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Flow Control with Local Electromagnetic Braking in Continuous Casting of Steel Slabs

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Abstract: Electromagnetic forces are an important tool to control fluid flow in the mold, combined with other casting conditions, nozzle, and mold geometry. The effects of varying EMBr field strength and SEN submergence depth on fluid flow in the mold cavity is investigated with computational flow models and plant measurements. Magnetic field contours for a localized static EMBr field were measured in an operating thin-slab caster and incorporated into a three-dimensional (3-D) steady k-ε model of the nozzle and liquid cavity in the mold using the magnetic induction method in FLUENT. The model was first validated by comparing results with an analytical solution. It was further validated with plant measurements of surface velocity using nail boards and surface profile using oscillation mark measurements. Using the knowledge gained from the model and measurements together, electromagnetic forces and submergence depth can be controlled together to stabilize the fluid flow in the mold cavity and thereby minimize casting defects.

Key words: continuous casting, local EMBr, nail board, plant measurements, CFD, modeling

0 Introduction

Fluid flow in the mold is critical to steel quality: surface velocity should be kept within an optimal range in order to avoid slag entrainment (with excessive surface velocity) or surface defects (from level fluctuations or surface stagnation). Electromagnetic braking (EMBr) is useful to help to control the mold flow pattern in order to achieve optimal surface conditions. Systems include moving or static magnetic fields, and vary spatially from wide, rectangular areas ("ruler brakes") to circular areas.[1] This work investigates the simple local static magnetic field type EMBr using a computational model, which is validated with plant measurements. The effect of the submerged-entry nozzle (SEN) depth and EMBr field on the fluid flow pattern and meniscus are studied.

1. EMBr Magnetic Field Measurement

Plant measurements were obtained on the South slab caster at Nucor Steel in Decatur, AL. This caster features a standard bifurcated two-port SEN (Fig. 1) and a 90mm thick, straight, parallel mold with a sinusoidal oscillator. A local EMBr is used on this caster, and was set to 0.355T. Table 1 gives the casting conditions. A gauss meter was used to measure the magnetic field strength in the centerplane over a grid of points spaced 10cm horizontally and 5cm vertically. A typical three-dimensional (3-D) contour plot of the measured field strength is given in Fig. 2. The gray-hatched squares indicate the physical location of the magnets. The maximum strength of 0.32T is centered in an oval region, which is typical of local braking. The contour levels scale well with overall field strength.

2. Computational Model

A standard Reynolds-Averaged Navier-Stokes (RANS) model of turbulent fluid flow including electromagnetics is used to simulate the time-averaged flow pattern in the 90-mm thick slab-casting mold with local EMBr. The steady-state, incompressible, 3-D Navier-Stokes equations are solved in the nozzle and mold domain using the magnetic induction method for solving for electromagnetic force,[2] and the standard k-ε model in Fluent.[2] The mold domain consists of the liquid pool with the solidifying shell modeled with mass and momentum sinks.[1] The simulation conditions are given in Table 1. The nine cases, given in Table 2, investigate the combined influences of SEN depth and field strength on the flow pattern. Attention is focused on the surface velocity profile, turbulence levels, and surface level profile, which governs quality of the cast product. The surface level profile is calculated from the pressure field, based on a potential energy balance.[3]

Table 1 Casting and Simulation Conditions

Casting Speed	3.3m/min
Mold Width	1374mm
Mold Thickness	90mm
Meniscus Level Below Top of Mold	100mm
Domain Width	687mm
Domain Thickness	45mm
Domain Length	2500mm
ρ_{steel}	7000 kg/m^3
ρ_{slag}	3000 kg/m^3
μ	0.006 kg/m-s
σ	714,000(Ω-m)$^{-1}$
Gravity	9.81 m/s^2

Table 2 Parametric Study

	SEN Depth (mm)	EMBr Setting (T)
Case 1	250	0
Case 2	250	0.2525
Case 3	250	0.355
Case 4	300	0
Case 5	300	0.2525
Case 6	300	0.355
Case 7	350	0
Case 8	350	0.2525
Case 9	350	0.355

