Numerical Simulations of Electromagnetic Counteractions to Mold Fluid Flow Asymmetry Deviations

Martin Sedén¹ and Bengt Rydholm¹

¹ ABB AB, Industrial Automation, Process Industry, Metallurgy Products, Terminalvägen 24, 721 59 Västerås, Sweden

martin.seden@se.abb.com

Abstract. Asymmetric flow of the molten steel in a continuous slab casting mold may be detrimental to the quality of the solidified end product. Depending on the severity of the biased flow, local mold powder entrainment, non-homogeneous solidification around the perimeter of the initial shell or non-optimal inclusion seclusion may occur. In particular, nozzle clogging in the last slabs before an SEN exchange may cause strong and asymmetries in the upper regions of the mold. To avoid costly downgrades of steel quality in these slabs, it is vital to maintain stable and symmetric fluid flow conditions in the mold. The EMBR and the FC Mold are two flexible electromagnetic devices able to produce asymmetric braking/stirring along the width of the mold in slab casting, and in this way allow counteraction against e.g. biased mold flow or local excessive flow speeds. Numerical computations of mold fluid flow and magnetic flux have been carried out to quantify the required fields to symmetrize biased flow scenarios caused by e.g. SEN clogging. In conjunction with steel plant trial feedback, the simulation results have been used to setup control algorithms for the EMBR and FC Mold.

1. Introduction

Process stability during continuous casting is crucial in order to obtain homogeneous and constant conditions for the fluid steel to solidify evenly in the mold. In highly productive slab casters, the utilization of the submerged entry nozzle (SEN) is often maximized. In the last slabs before SEN exchange in non-calcium treated steels, clogging in the nozzle may be severe and inhomogeneous, leading to strongly asymmetric and biased molten steel flows in the upper portion of the mold. Not only SEN clogging, but also asymmetric stopper or slide-gate positioning, anisotropic argon injection, mold eigenfrequency excitations or turbulence in the flow through the SEN may trigger asymmetric flow patterns. As a consequence of the asymmetric mold flow pattern, local mold powder entrainment or non-optimal inclusion seclusion may occur with deteriorated steel quality as a result [4]. To avoid downgrades of steel quality, it is vital to maintain stable and symmetric conditions in the mold.

Building on the confirmed results of the electromagnetic actuators EMBR and FC Mold to stabilize and optimize the mold flow [2] in the continuous slab casting process, the next step is an increasingly flexible EM device able to catch and react on local casting deviations such as meniscus fluctuations, undesired fluid flow velocities or patterns, crack indications or flow asymmetries. Recent developments in mold sensor technology [7]-[9] now enable detection capabilities of much more localized phenomena in mold fluid flow. A highly flexible EM device is the other cornerstone in creating an automatic mold flow control system that can handle both local and transient deviations from ideal conditions.
Applying spatially asymmetric mold flow control, the casting process becomes more stable and symmetric. E.g., excessive meniscus fluctuations and flow speeds on one side of the mold can be mitigated by extra stabilization and braking in this area, or uneven speeds in the SEN jets due to clogging can be homogenized by applying more braking or stirring on one side of the mold.

Counter measures of biased flow deficiencies allow quality upgrades with productivity and financial benefits for the steelmaker. Generally, a homogeneous and stable casting process yields a homogeneous solidified end product, with improvements in quality and product performance for the end-consumer.

2. Electromagnetic Flow Control in Slab Casting Mold with EMBR and FC Mold

The EMBR is in continuous casting a well-established electromagnetic actuator [2] that exposes a static magnetic field \( B \) underneath the SEN, perpendicular to the flow in the mold, and as such applies a braking Lorentz force \( F \) in the opposite direction of the flow velocity \( v \),

\[
F = \sigma (E + v \times B) \times B.
\]

Recent ABB developments in EMBR technology offer the possibility to apply a strong magnetic braking field along the full width of the thin slab mold, but with a varying field magnitude on left on right sides as the coil currents are controlled by independent L/R drives. The ferromagnetic cores of the left and right sides can also be arranged flexibly in a bowl-shaped fashion to better accommodate for different incident flow jet directions from the SEN [12].

