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ROUND CONTINUOUS CASTING WITH EMS-CFD COUPLED

Abstract

This work is part of a larger project to develop a model of the transport and entrapment of inclusions in in a round billet continuous casting machine, equipped with an Electro-Magnetic Stirrer (EMS). The work presented here describes the mathematical simulation of fluid flow coupled with EMS, to study the effect of the rotating magnetic field on the fluid flow pattern and solidification. The transient magnetic flux generated via EMS inside the continuous casting mold region is modeled with the Maxwell electromagnetic code (ANSYS Electromagnetics [3]) and included in the CFD model using the Fluent MHD module [2]. This magnetic field of the stirrer is then validated by comparison with plant measurements. The heat flux between the copper mold and the solidified shell is calculated by a User Defined Function and applied as a boundary condition calculated iteratively, based on a transient solidification-heat-transfer model of the gap and mold using the CON1D [4] model. This model takes into account the effect of the mold, the molten mold powder, and air gap formation. Preliminary results show the effect of EMS on the fluid flow, superheat dissipation and shell thickness growth. This development provides the foundation for future work to study the influence of EMS on inclusion transport and entrapment.

Keywords

Electro-Magnetic Stirrer (EMS), Continuous Casting, CON1D, Solidification, Fluid flow, CFD, Maxwell.

1. Introduction

This work is the first step of a larger project that aims to study the transport and entrapment of inclusions in continuous casting of steel billets. The main parameters affecting fluid flow in the continuous casting mold are, among others, the casting speed, electromagnetic stirring (location, intensity and frequency), SEN location, meniscus level, mold sizing and the solidified shell. Understanding how the controllable casting parameters affect fluid flow in the strand is an essential first step in optimizing the process. The objective of this first step which is presented here is to develop and validate a numerical model able to describe all of these phenomena in continuous casting of a round steel billet strand.

Electromagnetic stirring in continuous casting has a great influence on steel billet quality. In recent years, steelmakers have achieved higher productions rates with higher quality products with the use of EMS. The stirring generated by the magnetic field in the mold

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region changes the original flow pattern inside the strand to achieve metallurgical improvements. Liquid steel flow in the mold has an important impact on the solidification microstructure, steel cleanliness, superheat distribution, segregation and porosity.

It is almost impossible to measure fluid flow inside the continuous casting mold. A few measurements are possible but mainly in the meniscus region. Therefore, physical models and especially numerical models are essential tools for understanding flow behaviour with EMS.

2. Model description

The computational model has two parts: the electromagnetic field calculation and the flow field-solidification model.

Firstly, a three-dimensional transient distribution of the magnetic field that evolves inside the strand is calculated using the electromagnetic finite-element code, ANSYS Maxwell [3]. Then, the magnetic field results are imported into the CFD code, ANSYS Fluent [1], using the MHD add-on module [2] which solves for turbulent flow field, including the coupled effects of the induced forces caused by the moving magnetic field, which are calculated using the Magnetic-induction option. Furthermore, heat transfer and solidification are also included in the model, so the temperature field and shape of the solid steel shell are also output.

The case under study is a round billet continuous casting machine with dimensions given in Table 1.

Table 1. CC Machine Description

CC Machine parameters	
Caster arc radius	8500 [mm]
Round billet diameter	200 [mm]
Copper mold length	1000 [mm]

Electromagnetic model:

The moving electromagnetic field distributions in the round billet copper mold are obtained by solving a low-frequency approximation of Maxwell´s equations.

$$\begin{cases} \nabla \cdot \vec{B} = 0 \\ \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{H} = \vec{J} \end{cases} \quad (1)$$

In addition to the stirrer, the copper mold and the steel strand are also included in the electromagnetic model. The whole geometry is surrounded by a 2 [m] air cylinder which enables calculation of the magnetic field distribution both inside and outside of the stator. The EMS stator geometry plus the mold copper modelled to solve the electromagnetic field are shown in Fig. 1.