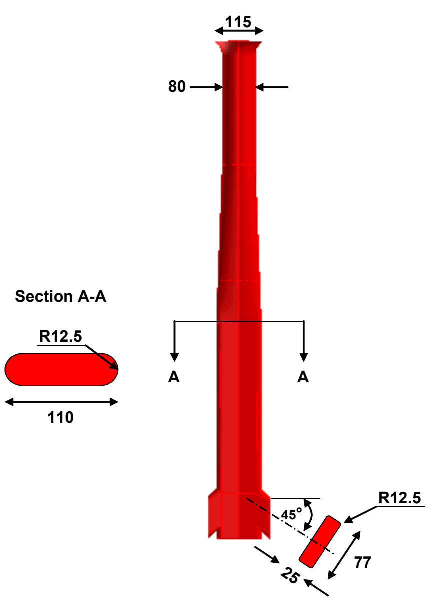

Fig. 1 Nozzle Geometry

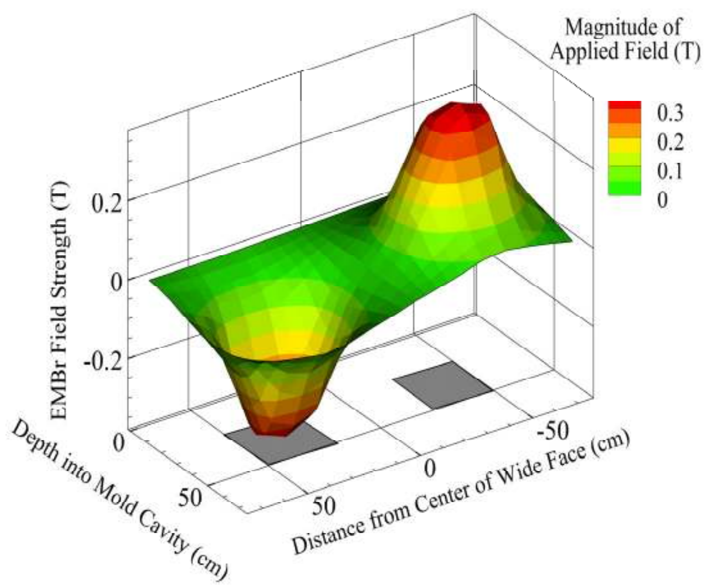

Fig. 2 Measured electromagnetic field contours (0.355T)

The typical computed flow pattern is shown in Fig. 3, which shows velocity vectors on the wide face centerplane, for Case 6. The jet exiting the nozzle travels across the mold cavity, impinges on the narrow face, splits into upward and downward jets, creating the classic upper and lower recirculation zones of a double-roll flow pattern. In the upper recirculation zone, fluid flows up the narrow face, back across the top surface, and down the SEN wall, to rejoin the jet exiting the nozzle. The brake causes some of the secondary jet flowing up the narrow face to split off early and flow back across the mold just above the brake region, altering velocities in the upper recirculation region. In the lower recirculation zone, fluid flows down the narrow face, across the mold cavity width, and up the center of the mold cavity. The lower recirculation zone is much larger and has lower velocities than the upper zone, because it is not confined. The upper zone is constrained by the top surface and the jet exiting the SEN, which tends to bend the jet slightly upwards.

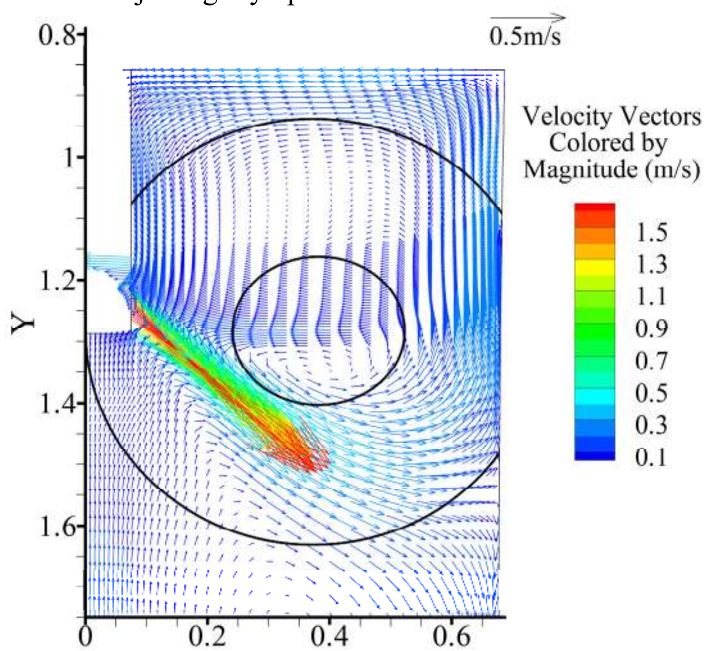

Fig. 3 Velocity vectors on the mold wide face centerplane for Case 6, with outer circle showing extent of EMBr field, and inner circle showing region of strongest field.