Electromagnets allow gradual field changes, and the EMBR and FC Mold provide seamless transitions between function modes in order to customize the applied magnetic forces according to the casting conditions at hand. For the FC Mold, DC and AC fields are available near the meniscus flow to enable braking if flow speeds are excessive, or acceleration by stirring if the flow speeds in this region are stagnant. Both DC and AC fields are applied simultaneously and the meniscus fluctuations can be stabilized at the same time as rotative stirring homogenizes the perimeter [8].

In modern EMBR and FC Mold generations, the travelling magnetic field to drive rotational stirring [8].

The FC Mold is a double-level EM device used for conventional slabs, producing a horizontal upper magnetic field distribution close to the meniscus, above the SEN outlet ports, and a bottom horizontally located field below the SEN ports in the lower part of the mold. In the lower level, a static DC magnetic field is created across the mold thickness. In the upper level, another DC field is applied together with a superimposed AC

Figure 1. Configuration of EMBR with L/R independent field control.

Figure 2. Bowl-type EMBR front cores.

Figure 3. Positioning of independent FC Mold top and bottom, left and right fields.
magnets and their electrical drives allow independent control of the fields in both the upper and lower levels, as well as on left and right sides.

3. Numerical Simulations of Molten Steel Flow in Casting Mold

A platform for numerical modelling of the fluid steel flow in the strand, incorporating a magnetohydrodynamics coupling to the CFD equations [6], has over the past decades been continuously developed by ABB and refined with improvements in computational hardware, software as well as feedback from real steel plant measurements of magnetic flux, fluid flow, solidification characteristics and steel quality [2], [8], [11]. Mold flow is in the computational fluid dynamics model [5] governed by SEN jet momentum, argon bubble buoyancy and the forces from applying static braking and alternating accelerating electromagnetic fields of different magnitudes.

The magnetic fields and induced eddy-currents from the EMBR and FC Mold are obtained by solving the Maxwell field equations for the magnetic vector potential \( A \) with a FEM model incorporating various non-linear dependencies in material properties in and around the casting mold:

\[
\nabla \times \frac{1}{\mu} \nabla \times A = - \sigma \left( \frac{\partial A}{\partial t} + \nabla V \right).
\]

A long history of manufacturing of ABB EM devices for metals production has enabled an accurate numerical prediction model based on a large database of measured data for validation and tuning [3].

The fluid dynamics model utilizes a transient, unsteady RANS model with an Eulerian representation of the two-phase flow. A Reynolds stress model has been used for turbulence approximations with an additional transport equation for the anisotropy of the turbulence caused by the magnetic field [1]. The magnetohydrodynamic coupling for static magnetic fields in the molten steel uses the electric potential and a velocity dependent Lorentz force source term in the transport equations for the travelling alternating fields. The boundary conditions are given by a predescribed solidified shell of and a flat free surface (steel/air) at the meniscus level. Isothermal conditions are assumed in the evaluation of the flow.

4. Flow Control Under Asymmetric Casting Conditions

A set of numerical CFD simulations has been conducted on the platform described above to illustrate the effect of asymmetric magnetic field distributions acting on an asymmetric flow field inside the mold. Nozzle clogging is difficult to predict as the flow of steel and argon through the SEN is highly turbulent and the buildup of Aluminum oxides on the inner walls of the nozzle is more or less stochastic. Both the spatial location of the clog and the time when it occurs are hard to foresee. The result is however many times a strongly biased flow out of the nozzle leading to an asymmetric flow pattern in the mold and inhomogeneous solidification and particle seclusion conditions.

Even casting for a perfectly new SEN with a smooth inner bore can lead to low frequency sloshing of the steel in the mold from one narrow face to another. The inherently turbulent nature of the flow through the SEN excites asymmetries that may trigger the eigenfrequencies of the bulk steel confined by the mold walls.

A simple model of an asymmetric mold flow, regardless of its cause, has been setup via a fictive linearly skew inlet flow condition over a cross section in the lower part of the SEN as illustrated in Figure 5. This creates a greater relative mass flow through the right nozzle port leading to a stronger SEN jet on the right side. This simple inlet condition has been applied to a set of different casting...
conditions to show the effect on the mold flow and to enable evaluation of relevant counter measures created by varying the magnetic field distributions.