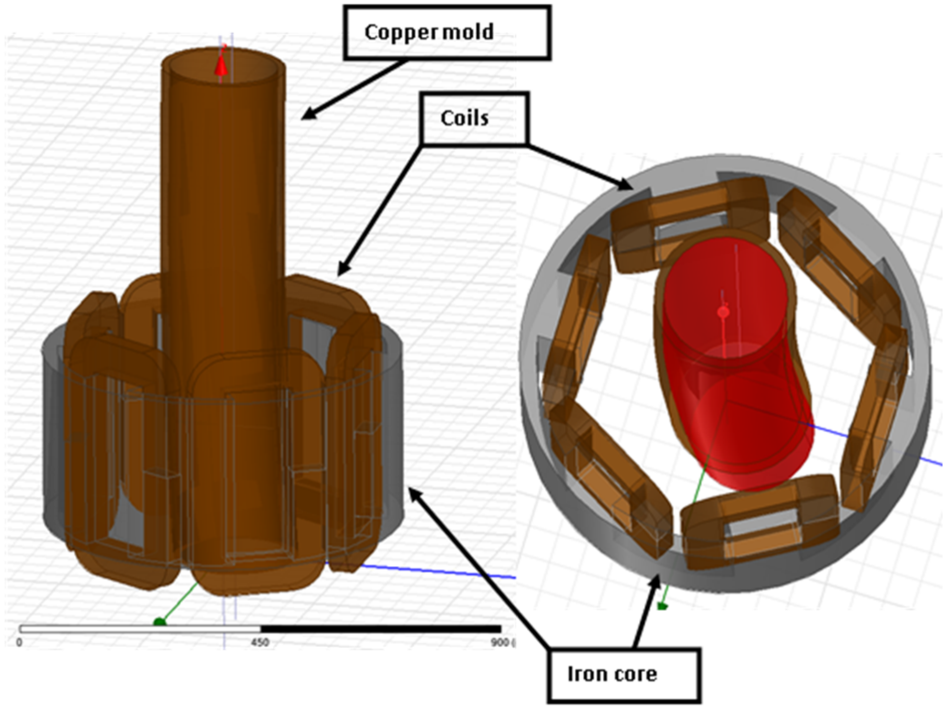

Fig. 1. EMS stator geometry used in Maxwell model

The characteristics and location of the EMS stator that generates the EMS field in the strand are given in Table 2.

Table 2. EMS stator parameters

EMS Stirrer	
EMS distance from mold top	1000 [mm]
Outside diameter	833 [mm]
Inside diameter	480 [mm]
Height	487 [mm]
Maximum current	325 [A](RMS)
Maximum frequency	15 [Hz]
Operating current	200 [A]
Operating frequency	2 [Hz]

With the aforementioned operating conditions of the stirrer, the magnetic field obtained in the simulation has been compared with data measured at a commercial steel plant. The field measurements were made with a Teslameter with air inside the copper mold and with a temperature of 25 ºC for the copper mold, with the same EMS operating conditions as used during actual casting, in order to validate the model.

The calculated magnetic field is shown in Fig. 2 in a typical horizontal section. A comparison of the predicted magnetic flux density with the measured field strength down the vertical axis show an excellent agreement, as shown in Fig. 3.

