ANNUAL REPORT 2007

Meeting date: June 12, 2007

Electromagnetic Control of Fluid Flow in the Mold

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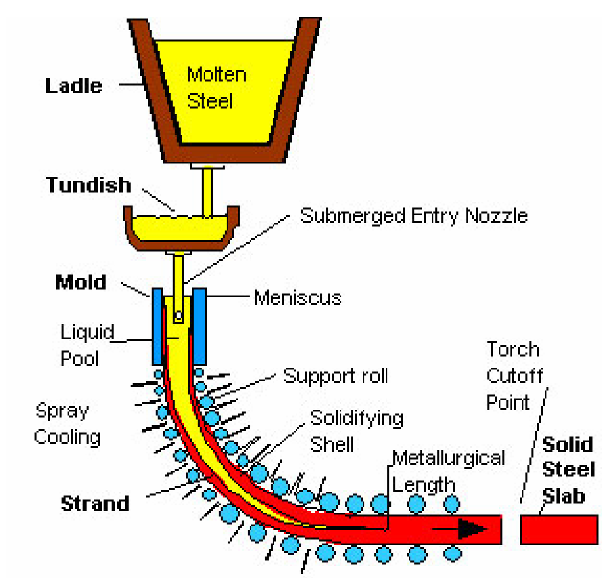
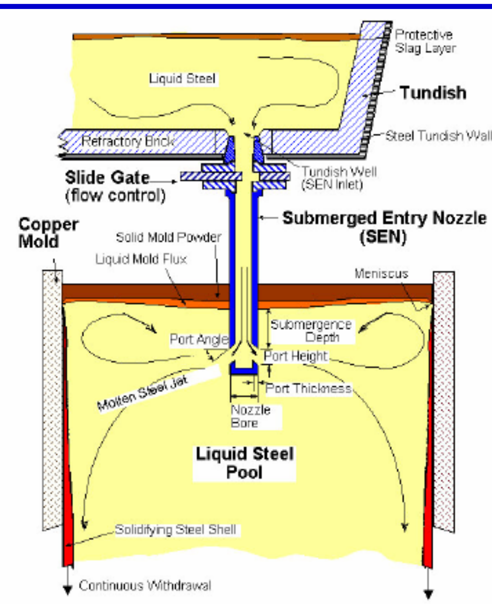
The Continuous Casting Process

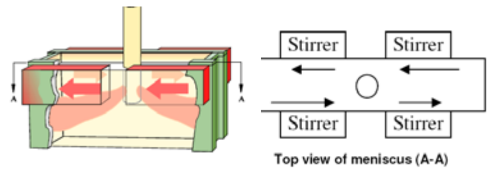


B.G. Thomas. "Overview of the Continuous Casting Process"

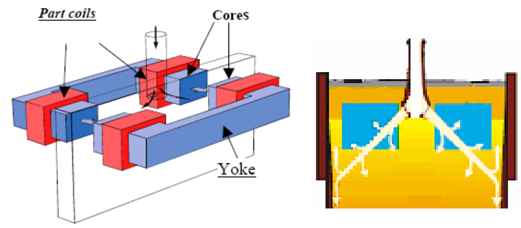


Why Add Electromagnetics?

- •Improve control of fluid flow in the mold
  - •Stabilize meniscus velocity
  - •Maintain a uniform mold level
  - •Reduce fluctuations in meniscus profile
  - •Reduce particle capture (i.e. bubbles, powder)
- •Improve internal microstructure
  - •Control superheat
  - •Discourage columnar grain formation
  - •Reduce centerline segregation
- •Two main types of electromagnetics
  - •Electromagnetic stirrers
    - •Use constantly varying AC current
  - •Electromagnetic brakes
    - •Use constant DC current
    - •Focus of this project



AC Electromagnetic Stirrer
Hackl *et al*, ABB Automation Technologies



DC Electromagnetic Brake
Trippelsdorf *et al*, International Scientific Colloquium,

Project Outline

- •Objective
  - •Discover how and why an electromagnetic brake affects steel flow in the continuous casting mold
- •Three phases to the project
  - •Experimental (in collaboration with Nucor Steel Decatur)
    - •EMBr measurement, nail board samples, and oscillation mark photos
  - •Computational Modeling
    - •Solve 3D Navier-Stokes Equations with FLUENT for flow in Nucor nozzle and mold with/without EMBr with 3 submergence depths
  - •Validation
    - •Compare computational results with experimental measurements

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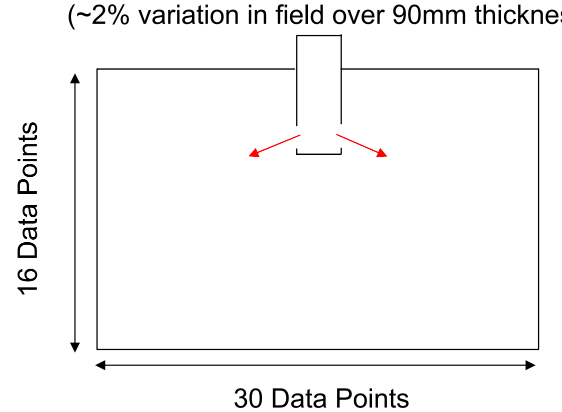
EMBr Measurements

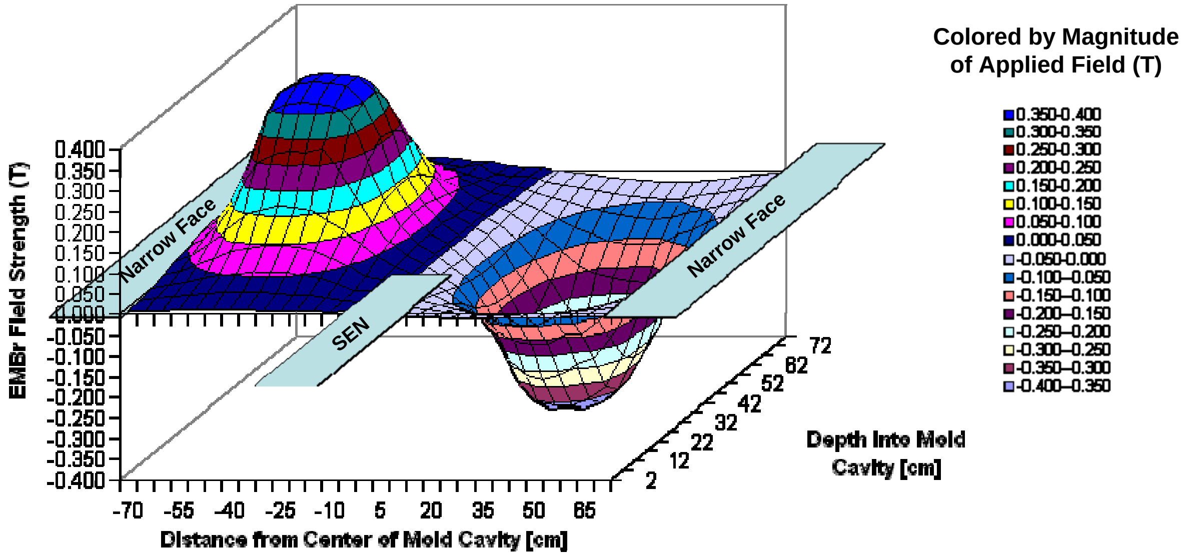
•Rather than guess at the behavior and magnitude of the magnetic field, Nucor allowed exact measurements of the field used in their casters to be obtained

•A Gauss meter was used to conduct the measurements

•Note that the magnetic field was assumed constant throughout the thickness of the mold (~2% variation in field over 90mm thickness)

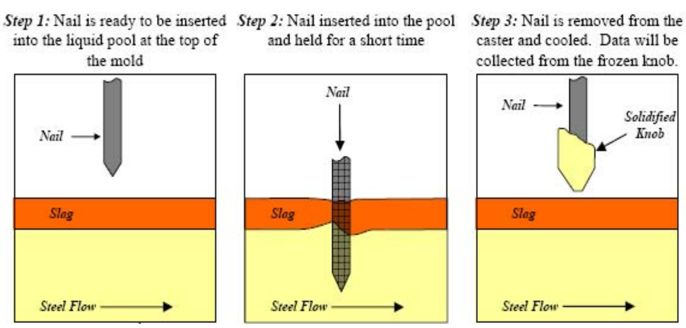


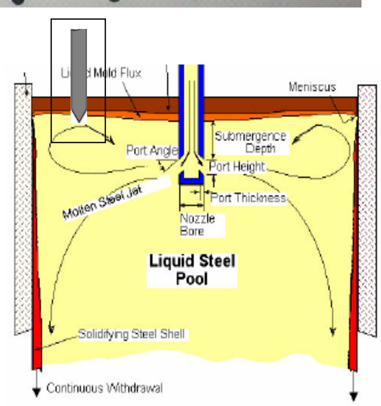
Example EMBr Measurement – 0.39T Set Point



•**For optimal braking efficiency, the applied magnetic fields on each mold half should be equal in magnitude and opposite in direction**