Velocity across the top surface is compared for all nine cases in Fig. 4, which shows velocity toward the SEN on a line across the wide-face centerplane 10mm below the meniscus. A parabolic velocity profile is seen, with a maximum about 450mm from the mold center. Without EMBr, surface velocity decreases with increasing SEN depth. With EMBr, this trends reverses, because the jet drops below the EMBr region, and maintains its momentum.

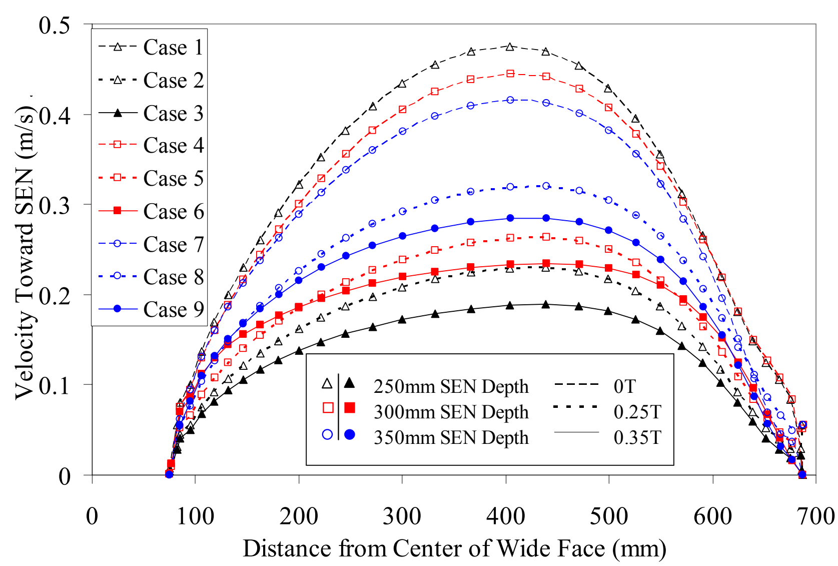

Fig. 4 Velocity across top surface toward the SEN for all cases (see Table 2)

3. Nail-board Measurement of Surface Velocity

The nail board dip test is a simple method to characterize flow at the meniscus. A row of nails is inserted into a long board, and dipped perpendicularly through the slag/steel inter-surface for 3-5 seconds. Upon removal, a knob of steel has solidified on the end of each nail. Nail board dip tests have commonly been used to determine the depth of the liquid flux layer that lies atop the molten steel.[4] This can be found by affixing an aluminum wire alongside the nails prior to performing the dip test, and recording the difference between the melted wire height and the solidified knob.

The angular profile of the knob can be further analyzed to gain insight into the flow pattern. The direction of the flow can be found by recognizing that the high end of the angular profile indicates the direction of steel flow past the nail, as shown in Fig. 5. Recently, Rietow used a carefully-validated computational model to determine a relation to correlate knob height difference, Δh, and nail diameter to surface velocity of the molten steel across the top of the mold.[5] Knob height difference is the difference in height between the low end and the high end of the knob profile, as shown in Fig. 6. This correlation, illustrated in Fig. 7, enables accurate, fast measurement of meniscus velocity in a plant setting. The height difference is most sensitive to velocity in the important range of 0.2 – 0.5 m/s. Within this range, height difference increases with increasing surface velocity and increasing nail diameter.

Nail-board tests are compared with the computational predictions of this work. Ten 7.5cm-long, 5mm-diameter nails were hammered into a 6.2cm wide, 2cm thick, 550cm long pine board to a depth of approximately 2.5cm. The nails were spaced 5cm apart, and 5cm from each end of the board. A typical nail from this test is shown in Fig. 6. Velocities measured at each nail are plotted across the mold in Fig. 8, together with the model-calculated surface velocity profile for the same conditions (Case 6). The numerical results match surprisingly well both near the narrow face and near the SEN.