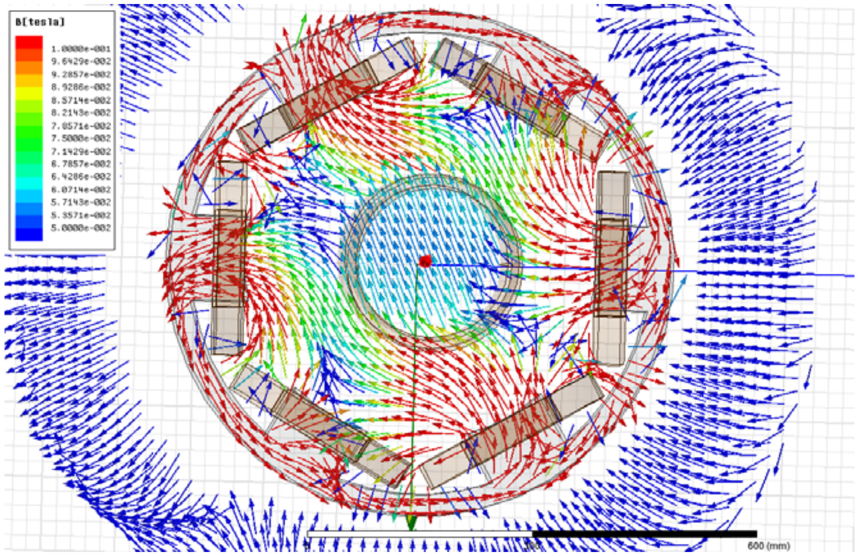

Fig. 2. Magnetic field vectors measured inside the EMS stator and surroundings

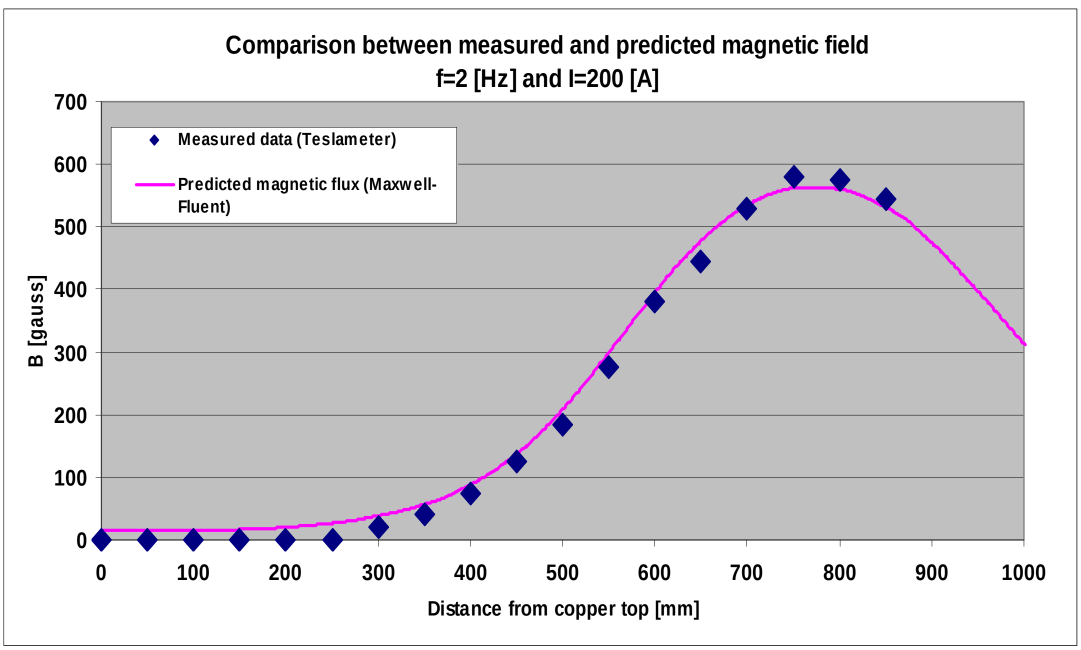

Fig. 3. Comparison between measured and predicted magnetic field strength

Having validated the magnetic field model in ANSYS Maxwell, a new simulation was performed to obtain the magnetic field with steel inside the copper mold (Fig. 4). The Lorentz forces with fluid flow interaction are calculated in ANSYS Fluent by the MHD module based on the imported magnetic field. In the real caster, the moving conducting fluid has a little effect on the applied field, due to the slip between the magnetic flux rotating frequency and the fluid rotation speed.

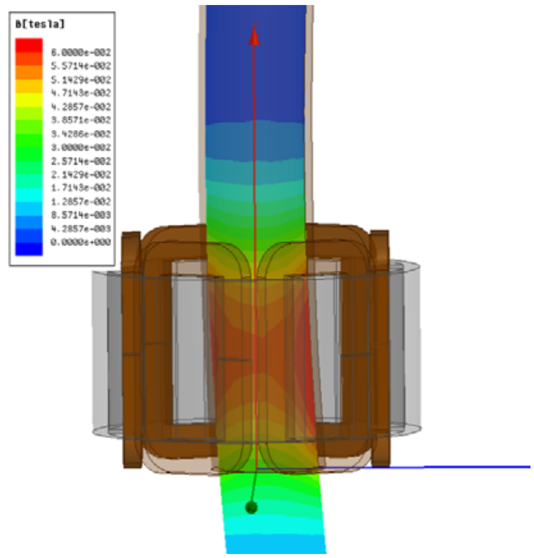

Fig. 4. Magnetic field results with steel in the mold (Maxwell)