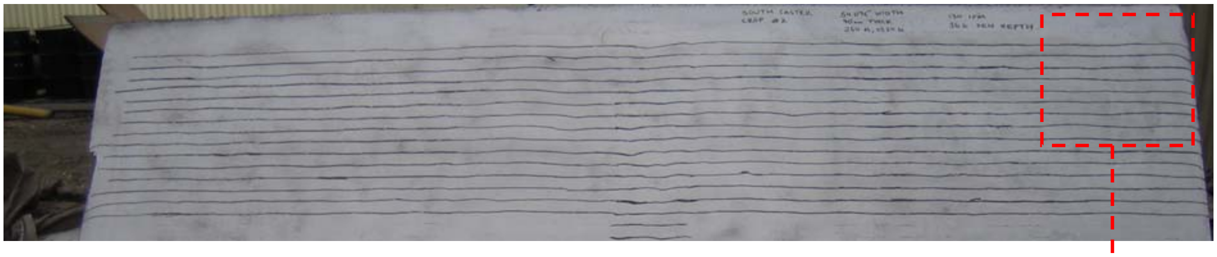
Nail Board Samples

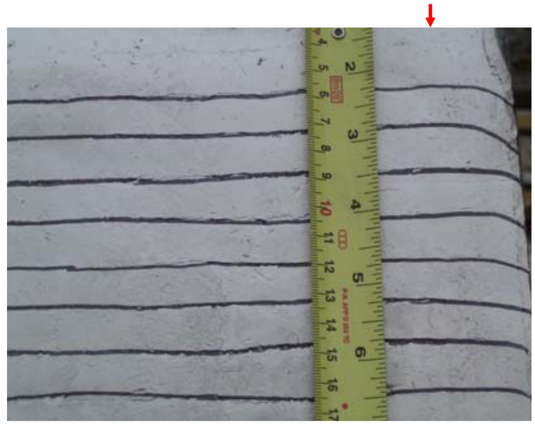




Rietow, 2007

Oscillation Mark Photos





- Slab crops were sandblasted, and oscillation marks were outlined to increase visibility
- The oscillation marks represent the meniscus profile, and will be compared with computational results for validation

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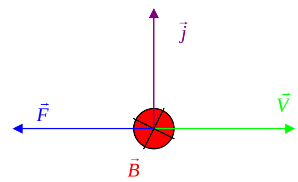
  - Validation
    - Compare computational results with experimental measurements

Electromagnetic Force Calculation

- Magnetic induction method
  - Flow of steel through an applied magnetic field will generate an induced magnetic field which, when coupled with the applied magnetic field, induces a force which opposes the flow



Coupled Equations

$$\vec{B} = \vec{B}_o + \vec{b}$$

$$\vec{j} = \vec{V} \times \vec{B}$$

$$\vec{F} = \vec{j} \times \vec{B}$$

$$\vec{F} = (\vec{V} \times \vec{B}) \times \vec{B}$$

Variables

$\vec{B}$ => Applied + induced magnetic field (T)

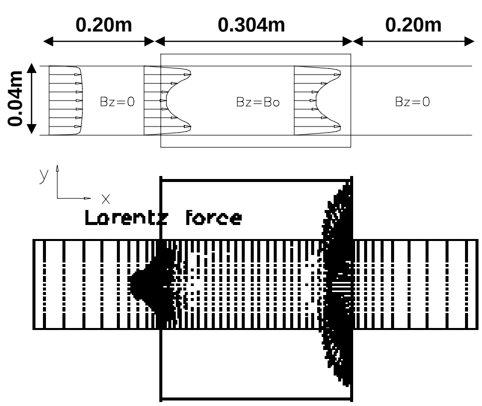
$\vec{V}$ => Velocity (m/s)

$\vec{j}$ => Current density (A/m^2)

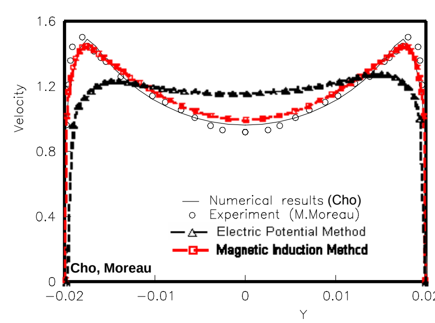
$\vec{F}$ => Lorentz Force (kg/m^3)

FLUENT Model Validation

- Test case provided by Dr. M.J. Cho and M. Moreau



- FLUENT Simulation Results



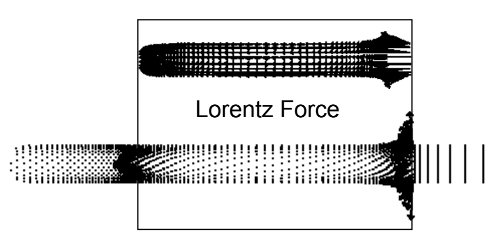
- Domain centerline velocity profile (above) and vectors of Lorentz force (below) for the magnetic induction method compare well with previous results

Material Properties:
ρ=1.355E+04 kg/m^3
μ=1.55825E-03 kg/m-s
σ=1.05E+06 (Ω-m)$^{-1}$

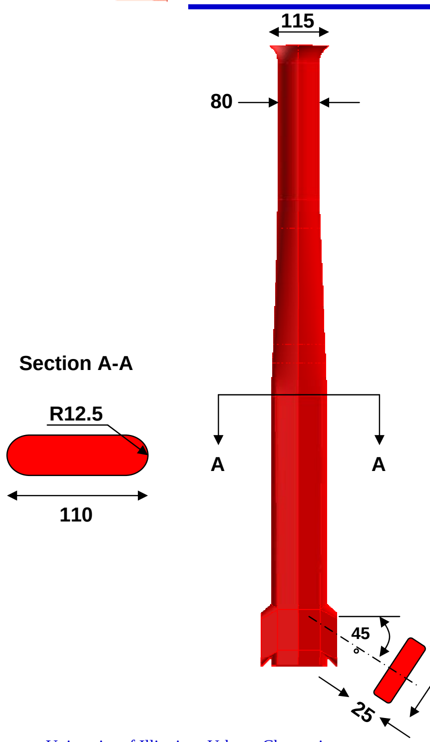
Boundary Conditions:
V_{in}=1.16141 m/s
k_{in}=5.99E-05 m^2/s^2
ε_{in}=7.529E-05 m^2/s^3
$P_{gage, outlet}$= 0
B_o= 1.3483 T

Electric Potential Method

Magnetic Induction Method



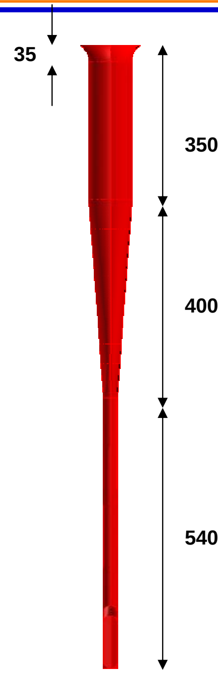
Nozzle Simulation



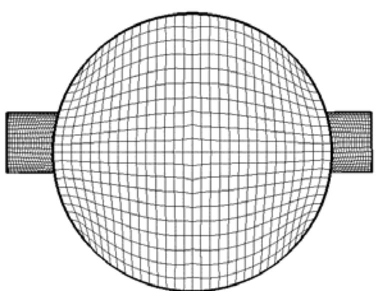
- All simulations solve the 3D Navier-Stokes equations in FLUENT using the standard $k-\varepsilon$ model for turbulent fluid flow
- Fully-developed velocity profile specified at the inlet, and P_{gage}= 0 specified at the outlet ports
- Working fluid taken to be steel with the following properties:
- ρ = 7000 kg/m^3
- μ = 0.006 kg/m-s
- σ = 714,000 (Ω-m)$^{-1}$

R12.5

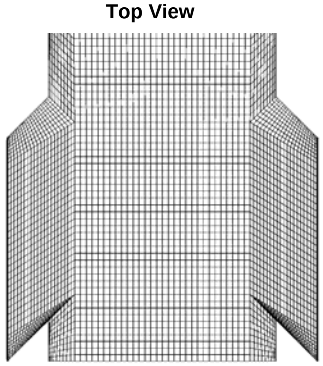
77



Nozzle Mesh

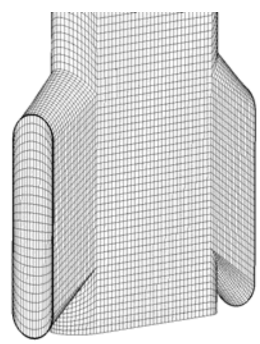


Top View

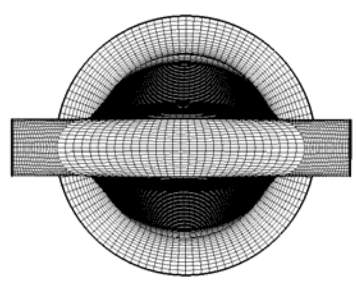


Front View

- A structured, hexahedral mesh of ~200,000 “brick” cells was used for the nozzle simulation
- The full nozzle was meshed and simulated
- To reduce computational complexity, the nozzle was simulated separately from the mold

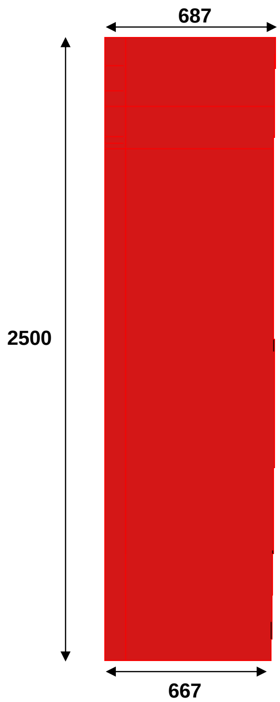


Isometric Port View

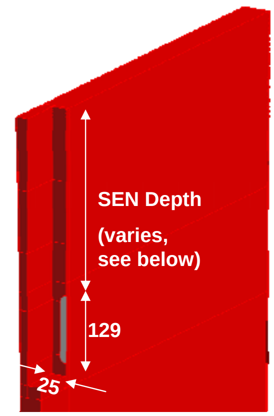


Bottom View

Mold Simulations



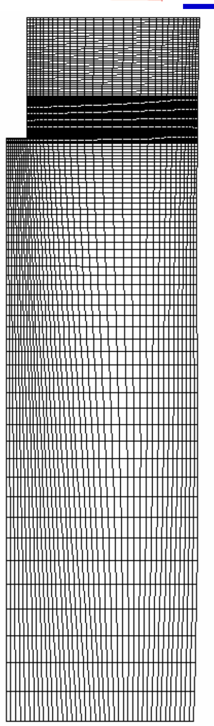
- •Casting speed: 3.3m/min
- •Shell profile calculated using CON1D and incorporated into mold cavity geometry
- •Symmetry assumed: ¼ of mold is simulated
- •Inlet conditions: Taken from nozzle right port velocity and turbulence parameters
- •Outlet condition: $P_{gage} = 0$
- •Solidification model: Mass and momentum sinks extract fluid through solidifying shell boundaries (from Bret Rietow, MS Thesis, 2007)