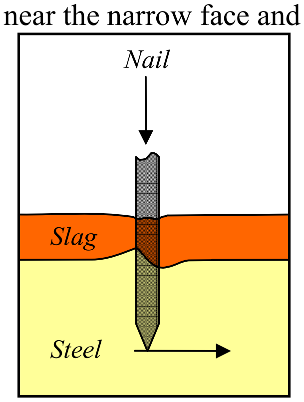

Fig. 5 Nailboard method to measure steel surface speed and direction

Fig. 6 Nail photo showing measurement of solidified knob

4. Oscillation Mark Profiles

Oscillation marks are small depressions in the surface of every steel slab caused by the partial freezing of the meniscus during a mold oscillation cycle.[6] These marks can be used to reveal the shape of the meniscus at the instant in time they formed. This gives another opportunity to validate the computational model; the simulated meniscus shape caused by the fluid flow pattern can be compared with the meniscus shape obtained from oscillation marks. Fig. 9 shows a photograph of oscillation marks traced on a sand-blasted surface of a sample of steel slab.

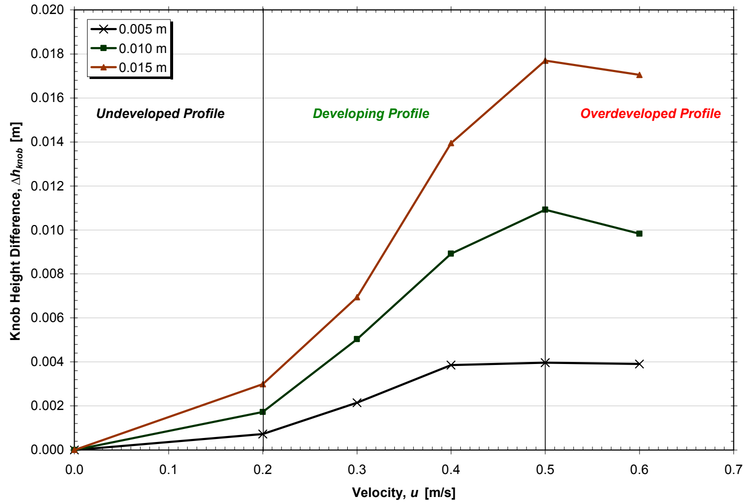

Fig. 7 Predicting steel surface velocity from measured knob height from nail-board test

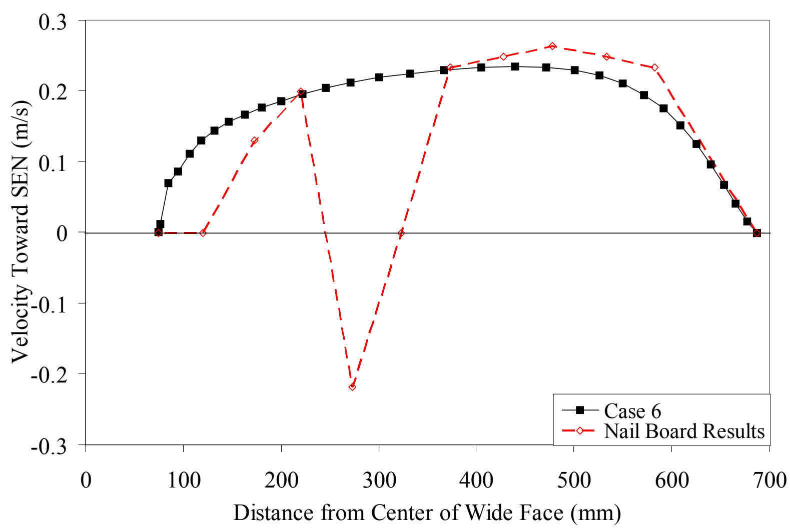

Fig. 8 Comparison of calculated and experimental meniscus velocity

Fig. 9 compares the calculated meniscus profile with eight separate oscillation marks. The oscillation marks were graphed such that the total "area under the curve" of each oscillation mark is equal to zero. The calculated profile roughly matches that of the oscillation marks. The trend of a high wave at the narrow face that slopes downward and stabilizes about halfway across the wide face before sloping slightly upward near the SEN is witnessed in both the experimental and numerical cases. The scale of the numerically calculated profile also matches that of the oscillation marks. The match is not exact, however, perhaps because the oscillation marks are transient by nature, as indicated by the variations between the eight oscillation marks. The standing wave heights range from 2.25mm to 6.0mm. The average measured height is 4.41mm, which is only 0.85mm smaller than the calculation. This shows that the model can roughly predict the average surface profile, both qualitatively and quantitatively, which is the best that can be expected from a steady-state model.

