ANNUAL REPORT 2011

UIUC, August 18, 2011

Mold Flow with Local EMBr and Evaluation using Nailboard and Oscillation-mark Measurements

Chuanbo Ji (Visiting scholar/Ph.D. Student)

&Brian G Thomas

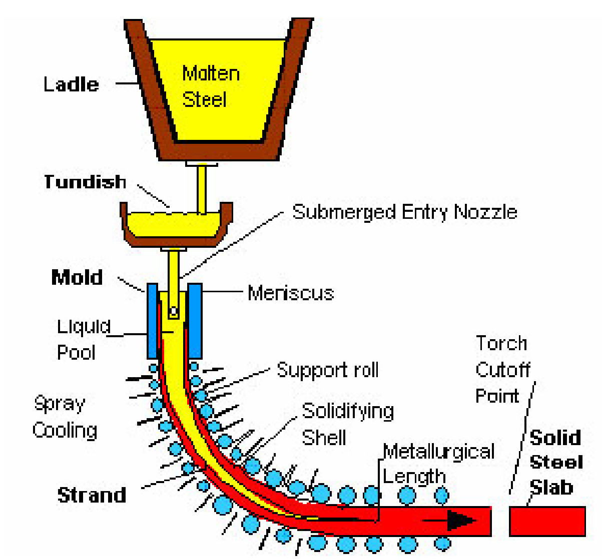
School of metallurgical & ecological engineering

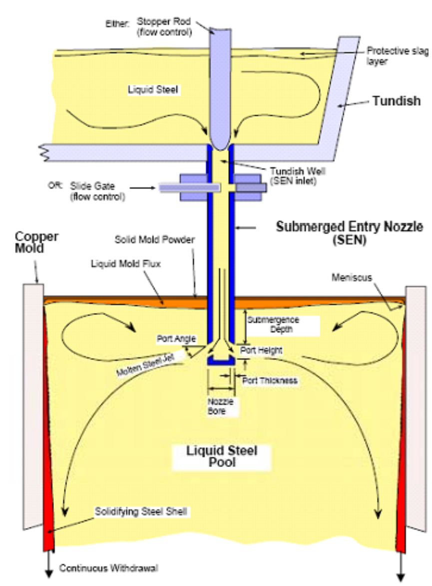
University of Science & Technology Beijing

Department of Mechanical Science and Engineering

University of Illinois at Urbana-Champaign

Background





Objectives

- To investigate how the electromagnetic brake affects the steel flow in continuous casting mold

  -3D Navier-Stokes equation for flow in Nucor steel nozzle and mold with 3 different magnetic field
- Experiment on nail board dip tests and oscillation mark measurements
- Validate the computational results with experimental measurements

Effect of electromagnetic forces

Magnetic fields greatly alter steel flow in the mold, with many potential benefits:

Control: surface turbulence, deep inclusion penetration, and internal microstructure

EMBr (DC): braking: slow down flow

EMS (AC): stirring: decelerate; accelerate

Local EMBr

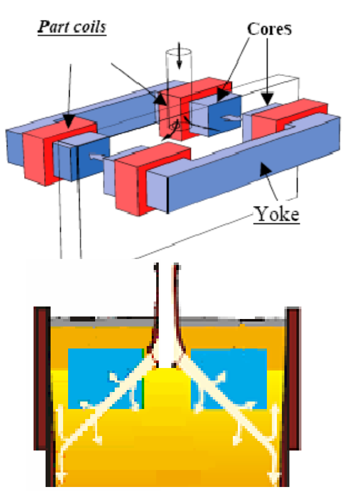
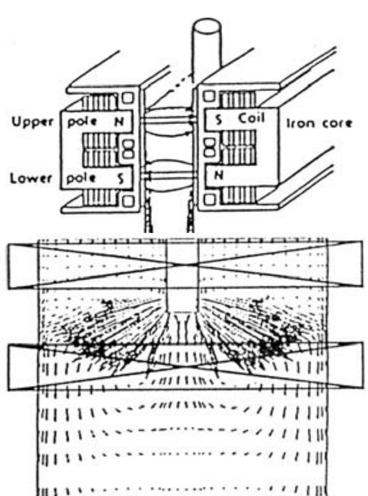
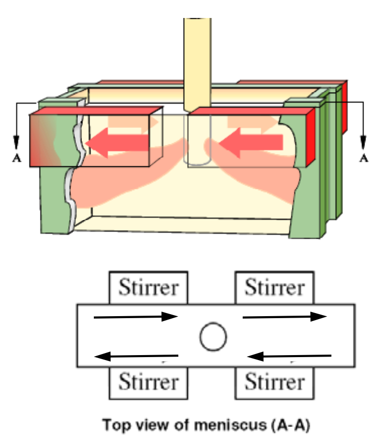