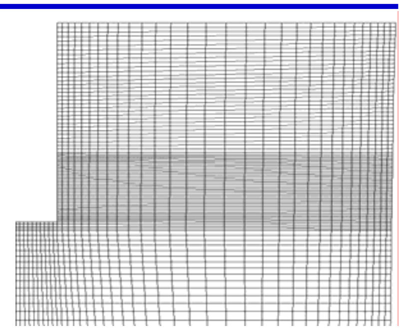
•3 SEN Depths:

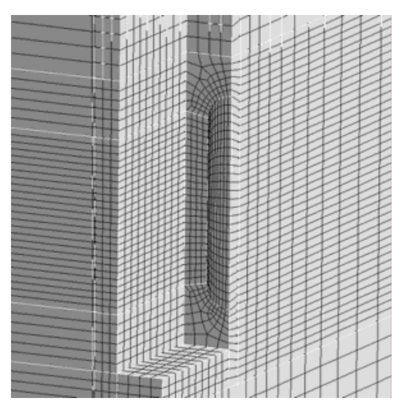
250mm (shallow)
300mm (validation case)
350mm (deep)

Mold Mesh

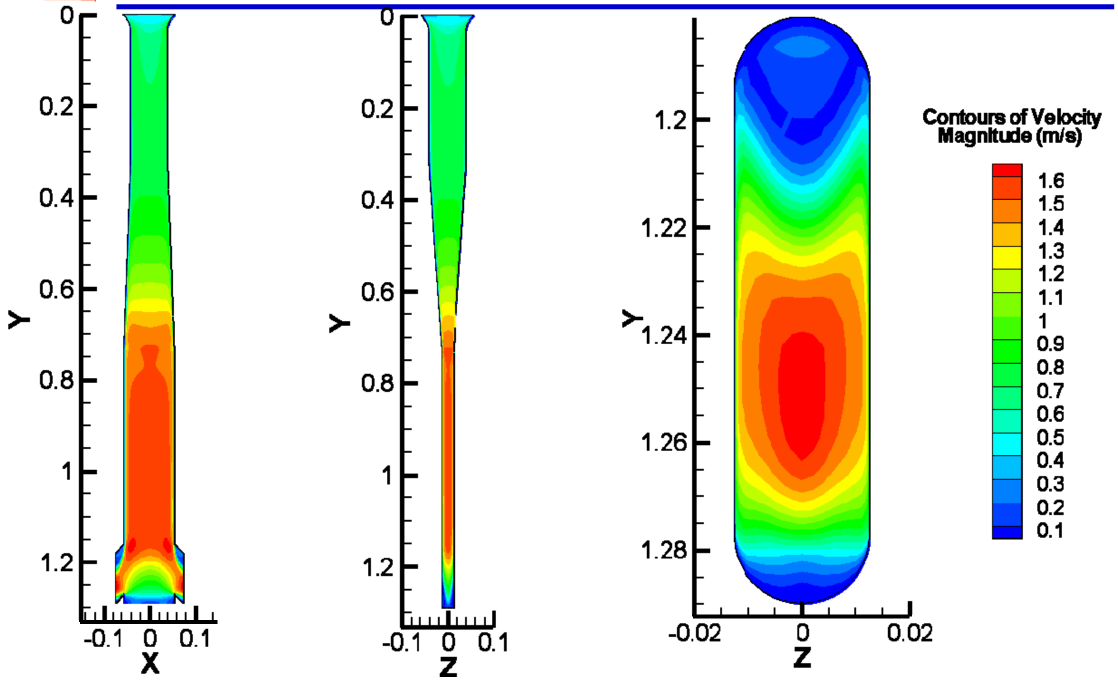


- •A structured, hexahedral mesh of ~50,000 "brick" cells was used for the mold simulations
- •Taking advantage of symmetry planes reduced computing time from 30 hours (full mold) to 5 hours (1/4 mold) without the EMBr, and from 48 hours (full mold) to 12 hours (1/4 mold) with the EMBr



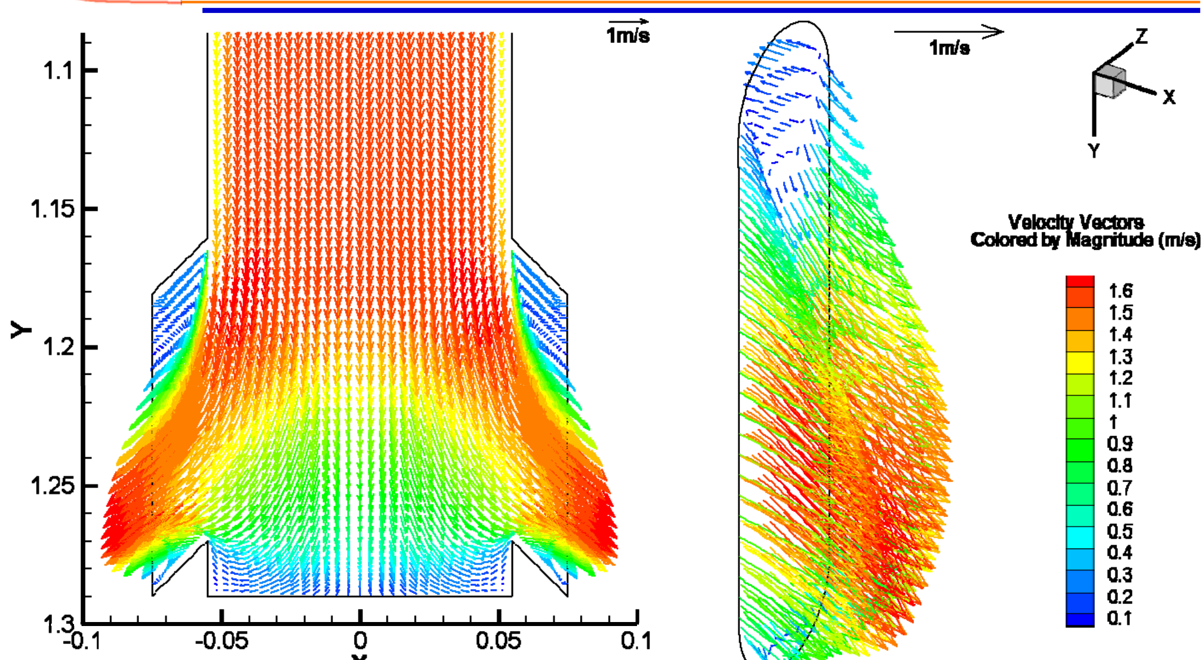


Nozzle Flow – Velocity Contours



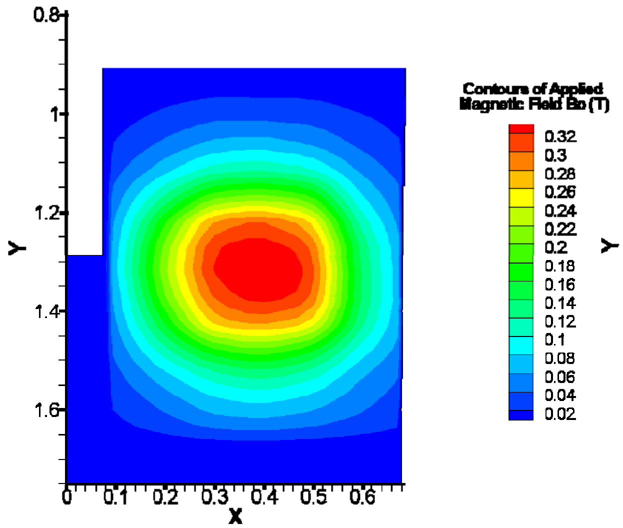
Slice through center of nozzle "wide face" | Slice through center of nozzle "narrow face" | View into right port

Nozzle Flow – Velocity Vectors

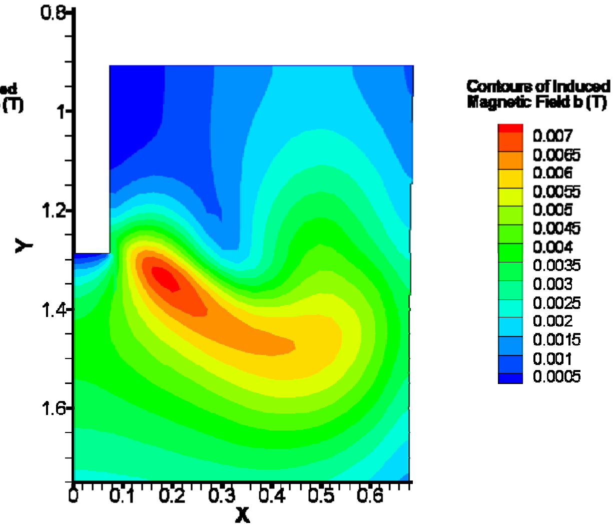


Slice through center of nozzle "wide face" | Isometric right port view

Applied and Induced Magnetic Fields – 250mm SEN Depth



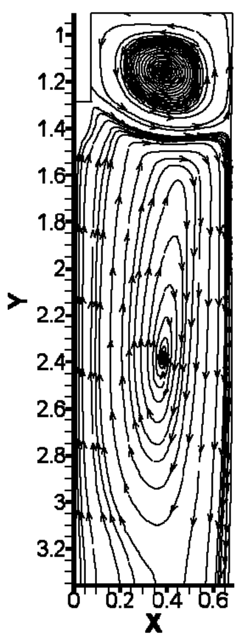
Applied Magnetic Field
(from Nucor measurement)