4.1. Asymmetry Counteraction in Conventional Slab Caster

In the simulation model, a 237x1100 mm slab format cast at 1.9 m/min in a rectangular mold with 8 NL/min of injected argon, has been evaluated for the asymmetric inlet flow conditions with a +/-50% variation.

A snap-shot of the simulated velocity distribution in the center slice of the mold during these conditions is shown in Figure 6 without the impact of an FC Mold on the left and for an asymmetric FC Mold field distribution on the right [13]. In Figure 7 the transiently simulated meniscus flow speeds at the center thickness of the mold, y=±0.385 m for the left and right sides, are shown for a time period of 210 s. In the first 60 s of the simulation, the FC Mold is turned off.

**Figure 6.** Simulated flow velocity distributions in mold center slice for skew inlet flow. Without FC Mold (left) and with asymmetric FC Mold DC field distribution with stronger DC field in the top right corner (right).

From here until t=75 s, horizontally homogeneous and symmetric DC magnetic field distributions in both levels of the FC Mold are ramped up, with the result that in 75-135 s, the meniscus flow speeds are reduced and fluctuations stabilized.

The gap between the left and right flow speed curves of Figure 7 is only closed in the last 60 s of the simulation when the biased flow is symmeterized. This is the result of a horizontally asymmetric field distribution in the upper FC Mold level where a 25% boost is applied to the DC magnetic flux density on the top right. The stronger flow speed on the right side of the meniscus is in this way subject to extra braking to obtain the same flow speed as on the left side. The

**Figure 7.** CFD simulated meniscus flow speeds on left (L) and right (R) sides in modelled skew inlet flow case for varying EM field configurations;

a. 0-60 s: No field,
b. 75-135 s: Homogeneous DC fields,
c. 150-210 s: Asymmetric DC fields.
flow speed pattern in the mold during asymmetric braking is illustrated on the right in Figure 6.

4.2. Asymmetry Counteraction in Thin Slab Caster

For a thin slab casting format of 100x1400 mm and casting speed 5.5 m/min, numerical simulations have been carried out with the above described linearly varying inlet speed method in a 2-port fish-tail nozzle to generate an initial mold flow asymmetry. This casting scenario is in the higher throughput range, calling for stabilization of the process. The DC field of the EMBR is applied below the SEN in a bowl-shape to stabilize the flow and to help guide momentum toward the meniscus in a double roll flow pattern, but at the same time minimize meniscus fluctuations and regulate meniscus flow speeds.

Figure 8. Simulated 100x1400 mm center strand flow velocity snap-shots for skew inlet flow. Without EMBR (left), with symmetric EMBR bowl-shaped fields (center) and with asymmetric EMBR DC field distribution with boosted DC field in the left side (right).

The application of the bowl-shaped EMBR fields generally leads to a decreased and stabilized meniscus flow speed, but when a skew velocity inlet condition with a ±50% variation is applied, the flow in the mold, even with a symmetric EM field, becomes asymmetric, see Figure 8. Figure 9 shows the transiently simulated sub-meniscus flow speeds at the center thickness of the mold, y=±0.440 m for the left and right sides.

Within a 230 s period, three different constant field exposure modes are simulated where the described asymmetric flow situation is: a. unaffected by magnetic fields, b. under the influence of symmetric EMBR fields, c. counteracted by an asymmetric EMBR field. The DC field in c. is 23% stronger on the left side to level out the meniscus flow asymmetry and dampen the flow speed peaks on the left side of the meniscus from time period b.

Figure 9. CFD simulation results of meniscus flow speeds on left (L) and right (R) sides in modelled skew thin slab inlet flow distribution for varying electromagnetic field configurations; a. 0-70 s: No field, b. 85-145 s: Symmetric EMBR DC fields, c. 160-230 s: Asymmetric EMBR DC fields.