ABB Automation Technologies

Ruler EMBr

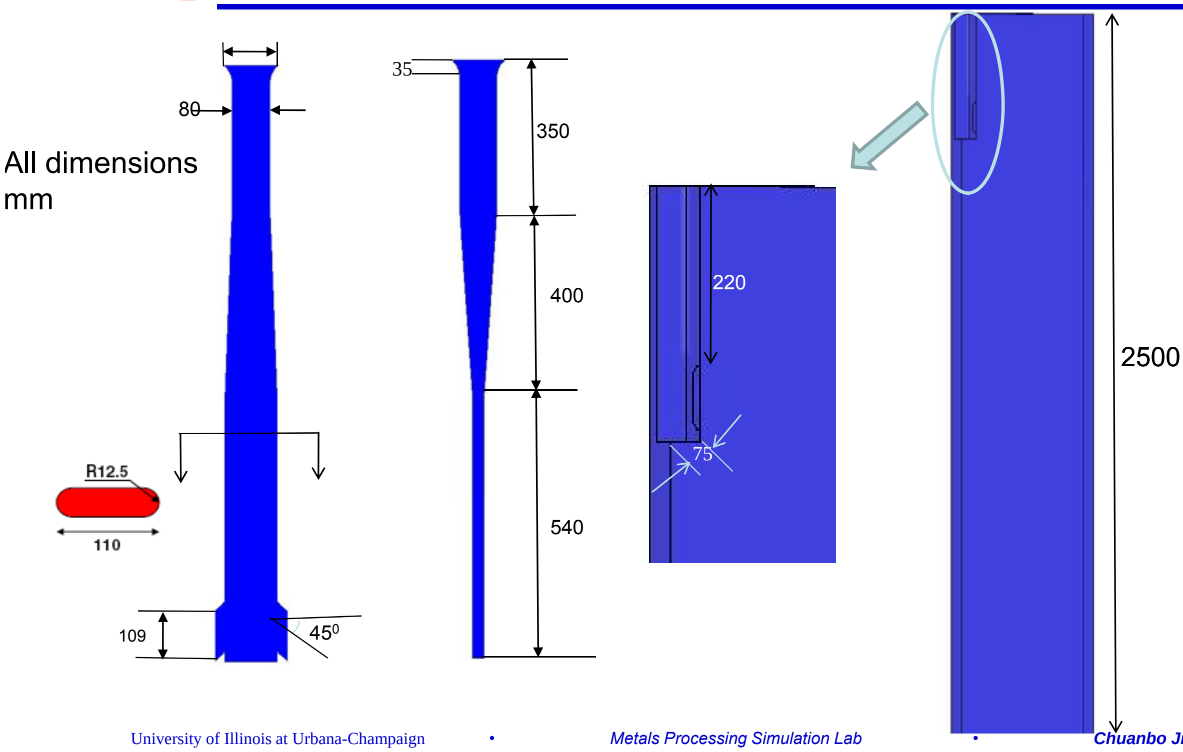


With FC Mold (B = 0.3T)



Suppliers: ABB, Danielli

Nozzle and mold simulation

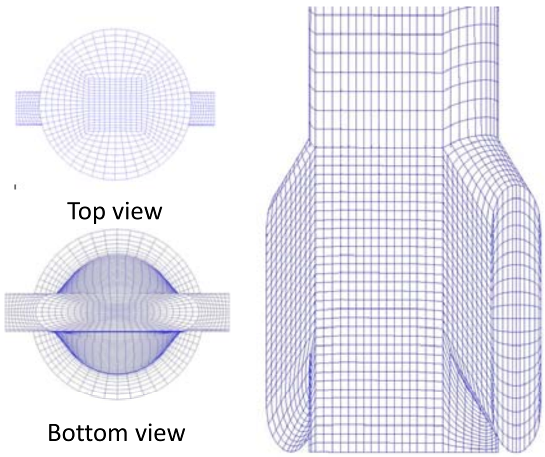


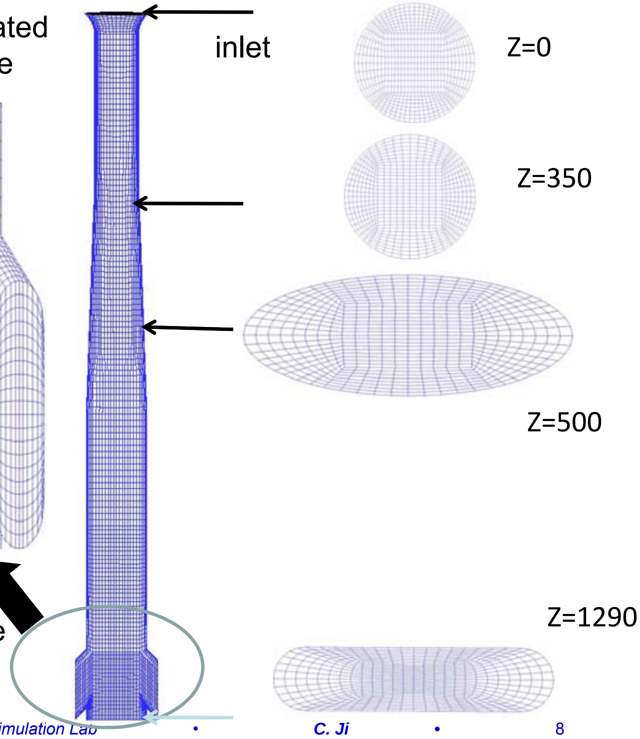
Process parameters

Nozzle inlet velocity	0.53 *m/s*
Casting speed	**3.0 *m/min***
Mold width	**1302 *mm***
Mold thickness	**90 *mm***
Mold length	**2500 mm**
Nozzle port dimension	25*mm*(width)×52*mm*(height) rectangular with top and bottom having 12.5 *mm* radius chamfered
Nozzle bore diameter (inner/outer)	110*mm*/150*mm*
SEN depth (from slag-steel interface to top of port)	**220*mm***
Density(ρ)	7000 kg/m^3
Viscosity(μ)	0.006 *kg/m s*
Nozzle port angle	45 degree downward
Shell	Yes
Gas injection	No