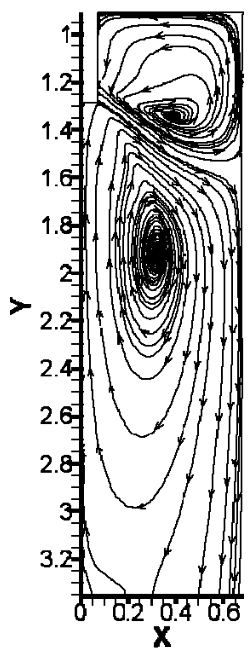
Induced Magnetic Field
(40x smaller than applied field)

Note: These and all subsequent contours, streamlines, and vectors shown on slices through wide face center

Streamlines – 250mm SEN Depth

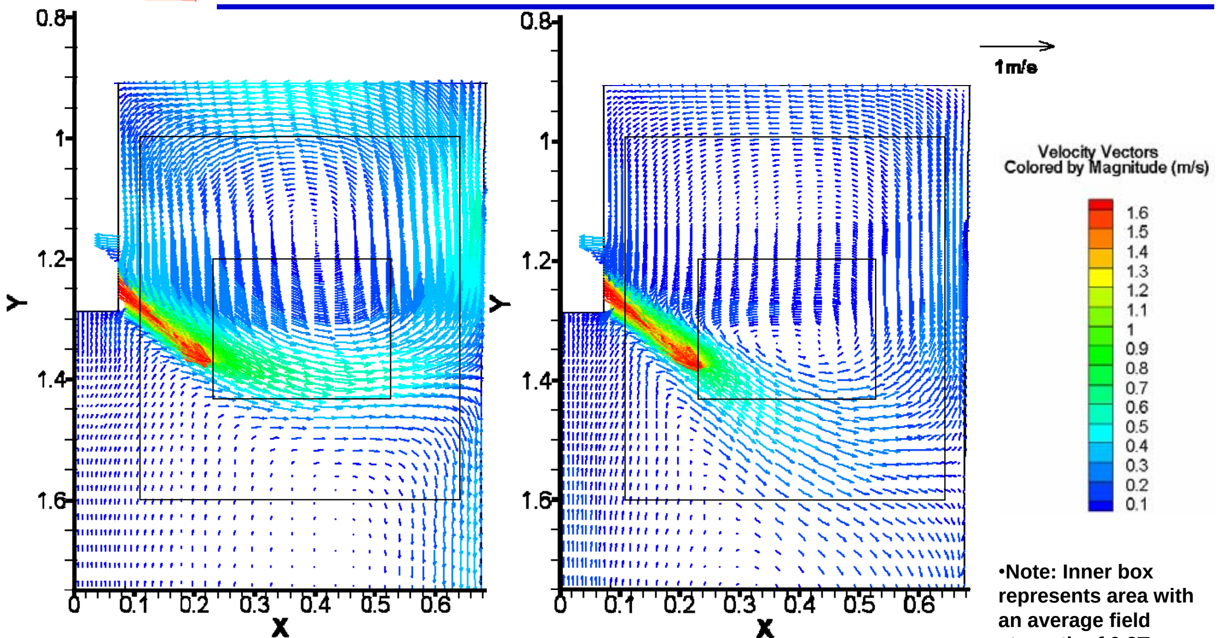


No EMBr



EMBr

Mold Flow – 250mm SEN Depth

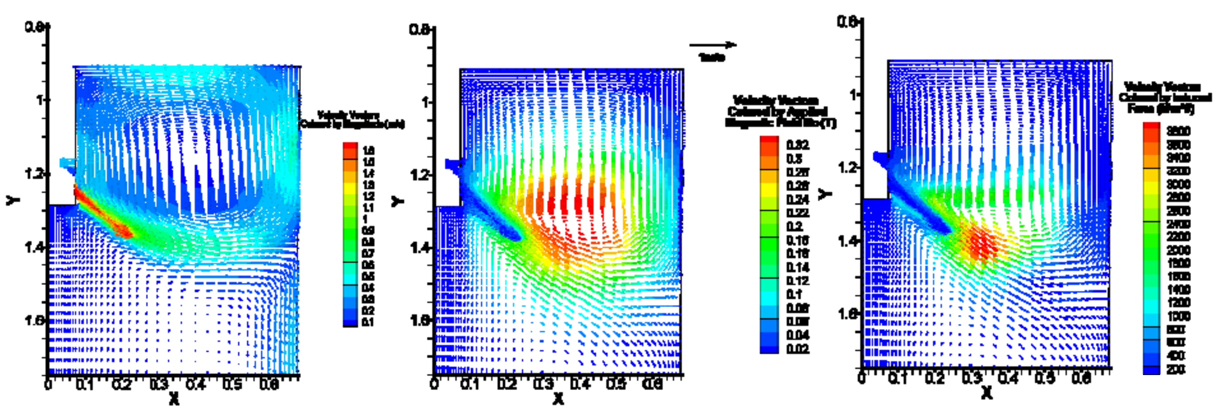


No EMBr – Jet impinges 490mm below meniscus

EMBr – Jet impinges 660mm below meniscus

•Note: Inner box represents area with an average field strength of 0.3T. Outer box represents approximate extents of magnetic field.

Effect of Induced Force and Applied Field on Mold Flow – 250mm SEN Depth

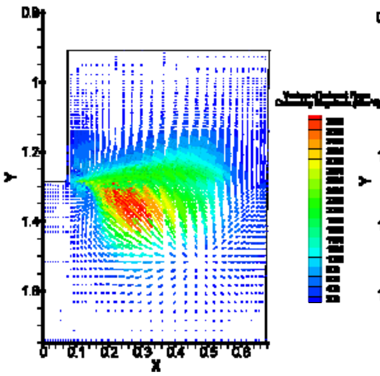


Flow without EMBr

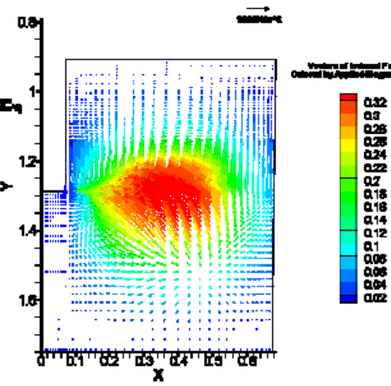
Flow with EMBr, colored by applied field

Flow with EMBr, colored by induced force

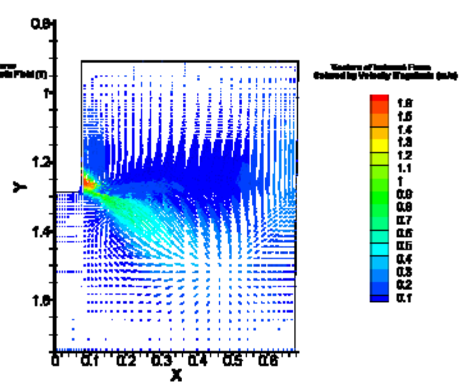
Effect of Applied Field and Velocity on Induced Force – 250mm SEN Depth



Induced force vectors
colored by magnitude

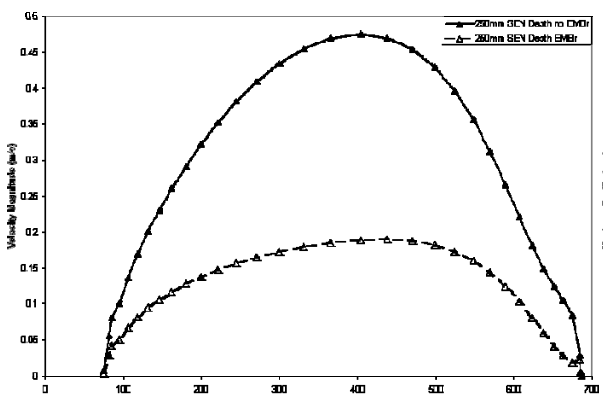


Induced force vectors
colored by applied field

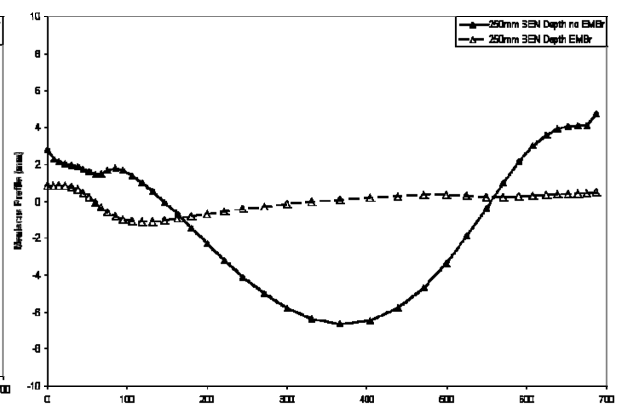


Induced force vectors
colored by velocity

Meniscus Velocity and Meniscus Profile Comparisons – 250mm SEN Depth



Comparison of velocity magnitude measured 10mm below top surface centerline

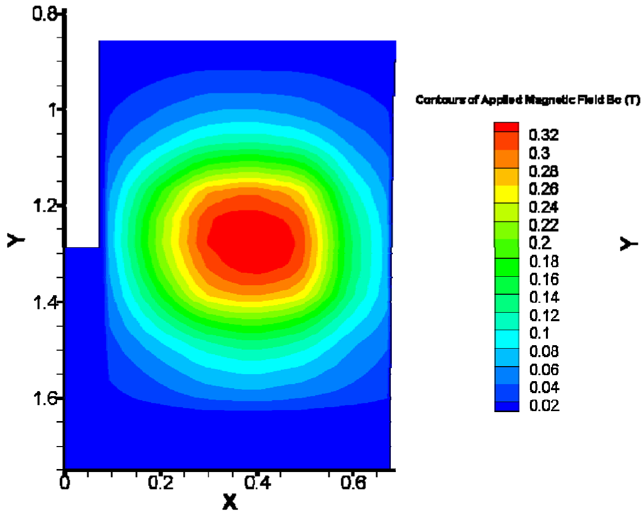


Comparison of meniscus profiles calculated using the following equation:

