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Optimizing the Flow Conditions in the Thin-Slab Casting Mold Using Electromagnetic Brake

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INTRODUCTION

Industrial thin slab casting (TSC) of the steel became nowadays important and effective continuous casting technology since its start in year 1989. It is featured by a slab size close to the final product shape, uniformity of the mechanical properties, reduced central macrosegregation, high casting speed and application in the direct rolling concept. Energy savings of more than 40% in comparison to conventional thick casting are vital for the steel industry. However a highly turbulent flow develops during the steel feeding via a submerged entry nozzle (SEN) into a narrow (typically funnel-shaped) thin slab mold. The intensive hot melt flow not only disturbs the calmness of the meniscus, moreover it causes the local remelting of the solidifying shell at the jet impingement area. The slag and non-metallic inclusions entrapment probability is enhanced; thinning of the solid shell can lead to break-outs below the mold exit; the rapid solidification during TSC increases defect formation risks. Thus applying a mold flow control technique is favorable. The electromagnetic brake (EMBr) is one of the well-known and widely applied technologies in the continuous casting of the steel. It allows reducing the impingement effect of the hot jets, promotes the calmness of the meniscus and enhances the super heat transport for stable flux melting rate, etc. However during the industrial practice due to the harsh conditions at the casting mill it is very hard or even impossible to immediately observe the effects from EMBr application and correspondingly adjust the device. Therefore the numerical simulation became nowadays a valuable tool to investigate and to optimize a wide range of the industrial technologies including those in the foundry field. In the presented study a magnetohydrodynamics (MHD) model is developed, verified and applied to simulate the effect of the EMBr in regard of the turbulent flow in the thin slab mold considering the solidification of the molten steel. A newly designed solver is presented in the current study, based on the finite-volume method (FVM) and developed in the open-source CFD package OpenFOAM®. Both the mathematical model and the solver are verified against the numerical solutions presented in the literature as well as against the laboratory measurements. After the model verification, an application of a ruler-type EMBr configuration is analyzed with regard to the magnitude of the applied magnetic field. Instantaneous meniscus superheat and velocity, temperature and flow distribution within the mold are selected to analyze the influence of the EMBr. Further extension of the presented studies for the industrial application is straightforward.

NUMERICAL MODEL

In the current work a constant density is assumed for the solidifying melt. Thus the flow in the continuous casting mold including magneto-hydrodynamic effects can be described as a set of Navier-Stokes equations for the incompressible fluid. The corresponding mass and momentum conservation equations are

$$\nabla \bullet \vec{u} = 0 , \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t} + \nabla \bullet \left(\vec{u} \otimes \vec{u} \right) = -\frac{1}{\rho} \vec{\nabla} p + \nabla \bullet \eta \left[\nabla \, \vec{u} + \nabla^{\mathrm{T}} \, \vec{u} \right] + \frac{1}{\rho} \vec{F}_{\mathrm{L}} , \tag{2}$$

with velocity $\vec{u}$, melt density ρ, kinematic viscosity η and pressure field p characterizing the fluid flow. In the current study the "coarse DNS" method is applied by using laminar model on the fine numerical mesh. The Lorentz force $\vec{F}_{\mathrm{L}}$ is included in momentum Equation (2) as following:

$$\vec{F}_{\mathrm{L}} = \vec{j} \times \vec{B}_0 \tag{3}$$

The electric potential method is applied being valid at low magnetic Reynolds numbers, at which the electric field $\vec{E}$ becomes curl-free $\nabla \times \vec{E} \equiv \vec{0}$ and the electric potential φ can be introduced as $\vec{E} = -\vec{\nabla} \varphi$. The electric current from the Ohm's law becomes

$$\vec{j} = \sigma \left(-\vec{\nabla} \varphi + \vec{u} \times \vec{B}_0 \right) , \tag{4}$$

where σ is the electrical conductivity. The electric potential φ is calculated by solving Poisson equation:

$$\nabla \bullet \left(\sigma \vec{\nabla} \varphi \right) = \nabla \bullet \left(\sigma \left(\vec{u} \times \vec{B}_0 \right) \right) \tag{5}$$