Nozzle Mesh, Boundary conditions

The full nozzle was meshed and simulated
120,592 Hexahedron cells in full nozzle





To reduce computational complexity, the nozzle was simulated separately from the mold

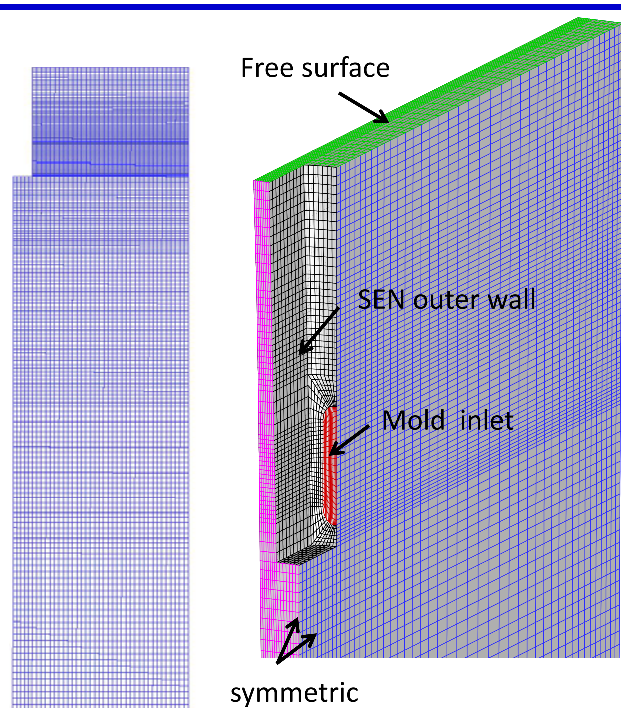
Mold mesh and Boundary conditions

- ~104,620 hexahedral cells in Quarter domain
- 1/4 mold was simulated with two symmetric plane to reduce computing cost

-Mold inlet: The velocity and turbulence parameters at the mold cavity inlet are specified using the results calculated at the nozzle port.

-Free surface: A zero-shear condition is specified at the mold top surface, Standard wall laws are used.

-Outlet: $P_{gage}=0$



Numerical model

- Continuity equation $\frac{\partial \bar{u}_i}{\partial x_i} = 0$
- Navier-Stokes equations: $\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j}\right) + \frac{\partial R_{ij}}{\partial x_j}$

Reynolds stresses: $R_{ij} = -\overline{u_i' u_j'}$

where, $R_{ij} = -\overline{u_i' u_j'} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \frac{2}{3} k \delta_{ij}$

To resolve excessive diffusion calculated by Standard k-ε Model, Filtered URANS model was applied to capture large-scaled transient features of flow.

$$\nu_t = C_\mu \min(1.0, f) k^2 / \varepsilon$$

$$f = \Delta\ \varepsilon / k^{3/2} \qquad \Delta = \sqrt[3]{\Delta x \Delta y \Delta z}$$

Johansen, J. Wu, W. Shyy, Filter-based unsteady RANS computations, Int. J. Heat and Fluid Flow, 25, 2004, pp. 10-21.

Where ,Δ is the constant filter size defined as the cube root of the maximum cell volume in the domain, for fine grids, f is smaller than 1, so viscosity decreases, and there is less “filtering” of the velocities relative to the standard k- ε URANS.

Mold Boundary conditions

- -Solidification shell: Mass and momentum sinks extract fluid through solidifying shell boundaries
- -Solid shell as a separate domain included in the model
- -Enhance wall treatment(EWT) applied at wall boundary

Numerical method

- Unsteady-state segregated solver
- Semi-Implicit Pressure Linked Equations (SIMPLE) method for pressure-velocity coupling
- 1^{st} order upwind scheme for convection terms
- Unscaled residuals were reduced below 1.0×10^{-04} to stagnant values.

MHD method

Two approaches can be used to evaluate the current density.

-magnetic induction equation;

-electric potential equation.

In this work, electric potential equation was used to solve the current density.

Ohm's law calculate the current density: $\boxed{\overline{j} = \sigma(\overline{E} + \overline{U} \times \overline{B_0})}$

the electric field $\overline{E}$ can be expressed as: $\boxed{\overline{E} = -\nabla\varphi - \frac{\partial \overline{A}}{\partial t}}$

φ and $\overline{A}$ are the scalar potential and the vector potential respectively. For a static, Ohm's law can be written as:

$$\boxed{\overline{j} = \sigma(-\nabla\varphi + (\overline{U} \times \overline{B_0}))}$$