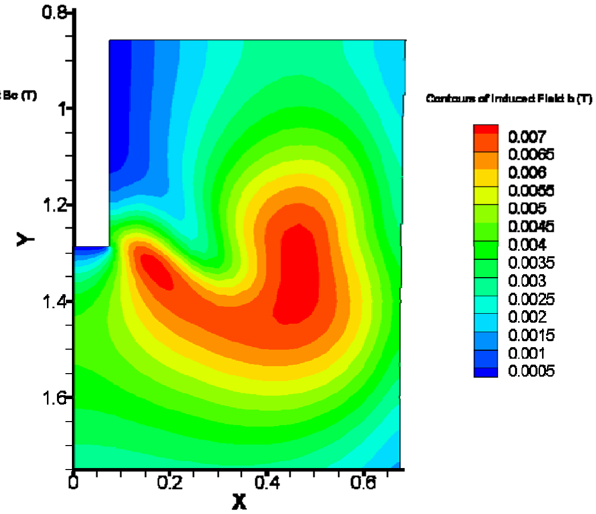
$$Meniscus\ Height = \frac{P_{static} - \overline{P}_{static}}{\rho_{steel} * g}$$

•Pressures measured along top surface centerline

Applied and Induced Magnetic Fields – 300mm SEN Depth

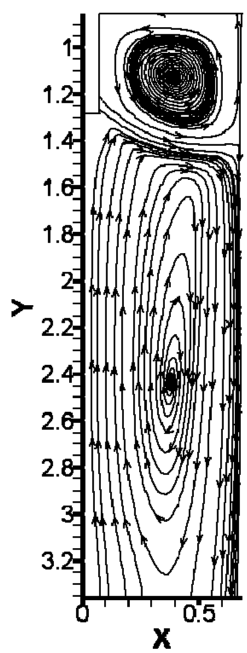


Applied Magnetic Field

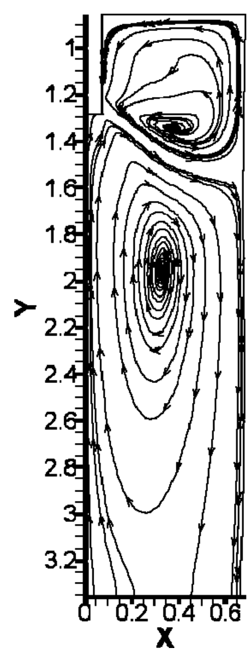


Induced Magnetic Field

Streamlines – 300mm SEN Depth

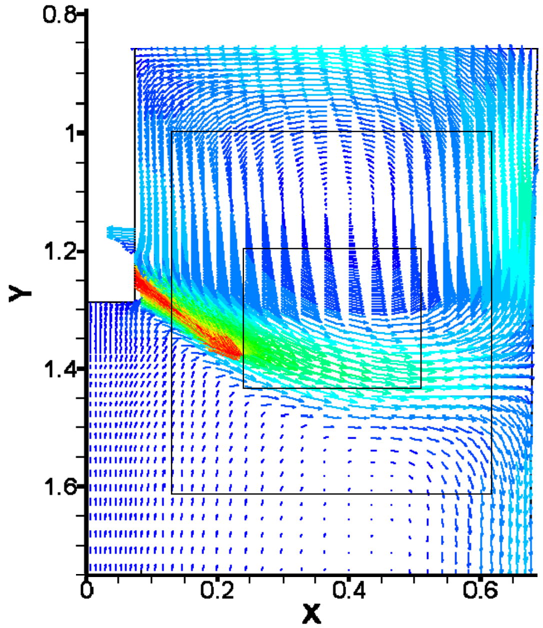


No EMBr

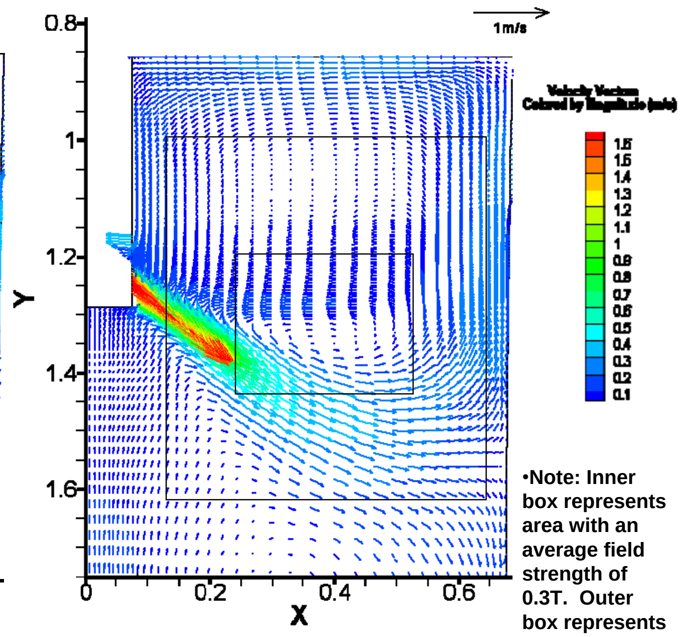


EMBr

Mold Flow – 300mm SEN Depth



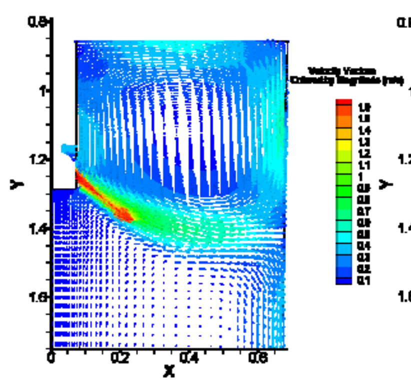
No EMBr – Jet impinges 560mm below meniscus



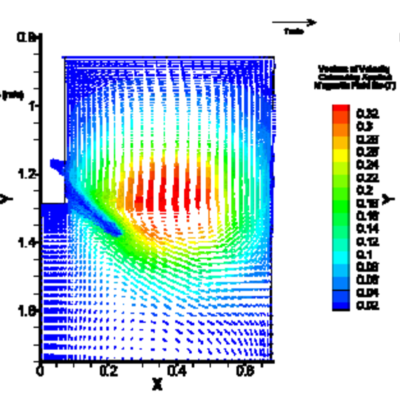
EMBr – Jet impinges 700mm below meniscus

•Note: Inner box represents area with an average field strength of 0.3T. Outer box represents approximate extents of magnetic field.

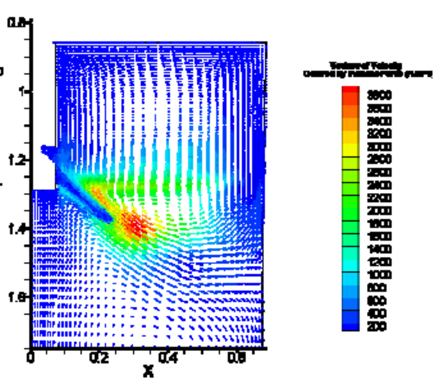
Effect of Induced Force and Applied Field on Mold Flow – 300mm SEN Depth



Flow without EMBr

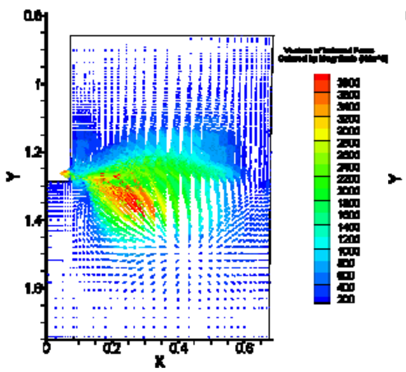


Flow with EMBr, colored by applied field

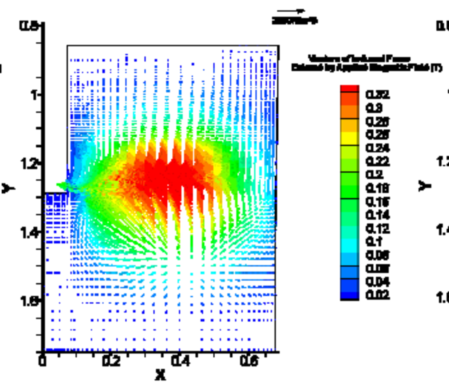


Flow with EMBr, colored by induced force

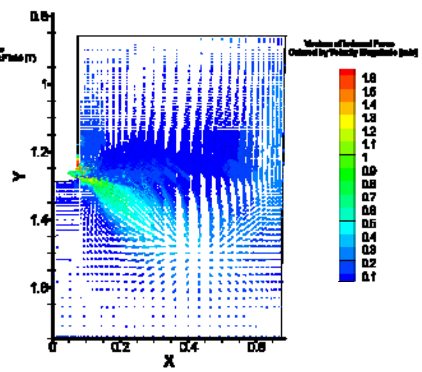
Effect of Applied Field and Velocity on Induced Force – 300mm SEN Depth