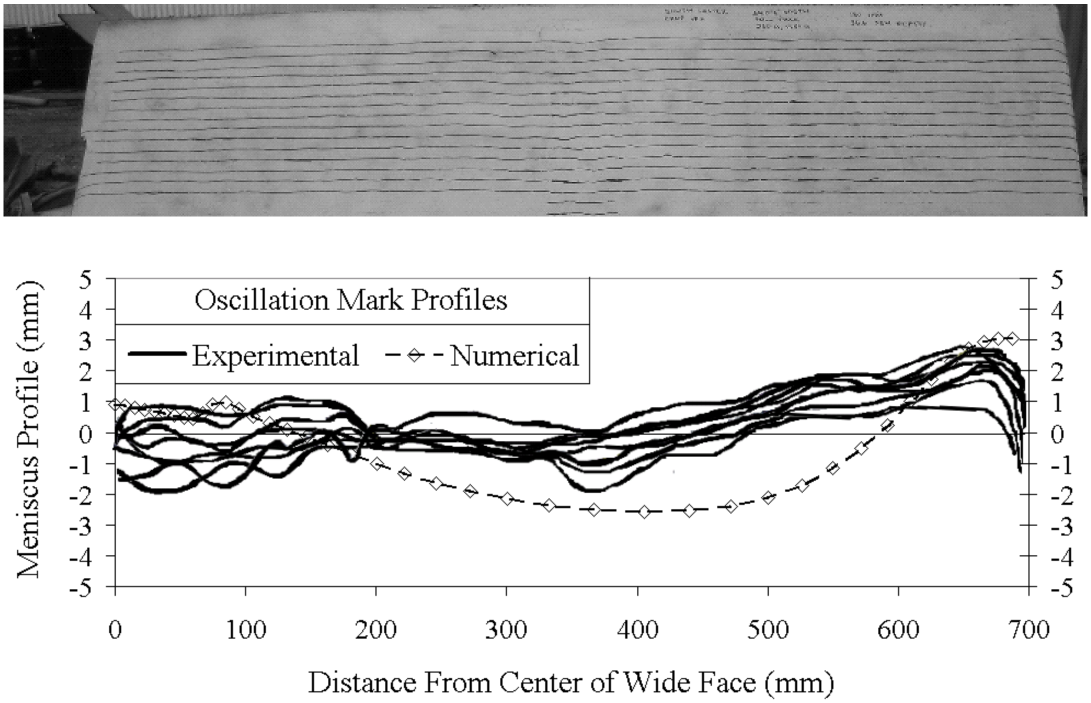

Fig. 9 Comparison of calculated meniscus profile with oscillation marks (Case 6)

5. Summary

Fluid flow in a continuous casting nozzle and mold cavity under a local EMBr has be investigated quantitatively using a 3-D steady flow model with the k-ε turbulence model in FLUENT. The EMBr field at Nucor Steel in Decatur, Alabama, USA was measured for use in the mold cavity simulations. After validating the model with a test problem, the results were validated by comparing with plant measurements of surface velocity from nail boards and meniscus shape (standing wave height) from oscillation mark profiles. As explained in further detail elsewhere,[1] a parametric study on the combined effects of EMBr and SEN depth revealed the following:

1. Increasing EMBr field strength at constant SEN depth causes a steeper downward jet angle, lower impingement point, lower velocities deep in the caster, expanded weaker upper recirculation zone with lower top surface velocity and flatter meniscus profile.

2. Increasing SEN Depth without EMBr has almost the same effects as increasing EMBr listed above. The only exception is that jet dissipation is not increased, so downward velocity increases at depths more than 0.5m into the mold cavity.

3. Increasing SEN Depth with EMBr has almost exactly the opposite effects as increasing EMBr. This is because the jet tends to move below the EMBr region, so is less affected by the EMBr field.

6. Implications

This investigation provides insight into how to best operate this caster for these conditions. The local EMBr is beneficial, as it lowers surface velocity and flattens the meniscus profile (standing wave height). This prevents excessive surface velocities, and the corresponding slag entrainment, level fluctuations, inclusions and surface defects that accompany casting without electromagnetics for this geometry and casting speed. The EMBr field strength should vary with SEN depth to maintain constant meniscus conditions. Optimum operation depends on the location of the EMBr field relative to the SEN port outlets. For this caster, higher EMBr field strength is needed with deeper SEN submergence.

7. Acknowledgements

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