Thermal-Flow and Solidification model with EMS:

To take into account the effect of the EMS on heat transfer and solidification, the thermal-fluid flow (CFD) problem is solved with ANSYS Fluent, activating its solidification module. Specifically, the Navier-Stokes equations and heat conduction equation are solved during the casting process, activating the Magnetohydrodinamics module to import the magnetic field obtained in the previous Maxwell simulation. Interaction between the fluid flow field and the magnetic field is solved with the magnetic induction approach. The realizable k-ε turbulence model with the enhanced wall treatment is used to predict kinetic energy and dissipation, needed to calculate turbulent viscosity in the momentum equations.

This thermal-flow model simulates the mold length plus 1.5 m of the strand below the mold, including some length of the secondary cooling area and the SEN. The mesh of the model has 538260 hexahedral cells.

The casting conditions are summarized in Table 3. The steel grade is a typical low carbon steel with temperature-dependant properties calculated with the IDS software [5] based on its composition.

Table 3. Casting parameters

Casting parameters	
Casting speed	2 [m/min]
Super Heat	44 [ºC]
Steel grade	Low carbon steel
Liquidus Temperature	1515.97 [ºC]
Solidus Temperature	1466.59 [ºC]
Copper mold thickness	16 [mm]
Primary cooling flow rate	1351 [l/min]
Primary cooling water Temperature	32 [ºC]
ΔT Primary cooling water Temperature	11 [ºC]
Mold flux consumption	0.105 [Kg/m^2]

For the calculation of the heat flux between the copper mold and the solidified shell, a User Defined Functions has been developed. This heat flux is applied as a boundary condition that is solved iteratively, based on the results of a transient solidification-heat-transfer model of the mold using the CON1D [4] equations implemented into the UDF. This model takes into account the effect of the mold, the crystallization properties of the molten mold slag, and air gap formation on the hot face and the water temperature and flow rate for the cold face of the mold. Also in the UDF, there is module to calculate the pull velocity at each point of the strand according to the strand curvature. A schematic of the heat transfer model used to account for the mold and interfacial gap is detailed in Fig. 5.

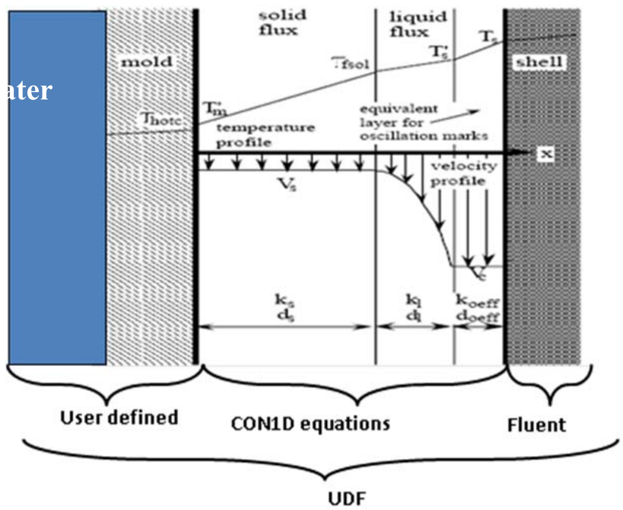

Fig. 5. Heat transfer description at hot and cold mold walls

The use of CON1D in the CFD thermal-flow solidification model gives a more realistic heat flux than with an empirical formula, because the effect of the superheat turbulent flow on the shape of the solidifying shell are taken into account at each point down the caster. Solidification in the flow zone is solved by a solidification model in Fluent, where an enthalpy-porosity formulation is used to treat the liquid-solid front. A comparison of the heat flux calculated empirically and that obtained in the simulation is shown in Fig. 6.

For the secondary cooling area included in the model, two different heat transfer coefficients are imposed 1600 [W/m^{2}K] for the first segment of sprays at mold exit and 800 [W/m^{2}K] for the others segments of sprays.