Electric conductivity σ is considered to vary 1.5 times between liquid melt and solidified shell. The correct prediction of the latent heat advection is crucial for the growth of the solid shell.[2,3] The corresponding energy equation is solved for the temperature field T in its general advection-diffusion form as

$$\rho C_{\mathrm{p}} \left[\frac{\partial T}{\partial t} + \nabla \bullet \left(\vec{u} T \right) \right] = \nabla \bullet \lambda \nabla T + \rho L \left[\frac{\partial f_{\mathrm{s}}}{\partial t} + \nabla \bullet \left(f_{\mathrm{s}} \cdot \vec{u}_{\mathrm{s}} \right) \right] \tag{6}$$

with specific heat C_{p}, thermal conductivity λ, latent heat of fusion L and corresponding solid fraction f_{s} and solid velocities $\vec{u}_{\mathrm{s}}$. For the details of the implementation and verification of the solidification model please refer to Vakhrushev et al.[2] The combined (NHD / solidification) solver is developed in the open-source CFD package OpenFOAM®.[4] According to developed numerical model described in Equations (1)-(6) a corresponding solver including fluid flow, action of the Lorentz force and taking into account the solidification was developed. The MHD model was previously verified as well by the authors by comparing the modelling results with the experimental measurements presented by Thomas et. al.[6] The primary studies for the influence of the highly conductive solid in the mold cavity were performed and presented by Liu et. al.[5]

SIMULATION RESULTS

Numerical setup

According to previous studies by the authors the melt flow in the continuous casting mold has strong influence on the formation of the solidified shell.[2,3] This can be seen from the typical modelling results presented in Figure 4 where the areas of the melt flow above 0.3 m/s align of the local zones of the growing shell thickening.

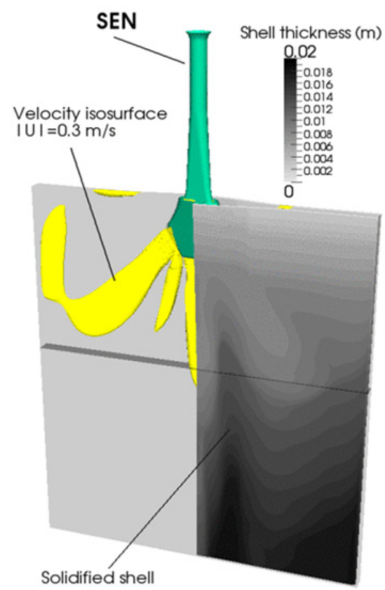

Figure 1. Results of the thin slab casting modelling.

To investigate the influence of the applied magnetic field to control the mold flow using EMBr technology the variation of the imposed magnetic field was performed between 0.3 and 0.6 tesla using one of the most typical EMBr arrangements (please refer to Figure 2) according to the review by Thomas and Cho.[7]

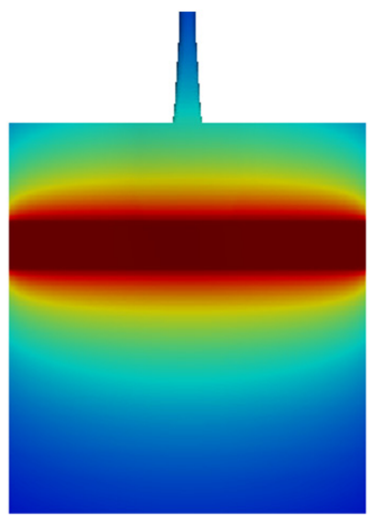

Figure 2. Ruler-type EMBr magnetic field.

Thin slab simulation

Next the thing slab casting simulation was performed using developed combination of the solidification and MHD solver. The results were analyzed for the ruler-type EMBr by comparing the flow and solidification modelling for the case with no magnetic field and those with applied EMBr of 300, 400, 500 and 600 mT. As it can be seen from the Figure 3 the velocity magnitude and the temperature distribution slightly change between no magnetic field case and the one with the 300 mT been applied: velocity slightly decreases, but not significant temperature field alternation is observed. Further EMBr increase leads to severe calming of the top surface. Temperature remarkably grows and for 500-600 mT becomes considerably above the liquidus.

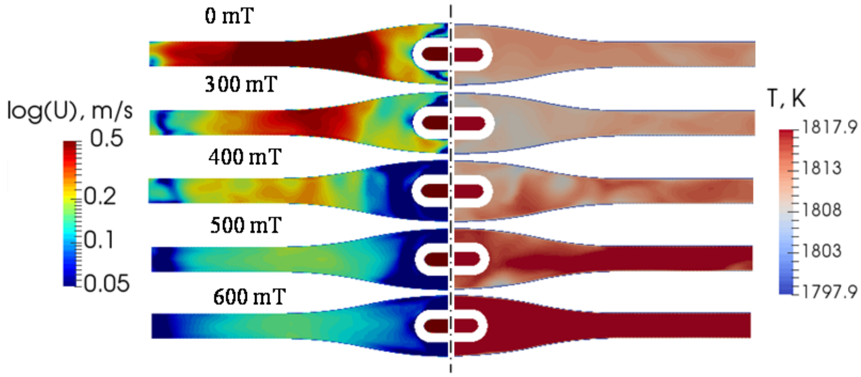

Figure 3. Meniscus velocity (left) and super heat distribution (right) for ruler-type EMBr simulation.