4.3. Summary

A flexible control of the EMBR/FC Mold would not apply the rugged method of constant field strengths over time as in this investigation, but rather a proportionate field strength variation.
depending on the response from an online mold flow sensor. However; to shed some light on the underlying control mechanisms, these two examples show that asymmetric meniscus flow can be counter-acted by appropriate magnitudes of the left and right DC magnetic fields.

In combination with an online flow measurement sensor such as mold level sensors or the OptiMold Monitor® which detects flow parameters such as the meniscus speed on the left and right sides of the mold [10], an automatic asymmetry control based on these principles can be set up. In addition to flow symmetrization, such a control set-up can also regulate the meniscus flow speed to a desired level.

5. Conclusions
Mold flow asymmetry can according to these numerical results be counter-acted by an asymmetric magnetic field distribution to achieve a homogeneous flow speed distribution over the entire meniscus level. This is valid both for conventional slab casting cases with the FC Mold and for thin slab casting with the EMBR. With modern ABB EM equipment, the magnetic fields are configurable independently, not only in the upper and lower levels, but also on the left and right side regions. This, in combination with a flow speed detection sensor such as the OptiMold Monitor®, makes it possible to control the magnetic fields of the EM actuator autonomously against flow speed and mold flow asymmetry unlocking potential for improved process stability, slab cleanliness and surface quality of cast steel.

References
[1] Widlund O et al 2000 Modeling of anisotropic turbulent transport in simulations of liquid metal flows in magnetic fields 3rd Int. Symp. on Electromagnetic Processing of Materials (Nagoya) pp 97-102
[2] Yamamura H Toh T et al 2001 Optimum magnetic flux density in quality control of casts with level DC magnetic field in continuous casting mold ISIJ Int. 41 10 pp 1229-1235
[3] Löfgren P and Bel Fdhila R 2003 Modeling of the continuous slab casting process. Part3: Comparison between algebraic slip model and 2-phase model & water case validation (Västerås) Tech. Report SECRC/AT/TR-03/023
[4] Miki Y and Takeuchi S 2003 Internal defects of continuous casting slabs caused by asymmetric unbalanced steel flow in mold ISIJ Int. 43 10 pp 1548-1555
[5] Chaudhary R 2011 Studies of Turbulent Flows in Continuous Casting of Steel With and Without Magnetic Field Ph.D. Thesis (Urbana-Champaign: Univ. of Illinois at Urbana-Champaign)
[6] Chaudhary R, Thomas B G and Vanka S P 2012 Effect of electromagnetic ruler braking (EMBr) on transient turbulent flow in continuous slab casting using large eddy simulations Metall. Mater. Trans. B 43 3 pp 532–553
[7] Lieftucht D et al 2013 HD Mold – a new fiber-optical-based mold monitoring system AIST Trans. Iron and Steel Technology 10 12 pp 87-95
[8] Sedén M, Jacobson N, Lehman A and Eriksson J 2014 Control of flow behavior by FC Mold G3 in slab casting process Proc. 8th European Continuous Casting Conf. (Graz) pp 558-569
[9] Spierings A et al 2017 Development and application of fiber bragg gratings for slab casting Proc. AISTech2017 (Nashville)
[10] Sedén M and Jacobson N 2017 Securing dynamic mold flow control with FC Mold and OptiMold Monitor Proc. 9th European Continuous Casting Conf. (Vienna) pp 67-75
[11] Jacobson N, Sedén M, Go Y, Lim S, Kim K and Kim Y 2017 Flow control by FC Mold G3, operation and results from slab casting process Proc. 9th ECCC (Vienna) pp 199-208
[12] Hwang J Y, Cho M J, Thomas B G and Cho S M 2018 Numerical simulation of turbulent steel CEM mold under high mass flow condition 9th Int. Symp. on Electromagnetic Processing of Materials (Hyogo) IOP Conf. Ser.: Mater. Sci. Eng. 424 012033
[13] Sedén M and Jacobson N 2018 Online flow control with mold flow measurements and simultaneous EM braking and stirring 9th Int. Symp. on Electromagnetic Processing of Materials (Hyogo) IOP Conf. Ser.: Mater. Sci. Eng. 424 012015