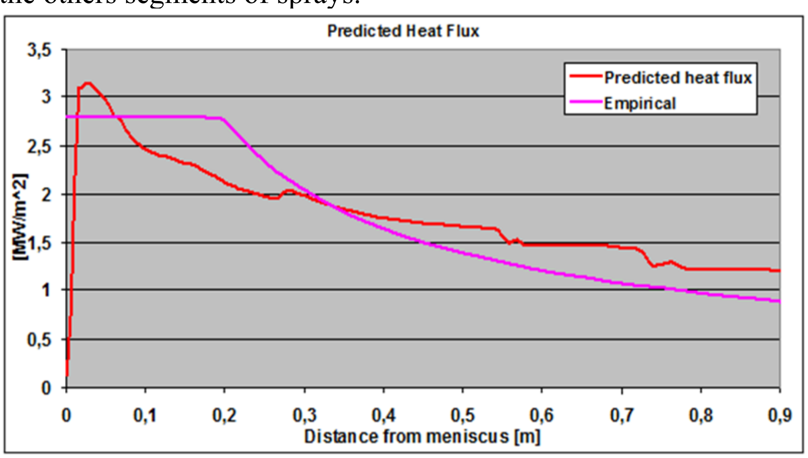

Fig. 6. Heat flux at mold wall

The temperature rise of the primary cooling water is not input to the model; only the initial water temperature is considered. So, the total heat removed is not specified as an input and is calculated by the UDF. The heat removal predicted in the simulation including the EMS is almost equal to the measured heat removal. The primary water temperature rise, ΔT, was measured in the steel plant to calculate the "measured" heat gain.

Predicted heat removal = 1.036[MW]

Measured **ΔT** = 11 [ºC] (1351 [l/min])
Measured heat gain = 1.037 [MW]

It should be noted that the model here predicts that EMS stirring has negligible influence on the total heat removal, which agrees with the conclusions of previous studies [17]. This is also another indication of the correct performance of the model.

Next, the shell thickness simulation results are compared with plant measurements. From experience in the steel plant, it is expected that a shell thickness of about 11 [mm] exists at the mold exit. The present model predicts 10.5 [mm] of shell thickness at mold exit if a liquid fraction of 0.3 is used to define the solidified layer and 11.3 [mm] if a liquid fraction of 0.4 is used.

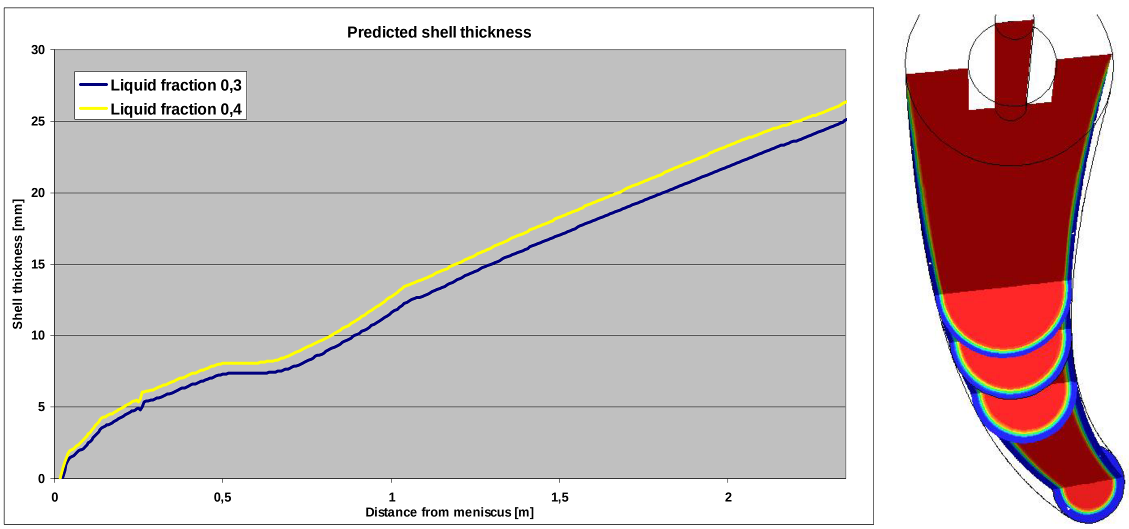

Fig. 7. Predicted shell thickness growth

3. Results

To investigate the effect of EMS on fluid flow in the billet caster, the validated model system is applied to conduct two simulations for the same casting conditions with and without EMS. Electromagnetic stirring effects are clear from observation of the flow streamlines. The typical roll pattern without EMS, Fig. 8 a), changes to a strong swirl flow inside the EMS stator, Fig. 8 b).

