# Overview of Electromagnetic Forces to Control Flow During Continuous Casting of Steel

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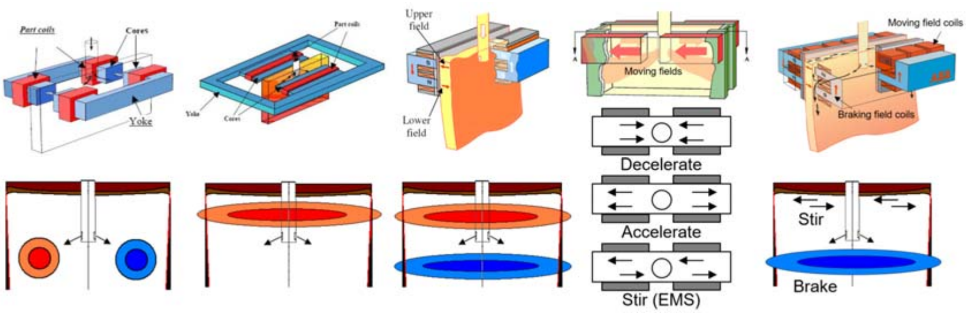
**Abstract**
During continuous casting of steel slabs, electromagnetic forces can be applied to help control the flow pattern in the mold, augmenting the effects of nozzle and strand geometry, casting speed, and argon injection. Specific configurations include: local, single-ruler, and double-ruler electromagnetic braking, traveling magnetic fields which actively drive flow in the upper mold, (speeding up, slowing, or stirring), and recently combinations of both systems together. Electromagnetic forces have the advantage of being changeable with casting conditions, and naturally adjust with flow variations. This gives this important flow-control tool the potential to stabilize flow in the mold, and to control molten steel velocities to lessen defects. To achieve these benefits in practice, however, requires good understanding of how the defects form, and the details of how the electromagnetic field(s) affect the transient flow. The best way to gain this understanding is by combining validated computational models with plant measurements. This paper shows recent advances using these tools to understand how different configurations affect both steady and transient flow behaviour, the formation of defects from level fluctuations, meniscus freezing, inclusion entrapment, and other mechanisms. These findings suggest promising ways to implement electromagnetic forces to lower defects to improve the process.

**Key words:** slab casting, electromagnetic braking, turbulence, transient flow, surface defects, inclusions

**Introduction**
The quality of continuous-cast steel depends greatly on fluid flow in the mold region of the process. Thus, the mold flow pattern must be controlled within acceptable process windows to avoid excessive surface velocities, large level fluctuations, meniscus stagnation, shell thinning, inclusion entrapment, and many other problems [1,2]. Together with the flow control system (stopper rod or slide gate), nozzle geometry, (port angle, shape, etc.), strand cross-section, submergence depth, casting speed, and argon injection, optimized electromagnetic forces offer an important way to maintain the flow pattern and velocity field within the optimal range for a given caster.

Schematics of the different electromagnetic system configurations that have been used in slab casting, and the magnetic fields which they produce, are shown in Fig. 1. ElectroMagnetic Braking (EMBr) applies a static magnetic field (using direct current) to restrict the flow through certain regions of the mold. The magnetic field strength through the strand thickness increases with the applied current according to the coil geometry. Movement of the conducting molten steel through this field induces a current in proportion to the field strength, but perpendicular to the field direction. The induced current in turn interacts with the flowing steel to generate a Lorentz force that increases with the steel velocity, and is rotated a further 90 degrees, so that it directly opposes the flow direction. Thus, the force naturally adjusts according to flow variations, giving it the potential to stabilize the flow.




(a) Local EMBr (b) Ruler EMBr (c) Double-ruler EMBr (d) Moving fields (e) Combined

Fig. 1. Types of electro-magnetic mold flow control systems showing hardware (top) and field shape (below).

**Tools to Study Electromagnetic Effects**

The best way to investigate electromagnetic effects is with validated computational models and plant measurements [3]. In addition to solving the Navier Stokes equations for the fluid flow, adding electromagnetics requires finding the magnetic field, by calculation or measurement, and solving Ohm's law and Maxwell's equations for the current and Lorentz forces [4]. Plant measurements include surface velocities, found from the solidified lumps on inserted nails [5], or deflection of inserted rods [6], and the surface level profile, found by tracing oscillation marks around the mold perimeter [7]. Lab experiments with flowing molten metal are helpful too [8, 9]. Finally, long-term plant studies to correlate defect incidence with casting conditions are essential.

