homogenization and inclusion separation in the tundishes. Two strand "T" shape tundish was considered for slab casting, and six strand "V" shape tundish was considered for the billet casting. Analysis were carried out for combination of various EMS and EMBR configurations for both two and six strand tundish. The effect of EMS suggest the needand advantages of stirring for both tundish configurations. The melt in the tundish with EMS gets homogenized thus reducing melt temperature difference significantly and inclusion separation rate increased especially for smaller inclusions. EMS with tundish heater helps in maintaining required uniform outlet temperature over time and across various strands in multi-strand tundish. The effect of EMBR at inlet, outlets and as tundish furniture needs further investigation to confirm their benefits in terms of avoiding vortexing and splashing while encouraging inclusion floatation.

References

1. Y. Sahai and T. Emi (2008), Tundish Technology for Clean Steel Production, World Scientific Publishing Co. Pvt. Ltd., Singapore.
2. M. Warzecha, T. Merder, P. Warzecha, G. Stradomski (2013), ISIJ International, 2013, 53 (11), 1983–1992.
3. J.de.J.S. Barreto, M.A.B. Meza, R.D. Morales (1996), ISIJ International, 36(5), 543-552.
4. Opera, User Guide, (2012), Vector Fields Software, Cobham Technical Services, England.
5. FLUENT (2013), ANSYS Fluent theory guide, ANSYS, Inc., Canonsburg, PA 15317.
6. C. Damle, Y. Sahai (1996), ISIJ International,36(6), 681-689.
7. D. Bershader, R. Landsho (1961), Magnetohydrodynamics: In Handbook of Fluid Dynamics, Streeter VL (ed.). McGraw-Hill Book Company, Inc.: New York.
8. M. Dubke, K-H. Tacke, K-H. Spitzer, K. Schwerdtfeger (1988),Met. Trans. B,19B, 581–593.
9. F. Felten, Y. Fautrelle, Y.D. Terrail, O. Metais (2004), Applied Mathematical Modelling, 28, 15-27.
10. K.R. Kumar, R. Chaudhary (2014), Electromagnetic Tundish, Internal Report, ABB Corporate Research, Bangalore.