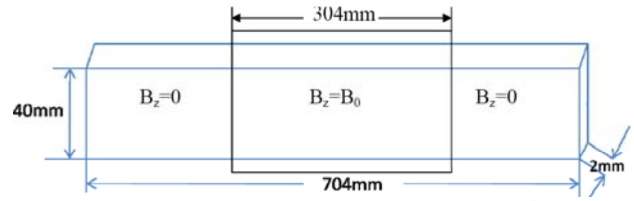
The boundary condition for the electric potential φ is given by

$$\boxed{\frac{\partial\phi}{\partial n} = (\overline{U} \times \overline{B_0})_{boundary} \cdot \overline{n}}$$

For the fluid momentum equation, the additional source term is the Lorentz force given by: $\boxed{\overline{f} = \overline{j} \times B}$

Fluent Model Validation

- To check MHD model, the typical 3D channel case is adopted.
- 3D steady SKE model
- Electrical potential method

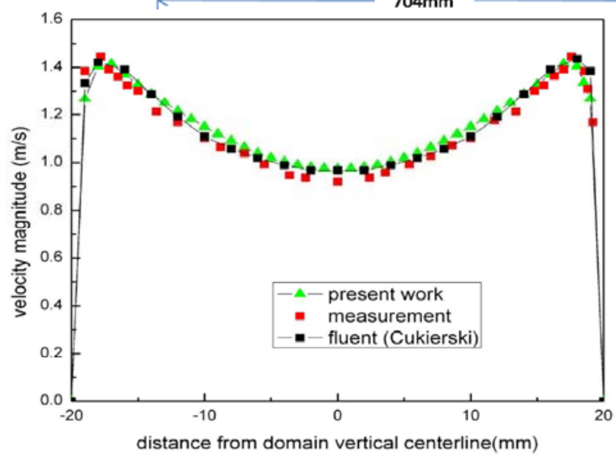


Material Properties:

ρ=1.355E+04 kg/m3
μ=1.55825E-03 kg/m-s
σ=1.05E+06 (Ω-m)-1

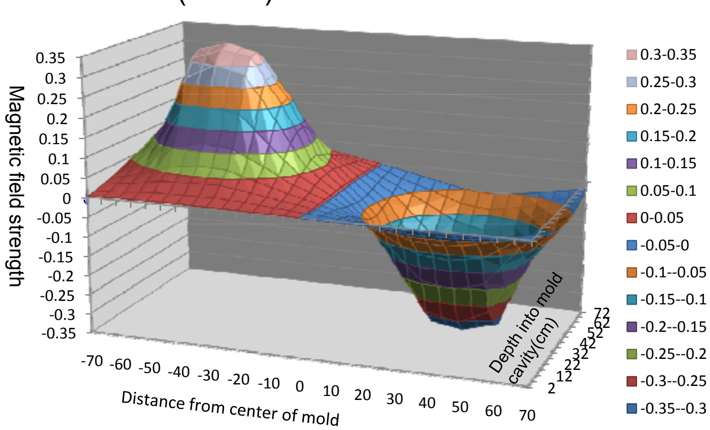
Boundary Conditions:

V_{in}=1.16141 m/s
k_{in}=5.99E-05 m2/s2
ε_{in}=7.529E-05 m2/s3
$P_{gage,\ outlet}$= 0
B_o= 1.3483 T

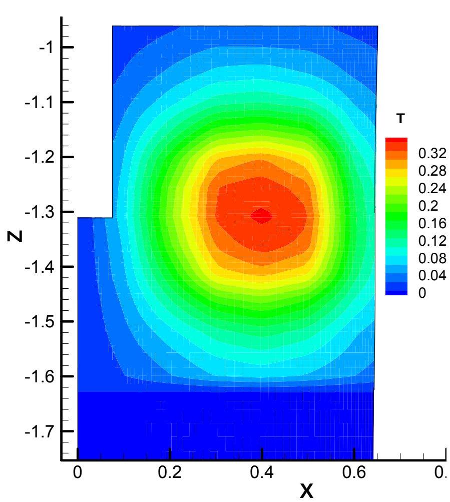


Applied magnetic field in mold cavity-260A

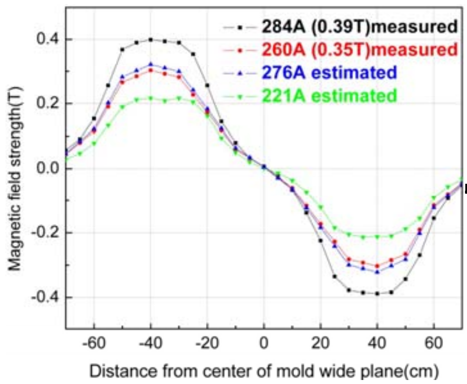
Contour of measured magnetic field strength for 260 A (0.35T)