Induced force vectors
colored by magnitude

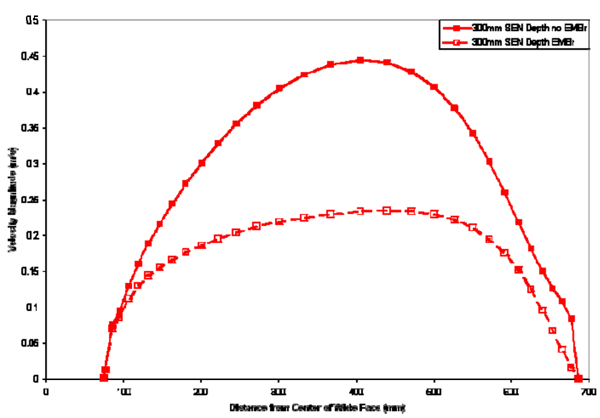


Induced force vectors
colored by applied field

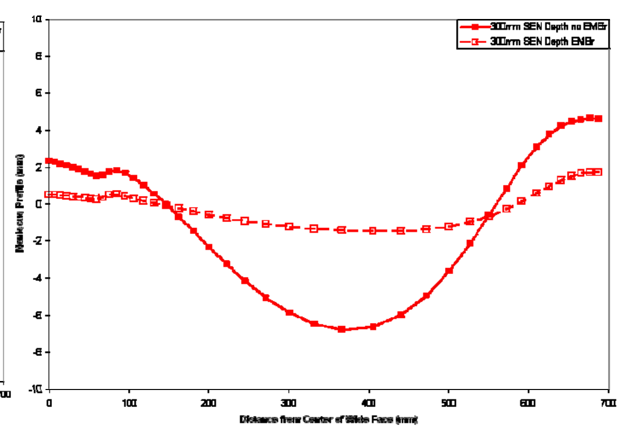


Induced force vectors
colored by velocity

Meniscus Velocity and Meniscus Profile Comparisons – 300mm SEN Depth

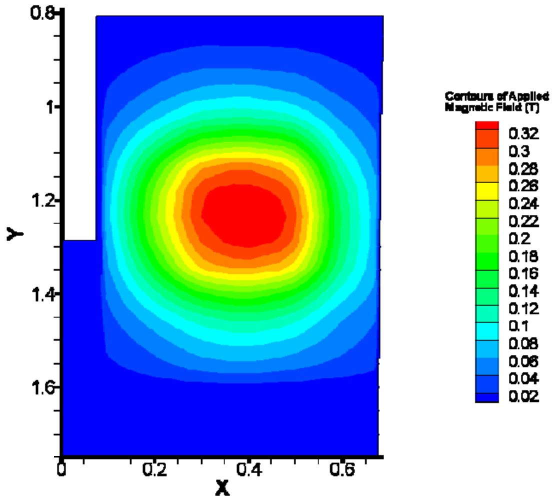


Comparison of velocity magnitude measured 10mm below top surface centerline

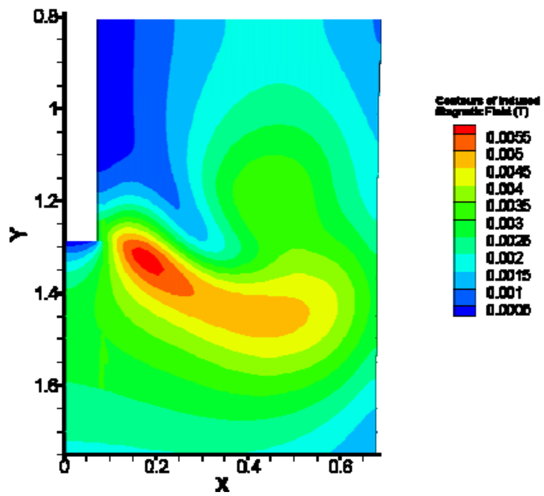


Comparison of meniscus profiles

Applied and Induced Magnetic Fields – 350mm SEN Depth

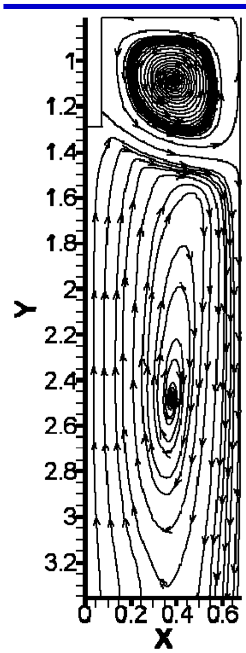


Applied Magnetic Field

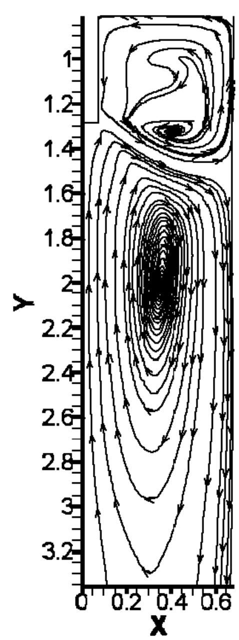


Induced Magnetic Field

Streamlines – 350mm SEN Depth

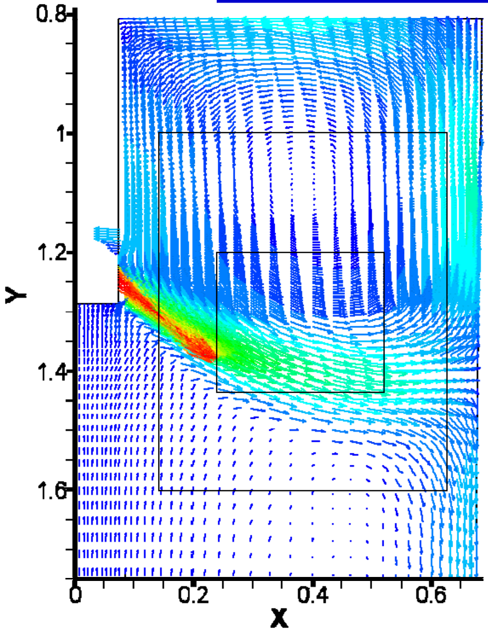


No EMBr

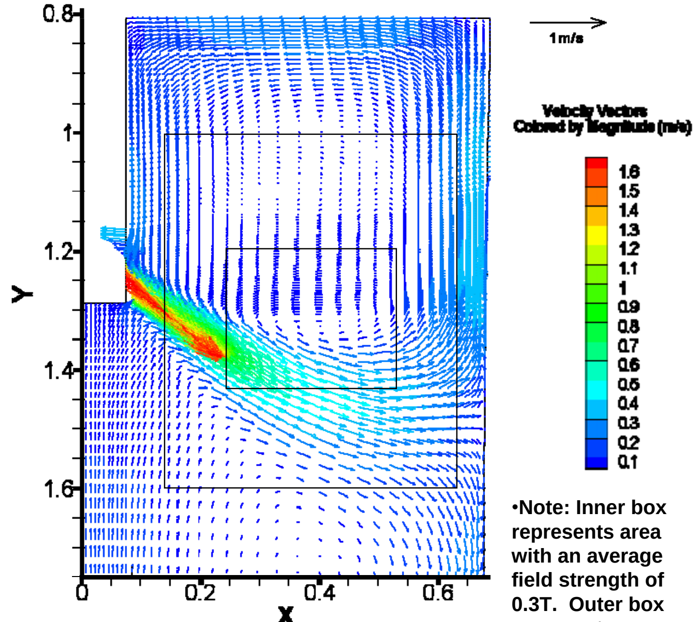


EMBr

Mold Flow – 350mm SEN Depth



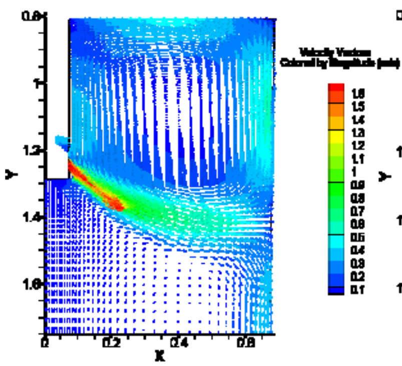
No EMBr – Jet impinges 620mm below meniscus



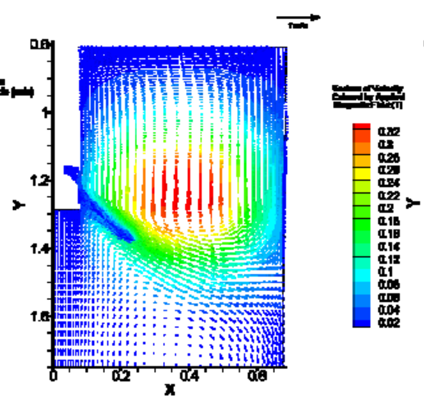
EMBr – Jet impinges 705mm below meniscus

•Note: Inner box represents area with an average field strength of 0.3T. Outer box represents approximate extents of magnetic field.

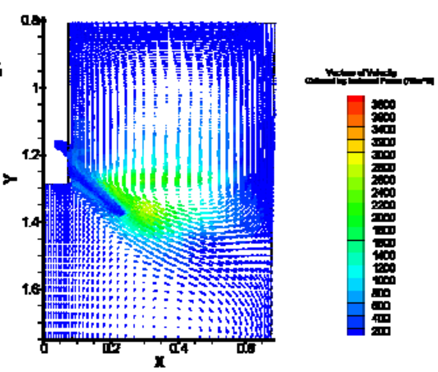
Effect of Induced Force and Applied Field on Mold Flow – 350mm SEN Depth



Flow without EMBr

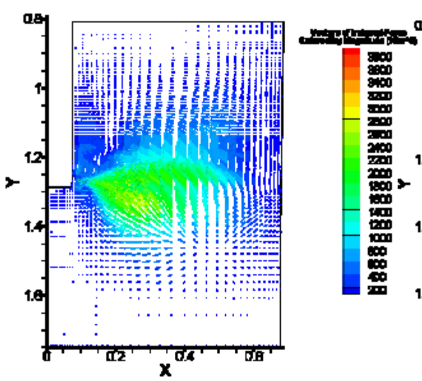


Flow with EMBr, colored by applied field

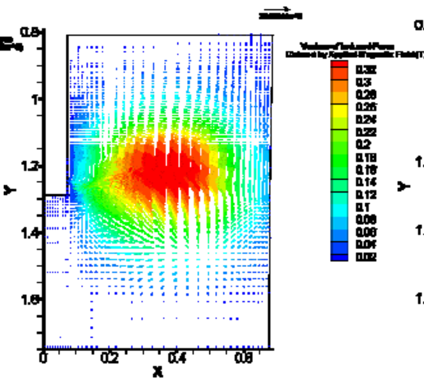


Flow with EMBr, colored by induced force

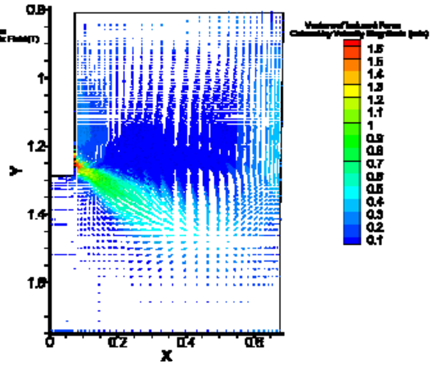
Effect of Applied Field and Velocity on Induced Force – 350mm SEN Depth