**Effect on Fluid Flow**

The best steel quality is reported with a stable double-roll flow pattern in the mold [1,2], with jets impinging and flowing up the narrow face, with surface velocities back towards the SEN falling within an optimal range. That range has been reported as 0.2 – 0.5 m/s [10], but depends on the specific geometry and casting conditions. Single-roll flow patterns, where the jet first impinges on the top surface and flows to the narrow faces, generate higher level fluctuations and defects, while complex flow patterns which are always unstable give the worst quality. In addition to maintaining an optimal time-averaged flow pattern, it is important to achieve stable flow that minimizes detrimental transient fluctuations, which are inherent in turbulent flow. Electromagnetic forces should be designed to avoid surface velocities that are either too fast or too slow, with an optimal turbulence level to promote mixing and melting of the slag layers, while improving flow stability.

Local EMBr fields create roughly circular regions of high flow resistance, positioned near the nozzle ports as shown in Fig. 2. They are designed to slow down jet flow, as it passes through these regions [11]. In practice, however, these regions tend to deflect the jets either up or down, according to the current submergence depth, which changes the port location relative to orientation of the circular magnetic field regions [7]. If the jet is below the region, it retains its momentum to impinge strongly against the narrow face, leading to high-speed surface flows and deep penetration of large particles. Worse is if the jet is above this region, so it will be deflected upwards to cause a detrimental complex flow pattern. Optimizing the field strength requires consideration of the submergence depth and mold width.

Single-ruler EMBr systems generally apply a static field across the entire top region of the mold, (Fig. 1b)) in order to slow down the flow, which is often useful to avoid excessive surface velocities in high-speed thin slab casters. However, the danger of a non-optimal single-ruler system is that surface velocities may become too slow if the field current is too high for the flow conditions. This can result in excessive cooling of the meniscus region, insufficient mixing of the mold slag layers, leading to meniscus freezing, where the accompanying subsurface hooks can capture inclusion-laden bubbles and mold slag droplets into the solidification front, leading to an increase in surface defects. Locating the single ruler below the nozzle ports can increase surface velocity and stabilize the flow [8,12,13]. In addition, vortex formation at the mold top surface, caused by biased surface flow due to nozzle misalignment, can be suppressed with single-rule EMBr together with optimized argon injection, field strength, and ruler location beneath the nozzle ports [14]. Care should be taken to avoid centering the magnetic field over the nozzle ports, as this creates flow instability [8,12,13].

Double-ruler EMBr sytems, also called "FC-Mold" [9], applies two rectangular-shaped magnetic fields across the mold width, with one above and the other below the nozzle ports, as shown in Fig. 1c). As pictured in Fig. 3, the upper ruler tends to slow surface velocities, decrease level profile variations, decrease level fluctuations, and dissipate high-frequency turbulent fluctuations if the field strength is increased [6] or if the ruler is located just above the nozzle ports, so it deflects the jet downwards [6,13,15-17].

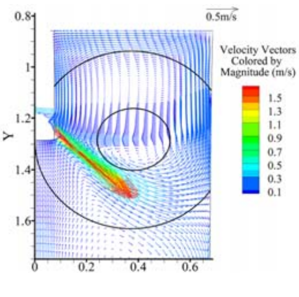



Fig. 2: Velocity vectors on the mold wide face centerplane with circles showing local EMBr field strength, and downward jet deflection [7].

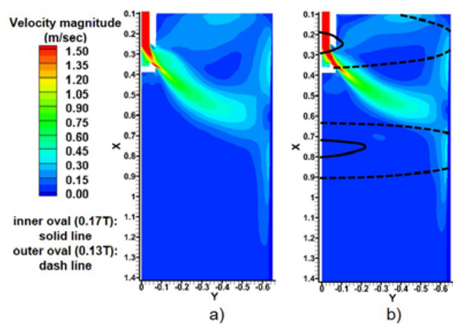



Fig. 3 Time-averaged velocity magnitude in mold centerplane a) without and b) with double-ruler EMBr, (0.17, 0.13T contours) [17].

The upper EMBr ruler also has an important strong effect on stabilizing flow through the nozzle, making it less subject to variations in swirl direction [17] or even suppressing swirl completely [6]. This helps to avoid surface velocity variations, which have been shown to originate with changes in swirl direction exiting the nozzle ports [17]. Increasing the strength of the lower ruler field tends to deflect the jet upwards, causing surface velocities and turbulence to increase. Thus, the two ruler strengths should be adjusted to achieve optimal surface velocity.