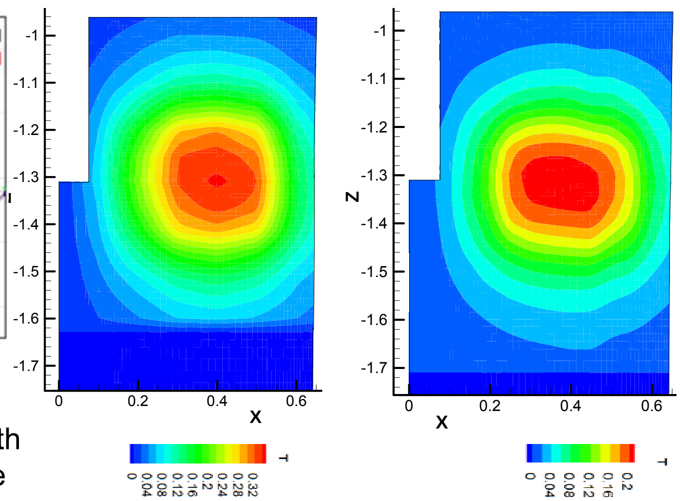


Magnetic field measured in mold cavity



Estimated magnetic field 276A, 221A



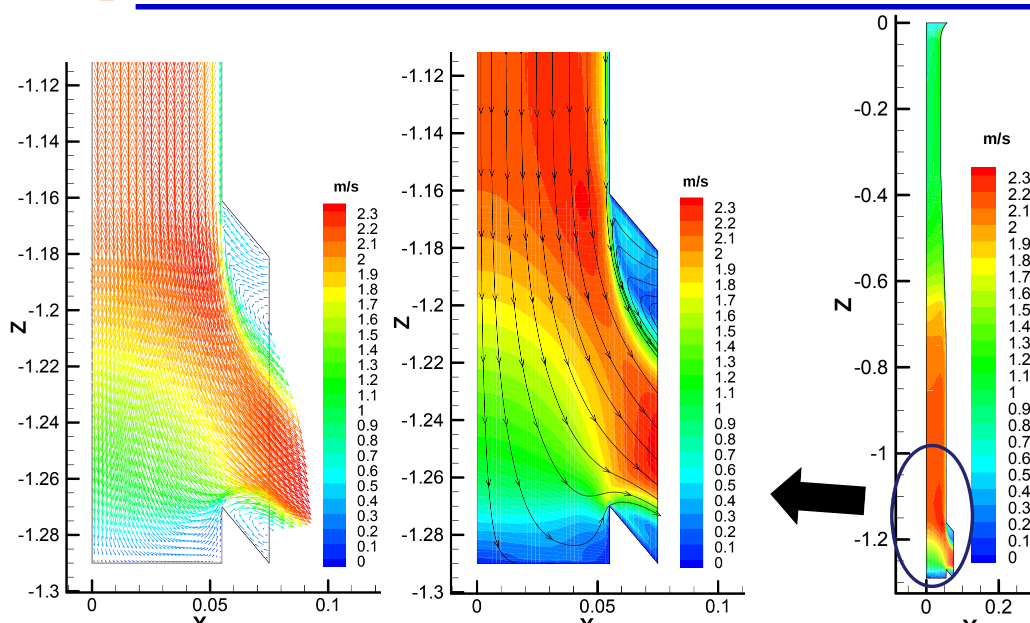


Two estimated EMBr field strength profiles(276A,221A) along a wide face centerline at 35 cm below the meniscus