Induced force vectors colored by magnitude

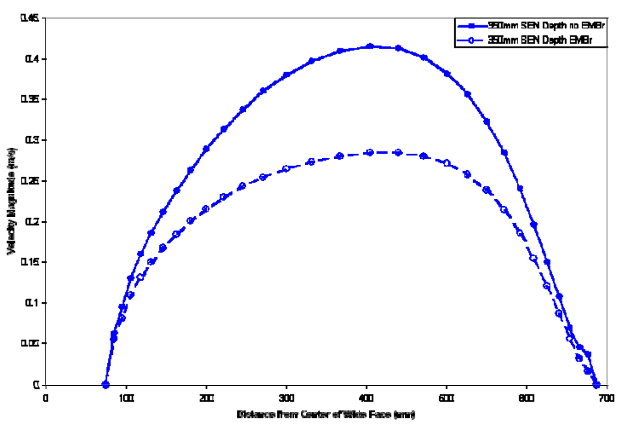


Induced force vectors colored by applied field

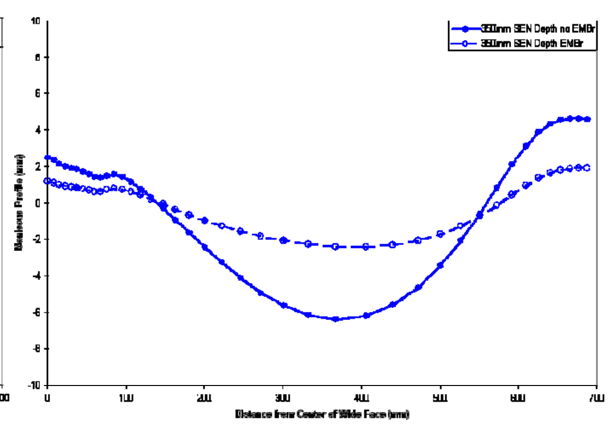


Induced force vectors colored by velocity

Meniscus Velocity and Meniscus Profile Comparisons – 350mm SEN Depth

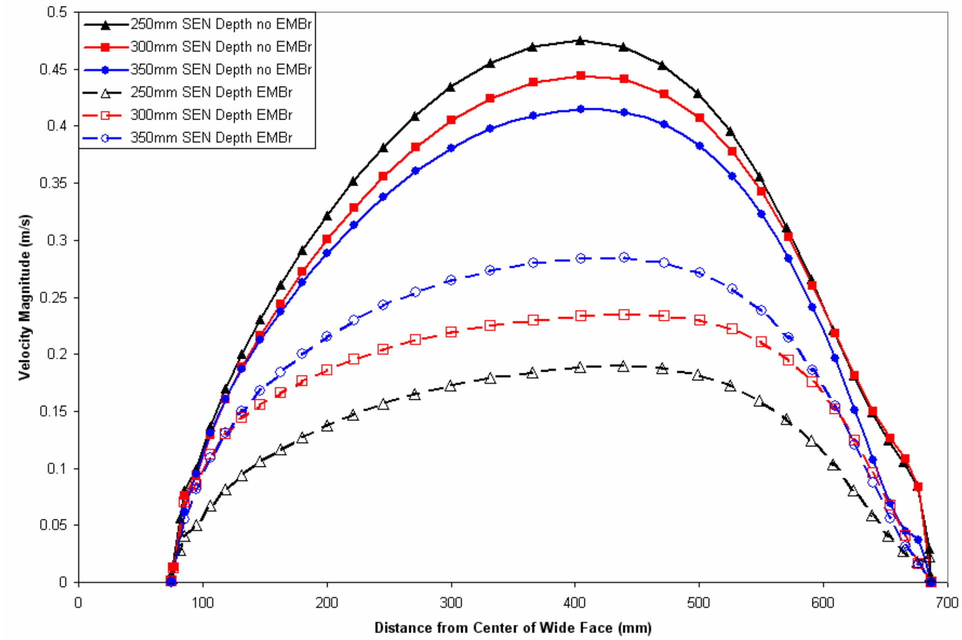


Comparison of velocity magnitude measured 10mm below top surface centerline

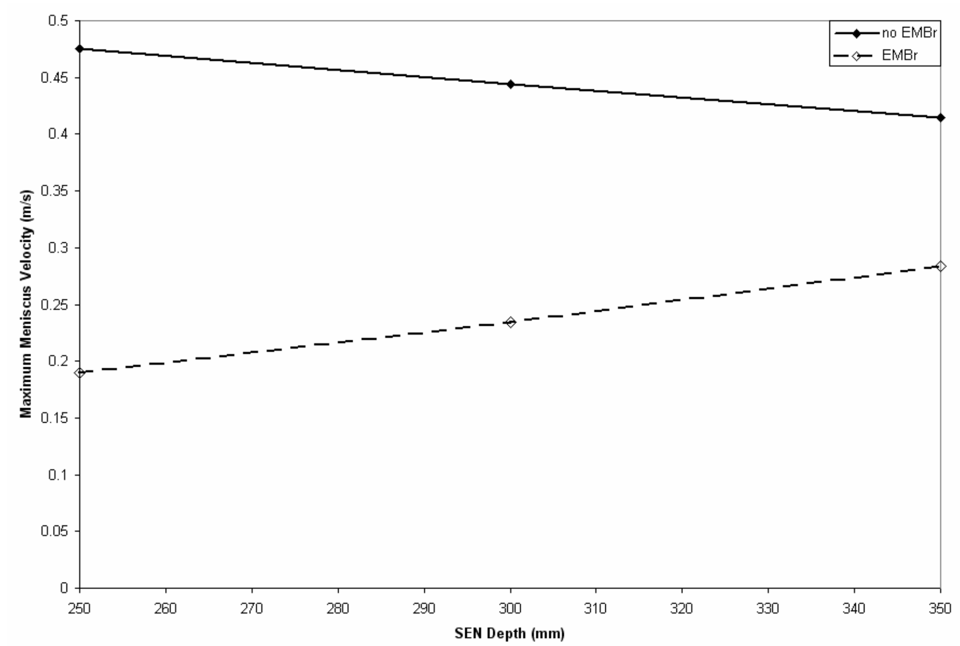


Comparison of meniscus profiles

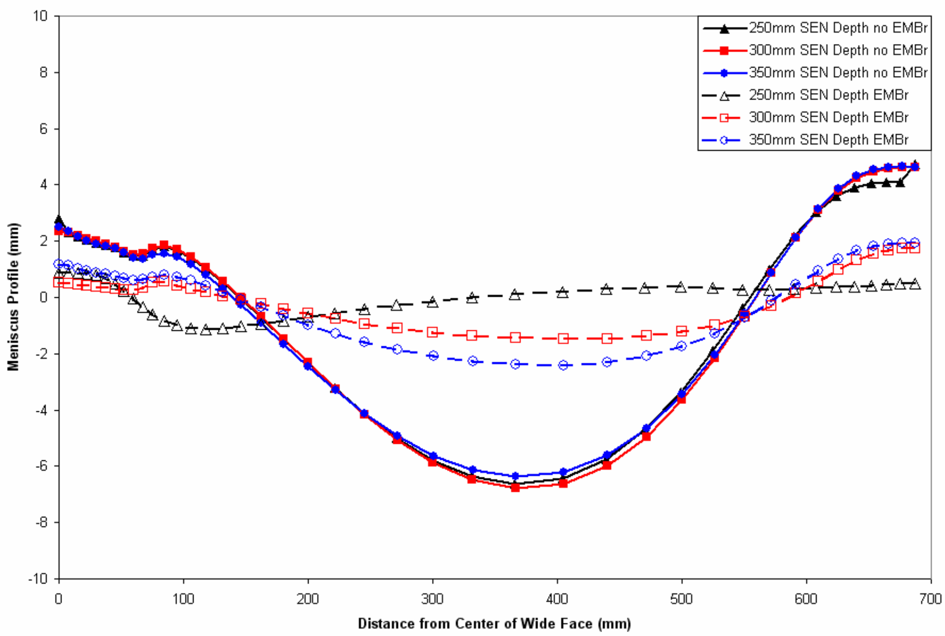
Meniscus Velocities of All Simulations



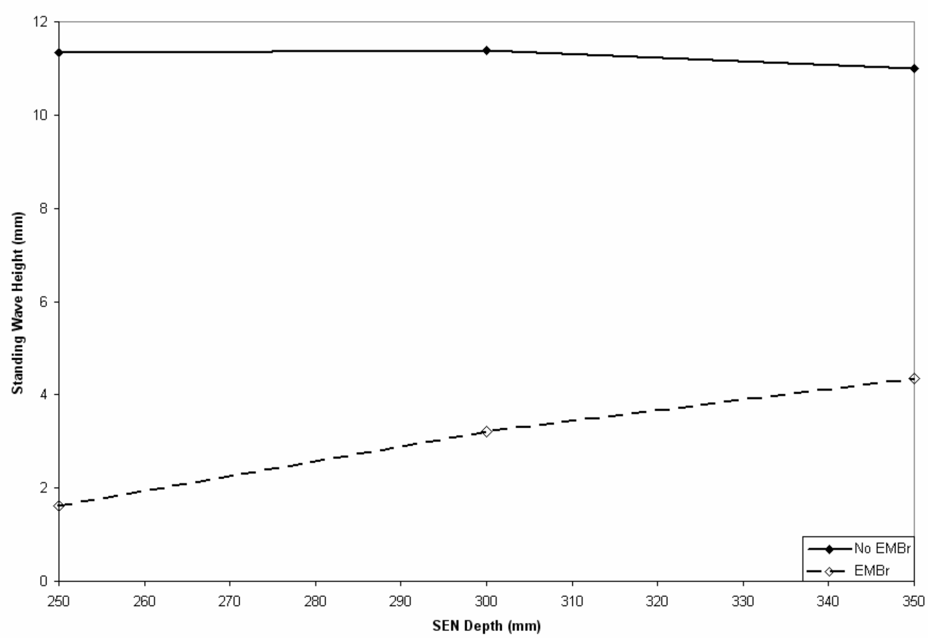
Trends in Meniscus Velocity



Meniscus Profiles of All Simulations

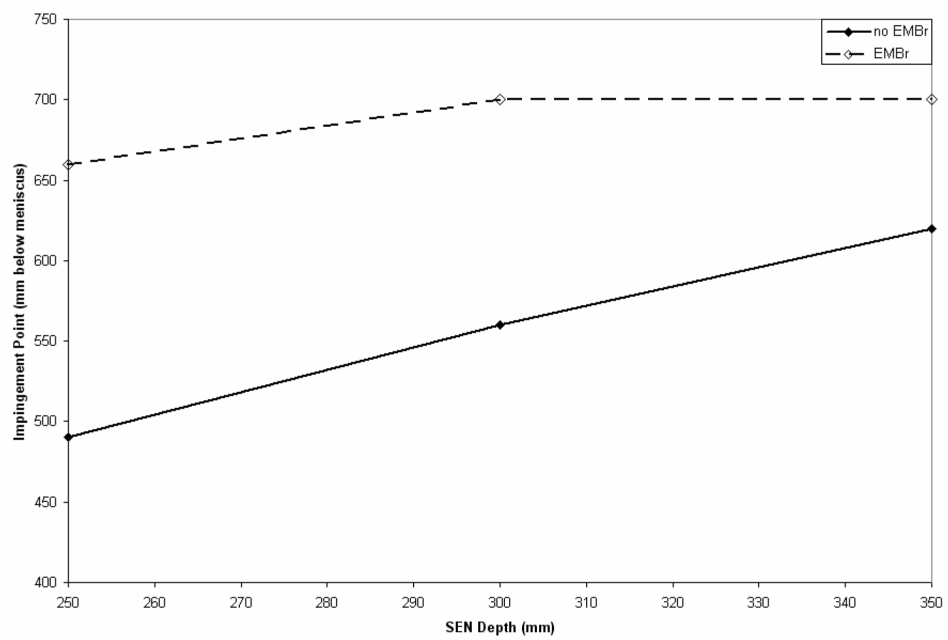


Trends in Standing Wave Height



Standing wave height = max meniscus profile height – min meniscus profile height

Trends in Impingement Point

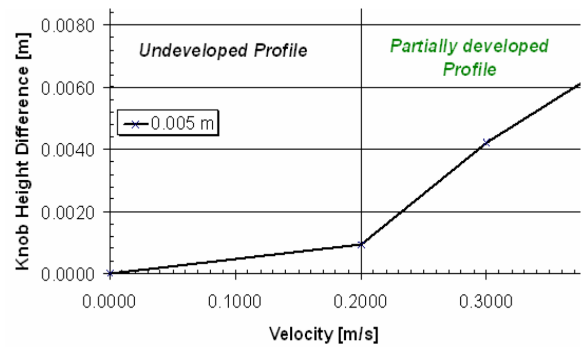


Project Outline

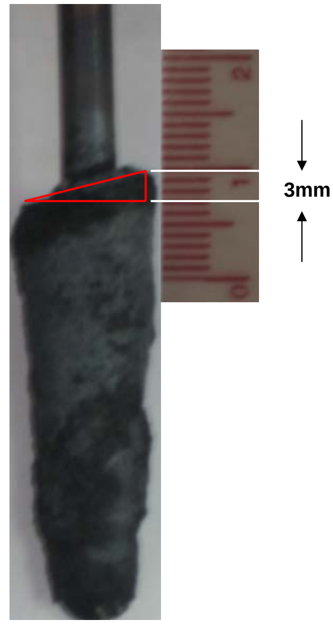
- Objective
  - Discover how and why an electromagnetic brake affects steel flow in the continuous casting mold
- Three phases to the project
  - Experimental (in collaboration with Nucor Steel Decatur)
    - EMBr measurement, nail board samples, and oscillation mark photos
  - Computational Modeling
    - Solve 3D Navier-Stokes Equations with FLUENT for flow in Nucor nozzle and mold with/without EMBr with 3 submergence depths
  - Validation
    - Compare computational results with experimental measurements

Nail Board Validation Method

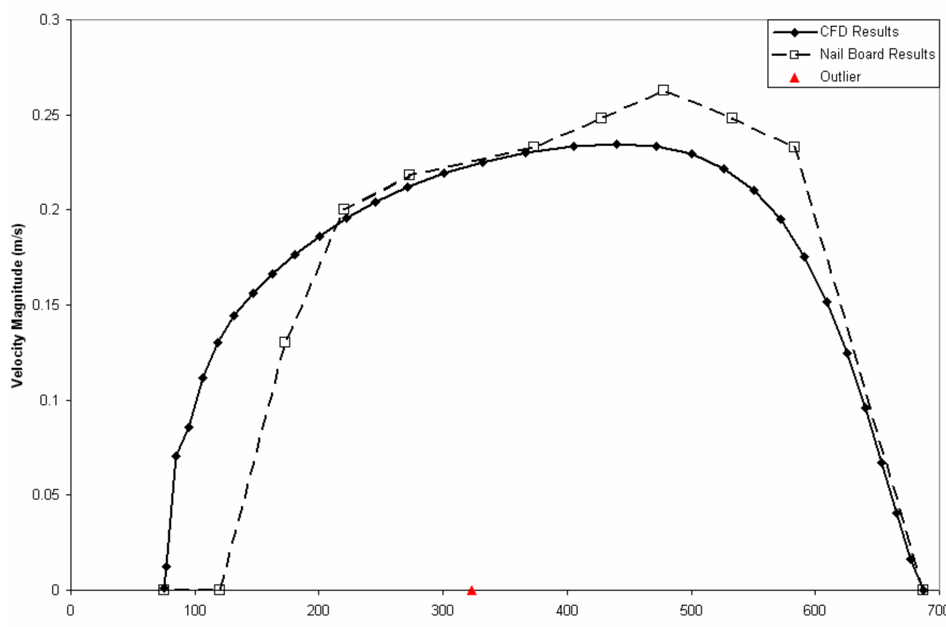
- Bret Rietow discovered an empirical relation correlating knob profile and nail diameter to flow velocity