Moving magnetic fields are created from alternating current through a series of magnets, each having a different phase shift in order to create an electric motor effect that generates a force to actively drive the flow tangentially across the wide face surfaces. The strength of the force depends on both the applied current and the effective frequency of the phase shift. By adjusting the direction of the phase shift (and force), moving fields can cause the flow to accelerate (EMLA), to slow down, (EMLS), or to create a stirring motion around the mold perimeter, (EMS), as shown in Fig. 1d) [1,18]. Stirring should increase the chances of large particles being washed along the dendritic solidification front without being captured, until they can safely be removed into the top slag layers. This hypothesized mechanism needs to be quantified and validated by modeling and plant testing.

Combining EMBr and moving field systems together is recently creating new systems, such as shown in Fig. 1e), which offer even more ways to adjust the electromagnetic forces that change the mold flow pattern [19]. One combination with good potential is to combine a lower ruler brake, with stirring around the upper regions of the mold. The lower ruler should stabilize the jet flow impinging on the narrow faces, by deflecting the jets upwards in proportion to their downward deviations, while stirring should lessen inclusion entrapment.

**Effect on Surface Defects**

In addition to average surface velocities, transient flow fluctuations greatly affect surface defects. Level fluctuations lead to slag entrapment at the meniscus, and large level profile variations cause slag infiltration problems [17]. The effect of double-ruler EMBr on surface velocities and level profiles are shown in Figs. 4 and 5. Both the Large Eddy Simulations (LES) and measurements show that EMBr slightly decreases the surface level fluctuations, and consequently makes the level flatter. The decrease in variations with EMBr is indicated by comparing the error bars on the measurements, and the range of the calculated instantaneous profiles.

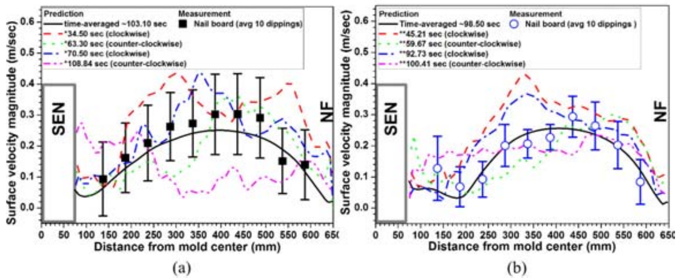



Fig. 4. Surface velocity profiles comparing LES modeling and measurements a) without and b) with EMBr [17].

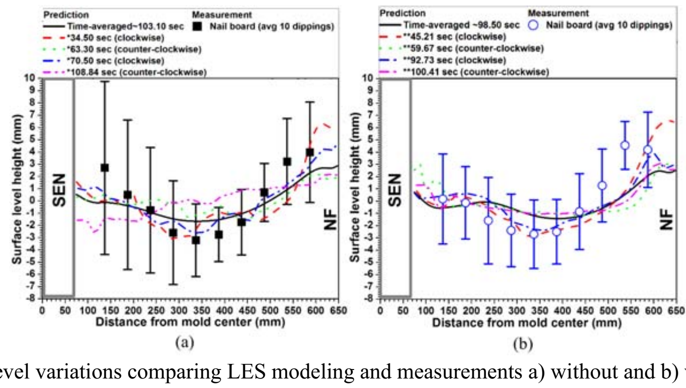



Fig. 5. Surface level variations comparing LES modeling and measurements a) without and b) with EMBr [17].

**Effect on Internal Inclusion Defects**

Inclusions transported into the lower recirculation regions are generally entrapped, leading to internal defects. Optimal application of lower EMBr ruler can slow the velocity of jets down the narrow faces, lessening the penetration of large inclusion-laden bubbles and slag droplets into the lower regions of the caster, thereby improving internal quality. LES results show that EMBr can also decrease the amount and rate of entrapment of smaller inclusions slightly, as shown in Fig. 6 [20].

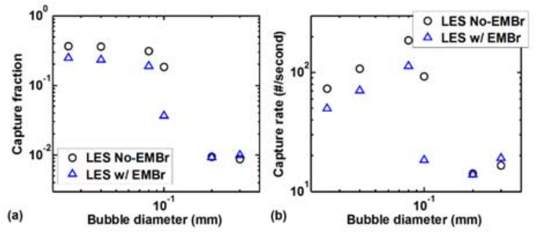



Fig. 6. Effect of EMBr on (a) capture fractions and (b) capture rates of bubbles [20].