276A

221A

Computational results: Nozzle flow

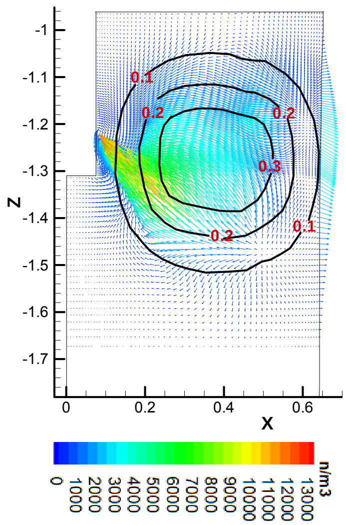


Nozzle velocity vectors on wide face center plane

Nozzle velocity contours on wide face center plane

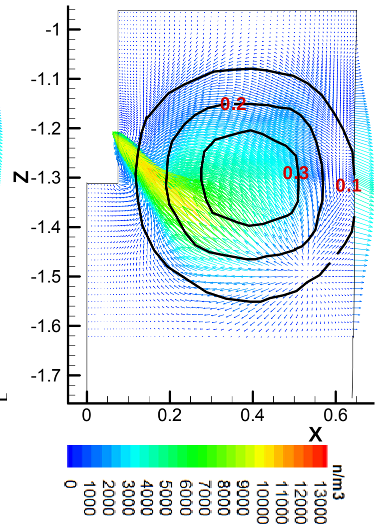
Continuous Casting Consortium

Lorentz force



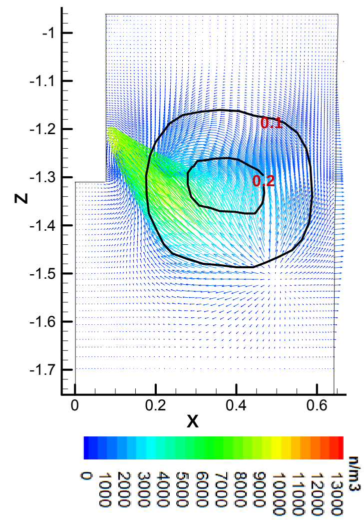
Max Lorentz force 12096 n/m^3

EMBr current 276A



Max Lorentz force 10748 n/m^3

EMBr current 260A

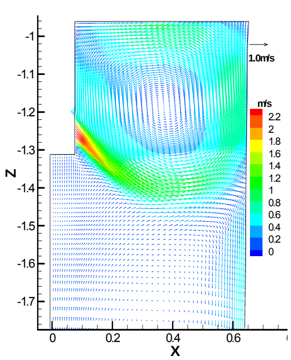


Max Lorentz Force 9582 n/m^3

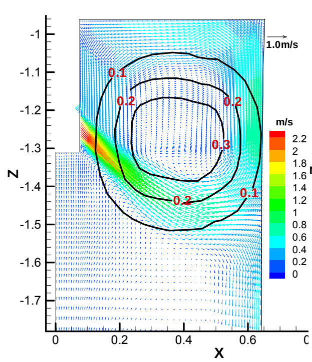
EMBr current 221A

Continuous Casting Consortium

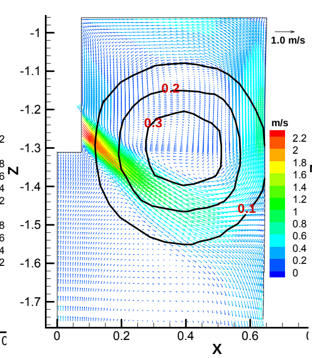
Mold flow with different EMBr current



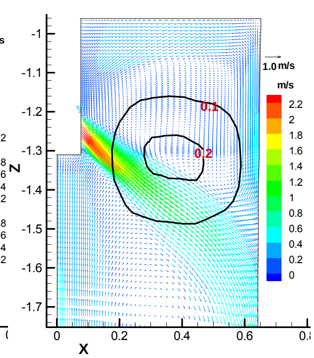
Max mold top surface velocity 0.49m/s
No EMBr



Max mold top surface velocity 0.33m/s
EMBr current 276A

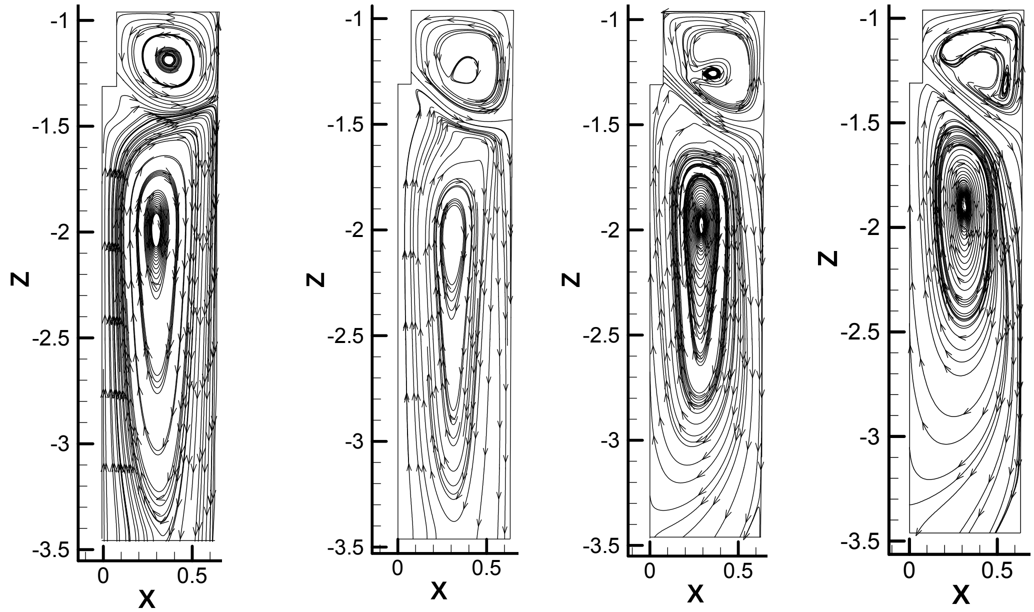


Max mold top surface Velocity 0.27m/s
EMBr current 260A



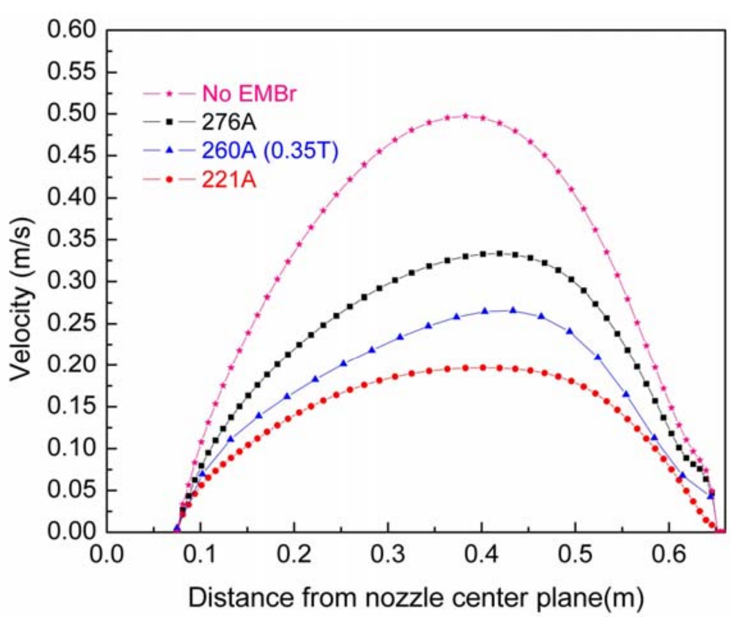
Max mold top surface velocity 0.20m/s
EMBr current 221A