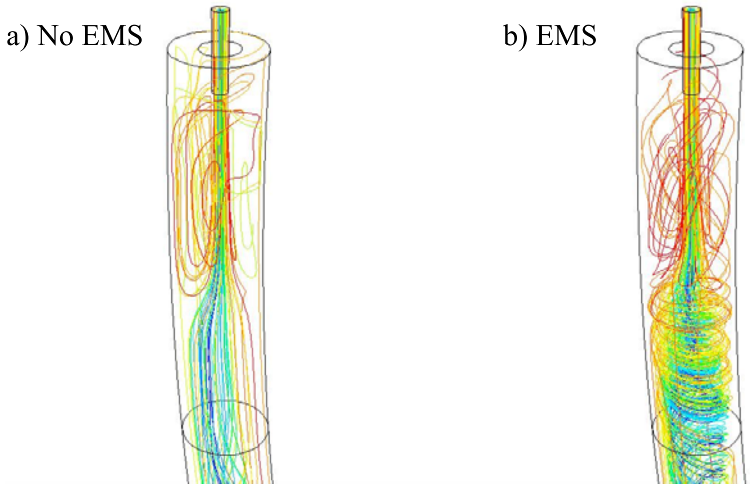

Fig. 8. Flow pattern with and without EMS

This change of the flow pattern indicates a significant change of the velocity distribution inside the strand, Fig. 9. It is obvious that the flow is more stirred. Speed is higher with EMS in the region of the EMS stator, especially near the solidification front. This produces a more uniform temperature distribution in the molten steel, which is intended to promote faster removal of superheat, and encourage a more equiaxed microstructure, with less center segregation problems. Temperature contours are shown in figure 10.