**Future Developments**

Unlike most parameters that control mold flow, such as nozzle geometry, electromagnetic forces are capable of active real-time adjustment in the steel plant. Based on differences in the flow conditions, the magnetic field current can be adjusted to respond to changes in the flow pattern. For example, the expected field requirements can be set up according to the current casting conditions, (speed, submergence depth, mold width, etc.) based on offline parametric studies with validated computational models. Another pioneering method, to adjust the field to respond to unpredictable local variations associated with turbulence and argon gas, is to infer the flow conditions from real time measurements of the surface level profile using two eddy-current sensors on the same side of the mold [1]. Alternatively, the surface level profile and other phenomena may be inferred from thermocouples or high-resolution mold temperature maps using fiber-Bragg-grating sensor systems [21,22].

**Conclusions**

1) Computational models, validated with plant measurements of surface velocities and surface level profiles, can accurately predict transient fluid flow in continuous casting systems, including the effects of electromagnetic forces. This is providing better understanding of surface defects and particle capture, which can enable optimization of caster operation conditions, including electromagnetic flow-control systems.
2) Electromagnetic forces can significantly affect flow in the mold, with benefits to lowering surface and/or internal defects if implemented properly. Recent developments in electromagnetic systems which combine braking and stirring together, high-resolution mold temperature sensors, and advanced computational models, offer great potential for electromagnetic systems to further improve steel quality.

**Acknowledgements**

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**References**

1. Dauby, P.H., Revue de Métallurgie, 109, (2012), 113-136
2. B. G. Thomas, Chapter 14. in Making, Shaping and Treating of Steel, AISE, (2003)
3. B. G. Thomas, Steel Res. Int., 89 (2018), 1700312: 1-21
4. R. Chaudhary, S. P. Vanka, and B. G. Thomas, Physics of Fluids, 22:7, (2010), 075102
5. R. Liu, B. G. Thomas, J. Sengupta, S. D. Chung, and M. Trinh, ISIJ Int., 54, No. 10, (2014), 2314-2323
6. Jin, K., S.P. Vanka, and B.G. Thomas, Metall. Mater. Trans. B, 48B:1, (2017), 162-178
7. K. Cukierski and B. G. Thomas: Metall. Mater. Trans B, 39B:1, (2008), 94-107
8. B.G. Thomas, R. Singh, S.P. Vanka, K. Timmel, et al, J. Manufac. Sci. Prod., 15:1, (2015), 93-104
9. A. Idogawa, M. Sugizawa, S. Takeuchi, K. Sorimachi, and T. Fujii, Mat. Sci. & Eng., A173, (1993), 293-297
10. J. Kubota, K. Okimoto, A. Shirayama, and H. Murakami, in Mold Operation for Quality and Productivity, ISS, Warrendalte, PA, (1991), 197-205
11. Y. Wang and L. Zhang: Metall. Mater. Trans B, 42B: 6, (2011), 1319-1351
12. R. Singh, B. G. Thomas and S. P. Vanka, Metall. Mater. Trans. B, 44B:5 (2013), 1201-1221
13. R. Chaudhary, B. G. Thomas and S. P. Vanka, Metall Mater Trans B, 43:3, (2012), 532-553
14. B. Li, T. Okane, and T. Umeda, Metall Mater Trans B, 32:6, (2001), 1053-1066.
15. S.-M. Cho, S.-H. Kim and B. G. Thomas, ISIJ Int, 54:4, (2014), 855-864
16. R. Singh, B. G. Thomas and S. P. Vanka, Metall. Mater. Trans. B, 45B:3 (2014), 1098-1115
17. S.-M. Cho, B. G. Thomas, and S.-H. Kim, Metall. Mater. Trans. B, 47B:5 (2016), 3080-3098
18. S. Kunstreich and P.H. Dauby, Ironmaking & Steelmaking, 32:1, (2005), 80-86
19. H. Yang, M. Sedén, N. Jacobson, J-E. Eriksson, and H. Hackl, AISTech Conf. Proc., AIST, (2012)
20. Jin, K., S.P. Vanka, and B.G. Thomas, Metall. Mater. Trans. B, 49B:3, (2018), 1360-1377
21. M. Sedén, ABB, Sweden, Personal Communication, (2017)
22. G. Hedin, A. Kamperman, M. Sedén, K. Fröjdh, and J. Pejnefors, SCANMET V Conf. Proc., Swerea, (2016)