Streamlines with different EMBr current



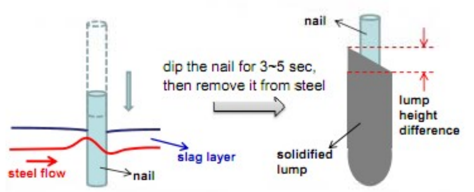
No EMBr | EMBr current 276A | EMBr current 260A | EMBr current 221A

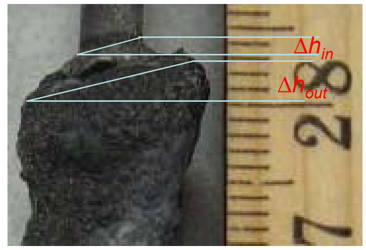
Top surface velocity with different EMBr current

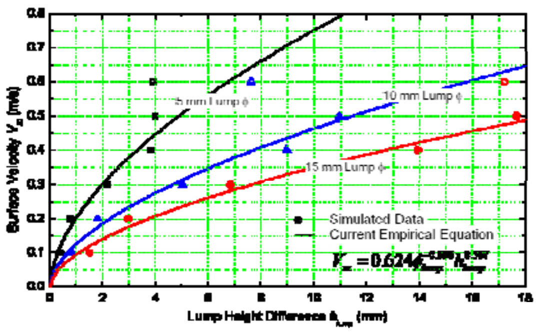


Strong magnetic field strength
High free surface velocity

Nail board test







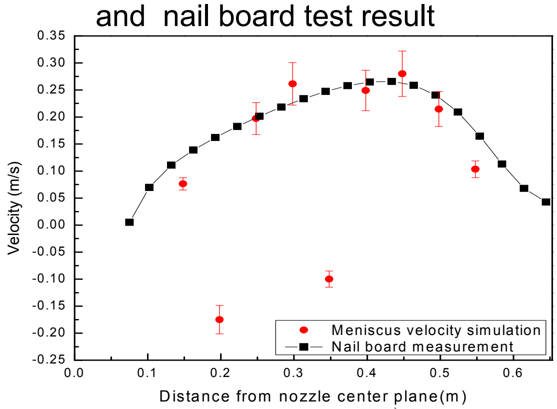
R. Liu ,etc. MEASUREMENT OF MOLTEN STEEL SURFACE VELOCITY WITH SVC AND NAIL DIPPING DURING CONTINUOUS CASTING PROCESS

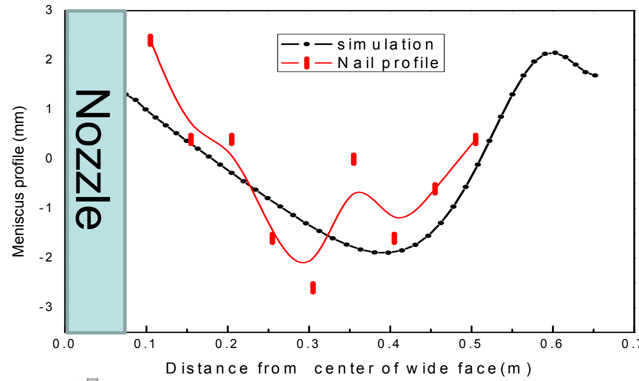
Nail board test result 260A

Nail	Δhin(mm)	Din(mm)	Δhout(mm)	Dout(mm)	Vin(m/s)	Vout(m/s)	Vavg(m/s)
1	0.4	5	0.5	9.9	0.12	0.09	0.10
2	1.2	5	2.4	10.2	0.23	0.20	0.21
3	2	5	1.5	11.1	0.30	0.15	0.22
4	1.5	5	3.5	10.8	0.26	0.24	0.25
5	1	5	0	10.8	-0.20	0.00	-0.10
6	2	5	3.2	11.5	0.30	0.22	0.26
7	1	5	2.3	10.8	0.20	0.19	0.20
8	1	5	1.5	10.5	-0.20	-0.15	-0.18
9	0	5	1.5	10.5	0.00	0.15	0.08

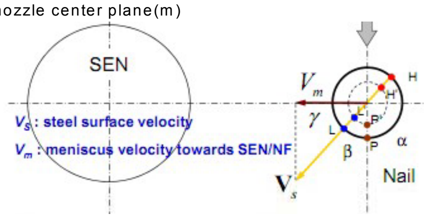
Meniscus velocity and profile with EMBr current 260A

Compare the mold top surface velocity between Computational result and nail board test result





H = High Point on Lump
L = Low Point on Lump
P = Reference Point
H' = High Point on Nail
L' = Low Point on Nail
P' = Reference Point on Nail
P' on the nail circumference
d1:arc length from point H' to point P' on the nail circumference
d2::arc length from point L' to point P' on the nail circumference