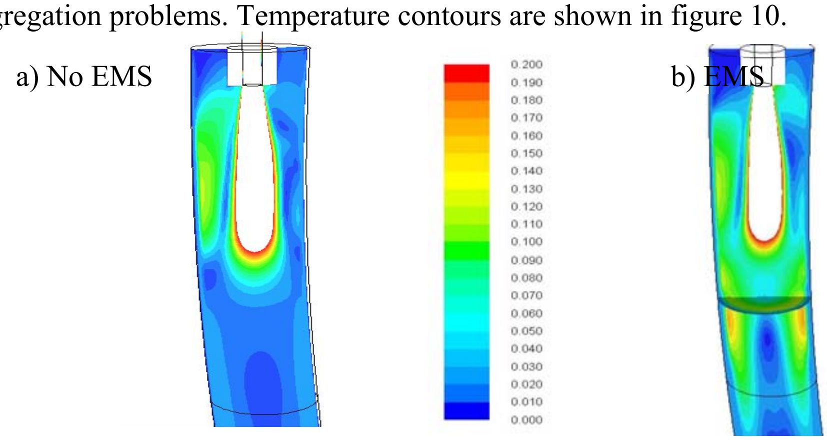

Fig. 9. Velocity magnitude distributions with and without EMS in m/s

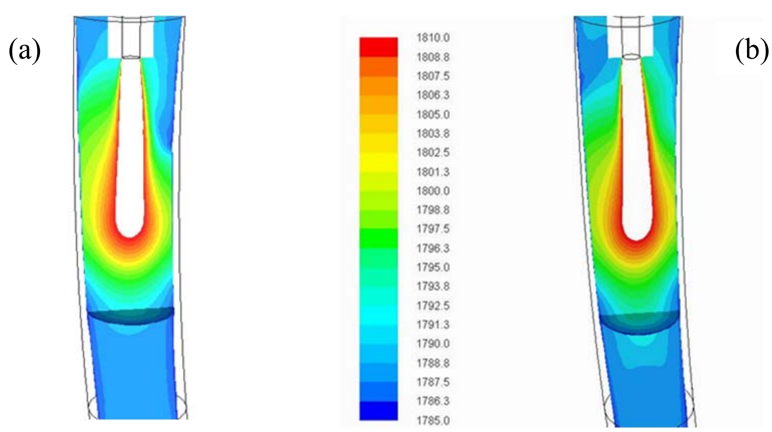

Fig. 100. Temperature distribution (a) without EMS and b) with EMS in Kelvin

The tangential velocity component is rather smaller than predicted in other works [8,9,10,11,12,13,14,15] due the influence of the solidified shell. When the effect of the solidified steel shell is not taken into account, higher velocities are reached. The highest Lorentz force values occur at the outer radius of the strand as shown in Fig. 12. If this region with the highest tangential forces is solidified, then the stirring effect is much smaller and the tangential velocity induced by the Lorentz force decreases. This effect is plotted on Fig. 11. Thus, when solidification is not considered, tangential velocities are overestimated.

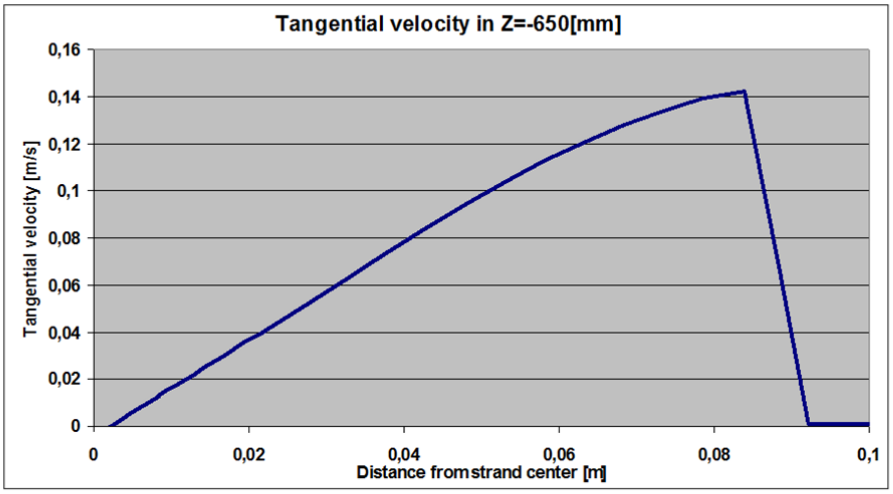

Fig. 11. Effect of mushy zone and solidified shell on tangential velocity

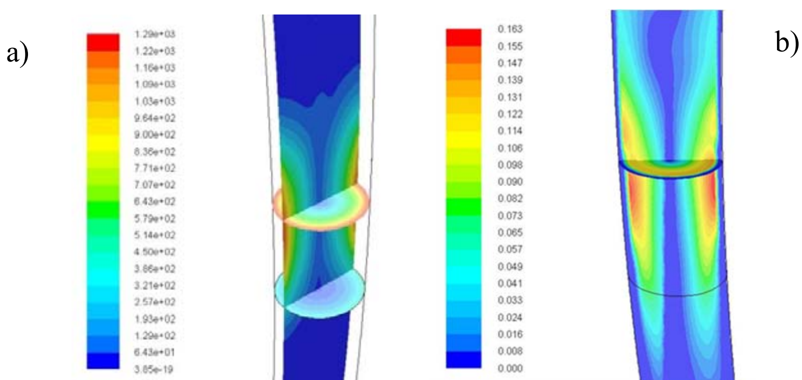

Fig. 12. Mean values of a) Lorentz Forces (N/m^3) and b) tangential velocity, in m/s

4. Conclusions

A model able to study the main parameters that govern flow inside a continuous casting strand with EMS has been developed and applied to a round steel billet caster. The rotating magnetic field is calculated with the electromagnetic finite-element code, ANSYS Maxwell. The calculated magnetic field matches well with measurements. The transient magnetic field is imported to ANSYS Fluent which calculates the induced Lorentz forces with the MHD add-on module and solves for the coupled turbulent flow velocity field. This model also simulates coupled heat transfer and solidification, including a reasonable treatment of the mold and interfacial gap. It predicts heat flux and solidified shell thickness, which has also been validated.

The preliminary results here show the importance of the solid shell in diminishing the tangential velocities induced by EMS to less than 0.2m/s for the conditions simulated. This work is a starting point for subsequent study of inclusion behavior in billet continuous casting.

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