- This method allows for quick and easy estimation of meniscus velocity from nail board test results



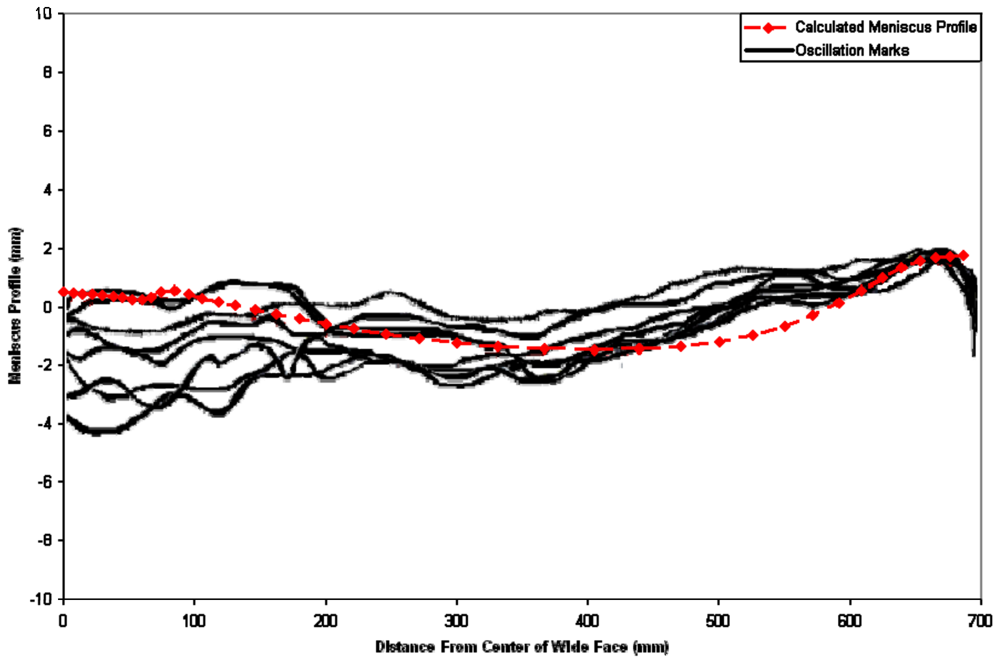
Rietow, 2007



Nail Board and CFD Meniscus Velocity Comparison



Comparison of Oscillation Marks to Calculated Meniscus Profile



Summary

•Electromagnetics can be used in continuous casting to control the fluid flow pattern in the mold and to improve the internal microstructure of the finished product

•One nozzle flow and six mold flow simulations were performed to investigate the effects that the EMBr and SEN submergence depth have on fluid flow in the mold

•Applying EMBr causes:

- •Reduced velocity at the meniscus and in the upper recirculation zone
- •Deeper jet impingement
- •Expanded upper recirculation zone
- •Widening and upward shift of lower recirculation zone
- •Smaller meniscus wave
(2-4mm with EMBr vs. ~11mm with no EMBr at 3.3m/min)

Summary

- Increasing SEN depth causes:
  - EMBr off
    - Decrease in meniscus velocity
    - Deeper jet impingement
    - Smaller meniscus wave
  - EMBr on
    - Increase in meniscus velocity
    - Deeper jet impingement
    - Larger meniscus wave
- Model predictions have been validated based on plant measurements
  - Velocities from nail board tests closely match calculated meniscus velocities
  - Oscillation mark profiles on strand roughly agree with calculated meniscus profile

Acknowledgements

- Nucor Steel Decatur (Ron O'Malley)
- The Continuous Casting Consortium
- Fluent, Inc. (Ashwini Kumar)
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- Brian Thomas and Pratap Vanka