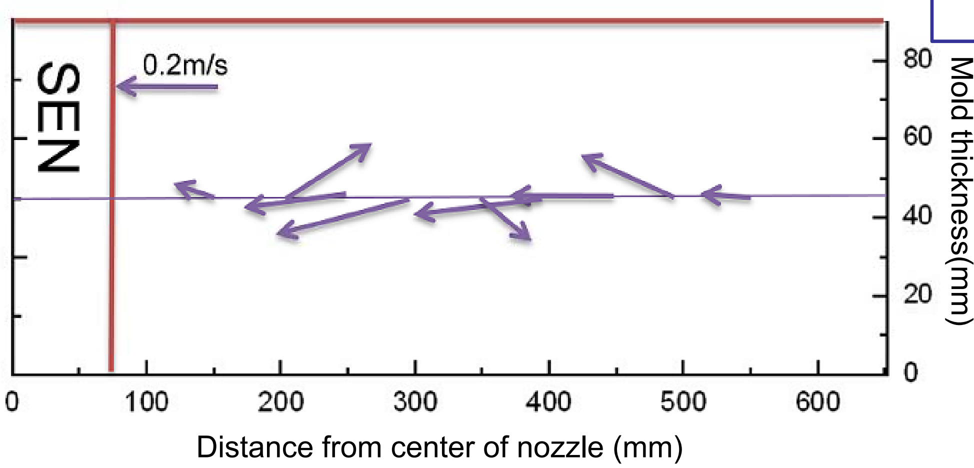
$$dV_m = \left|\left[\frac{a_2 h_{lump}^{b_2} - a_1 h_{lump}^{b_1}}{5}\cos\left(\frac{d_1-d_2}{d_{nail}}\right)\right]\right| d\left(d_{lump}\right) \rightarrow \pm 0.5mm$$
$$+\left|\left[\frac{15-d_{lump}}{5}a_1 b_1 h_{lump}^{b_1-1} + \frac{d_{lump}-10}{5}a_2 b_2 h_{lump}^{b_2-1}\right]\cos\left(\frac{d_1-d_2}{d_{nail}}\right)\right| d\left(h_{lump}\right)$$
$$+\left|\left[\frac{15-d_{lump}}{5}\left(a_1 h_{lump}^{b_1}\right) + \frac{d_{lump}-10}{5}\left(a_2 h_{lump}^{b_2}\right)\right]\sin\left(\frac{d_1-d_2}{d_{nail}}\right)\right| d\left(d_1-d_2\right)$$

The error estimation for nail board test is developed by Rui*. ***R.Liu etc, CCC annual report, 2010**

Meniscus profile comparison with nail board measurement

Reverse flow can be seen at 200mm 350mm from the center of nozzle

EMBr Current 260A

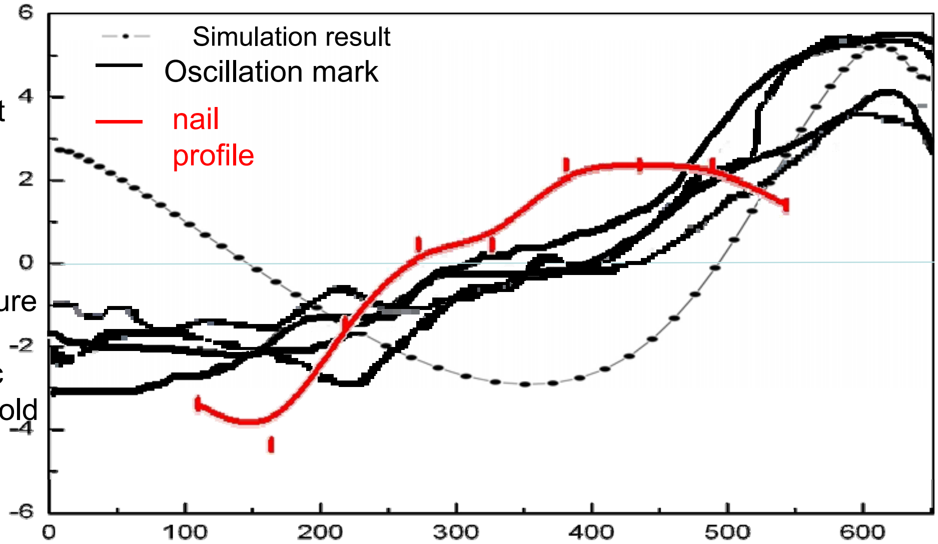


Meniscus profile-276A

The meniscus height
Was calculated by

$$\Delta h = \frac{P_{static} - \overline{p}_{static}}{(\rho_{steel} - \rho_{slag})g}$$

P_{static} is static pressure
At each point,
$\overline{P}_{static}$ is average static
Pressure over the mold
Top surface



Summary

- Electromagnetic brake was applied in continuous casting mold to control the flow pattern.
- Three different magnetic field strength simulations were performed to investigate the magnetic field effect on the mold flow.
- Increase the magnetic field strength in the mold cavity cause the high free surface velocity and increase the fluctuation at the meniscus.
- Nail board dip tests have been performed at Nucor-Decatur, and used to find:
  - Velocity profiles near the top surface steel/slag interface in the mold, including both speed and direction
  - Liquid level profiles
- molten steel velocity is highest about midway between narrow face and SEN, as expected.
- The oscillation mark can match the nail profiles in the surface of the molten steel. The trend of a high wave near the narrow face and then slopes downward across the wide face.

Acknowledgements

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, Posco, SSAB, ANSYS-Fluent)
- Nucor steel Decatur(Williams Bob; O'Malley Ron)
- CHINA SCHOLARSHIP COUNCIL
- Graduate students and visiting scholar in the lab