Analyzing velocity field changes in the mid-plane of the mold (see Figure 4) it can be again seen that no noticeable changes are reached with the magnetic field of 300 mT. However with increasing EMBr the flow gets a plug-like type already at 500 mT which becomes really pronounced at 600 mT.

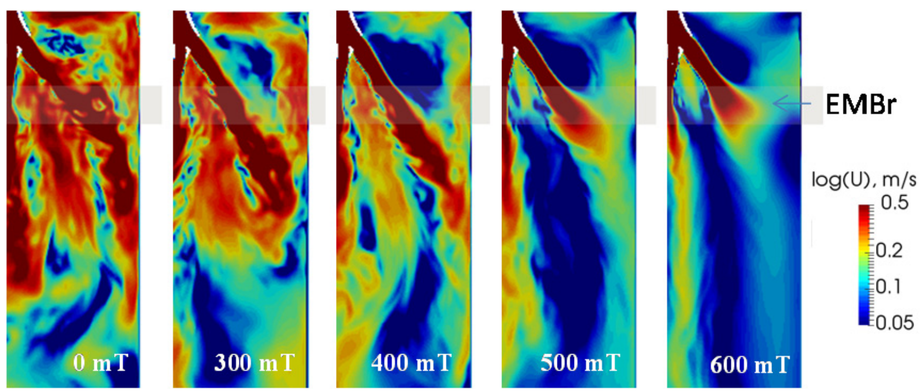

Figure 4. Instantaneous velocity distribution at the mid-plane of the mold.

The similar situation is with the temperature field as can be seen in Figure 5: superheat distribution becomes more uniform and hotter fresh melt is transported to the top surface of the mold.

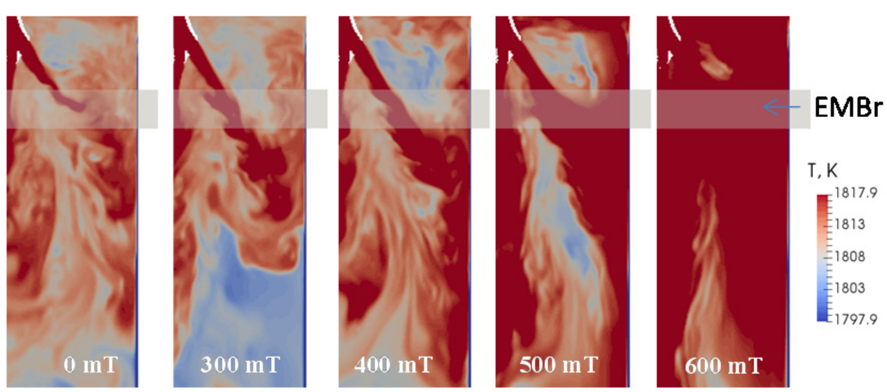

Figure 5. Instantaneous velocity magnitude distribution at the mid-plane of the mold.

However the flow becomes much more stable and it could be expected that no significant mixing will be observed leading to the macrosegregation enhancement and to formation of the stagnation zones with excessive solidification or remelting of the solid shell near the hot jet areas.

CONCLUSIONS

In the presented study an extended numerical model was developed combining the solidification of the solid shell during the continuous casting and taking into account the influence of magnetohydrodynamics effects due to the applied magnetic field using electromagnetic brake technology. A ruler-type EMBr flow controlling effects were investigated by varying the maximum applied magnetic field between 300 and 600 mT.

It was found, that at the lower range no significant flow and temperature alternation is observed, leading however to calmer meniscus surface. The late effect continuously grows when the EMBr is increased till the upper limit of 600 mT in this study. The submeniscus flow becomes very stable and its temperature is considerably above the liquidus.

However in the area between the submerged entry nozzle and the mold funnel the formation of the stagnation zones is detected, that could lead to excessive solidification and solidified bridges formation. On the contrary the remelting will be enhanced at the hot jets area. Additional damping of mixing is observed when the flow changes to the plug-type.

To conclude, the application of the electromagnetic brake is desirable and effective toll. However its setup should be carefully investigated for different SEN and mold designs to evaluate casting process improvements.

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