MechSE

ANNUAL REPORT 2008

UIUC, August 6, 2008

Electromagnetic Control of Fluid Flow in the Mold

Choul Hong Min
(MS Student)

Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

Acknowledgements

- Continuous Casting Consortium Members
  (Baosteel, Corus, Goodrich, Labein, LWB Refractories, Mittal, Nucor, Postech, Steel Dynamics, Ansys Inc.)
- National Science Foundation
  - DMI 07-27620 (Strip);
  - DMI 05-28668 (Sensor);
  - GOALI DMI 05-00453 (Online)
- National Center for Supercomputing Applications (NCSA) at UIUC
- Ansys Inc. (Fluent)
- Kevin Cukierski, Rajneesh Chaudhary, SY Kim, BG Thomas, & GG Lee.

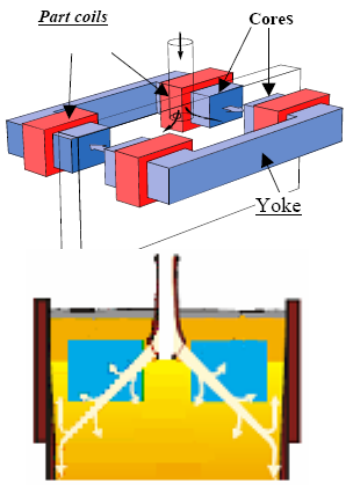
Types of electromagnetic forces

Magnetic fields greatly alter steel flow in the mold
Control surface turbulence, deep inclusion penetration, and internal microstructure

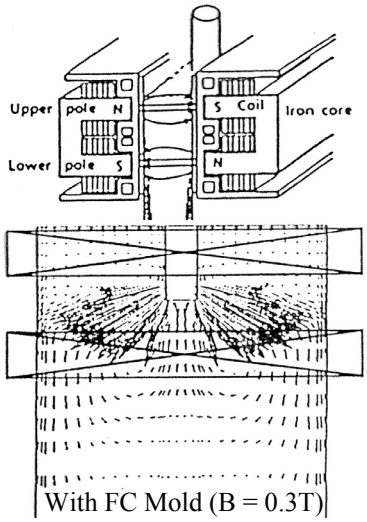
EMBr (DC): braking: slow down flow

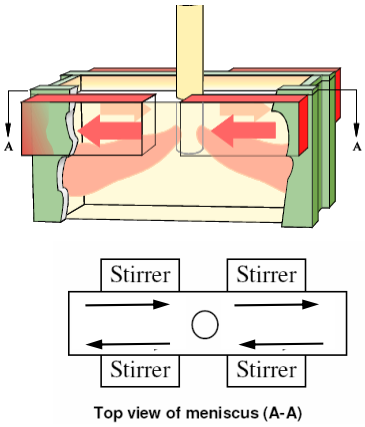
EMS (AC): stirring: decelerate; accelerate

Local EMBr



Ruler EMBr



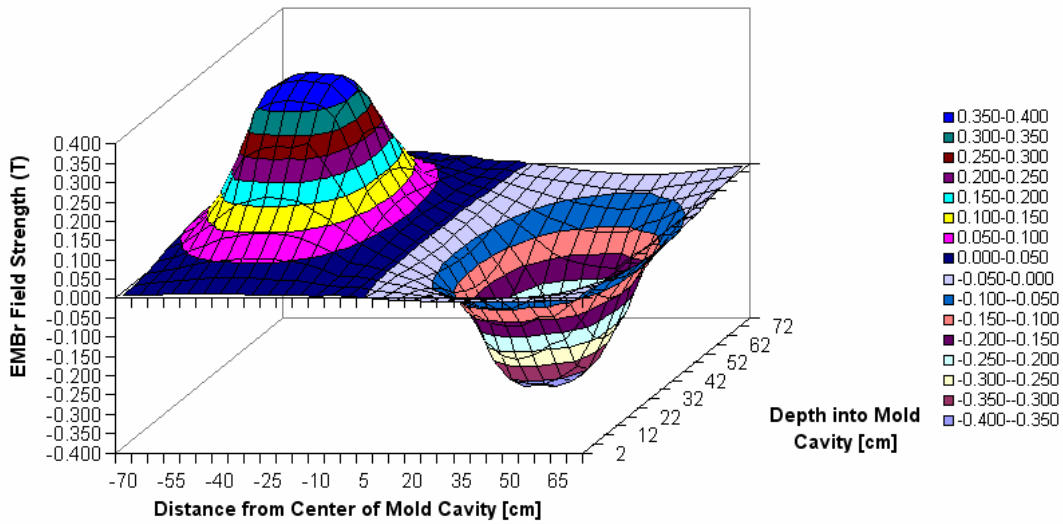


Eg. FC mold, ABB, Danielli

Project Outline

- Objective
  - Investigate how electromagnetic brake affects steel flow in the mold
- Computational Modeling
  - Solve 3D Navier-Stokes Equations with local electromagnetic forces in FLUENT for flow in Nucor nozzle and mold with/without EMBr with various submergence depths

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**

Cukierski & Thomas, Met Trans B, 2008

Simulation Parameters

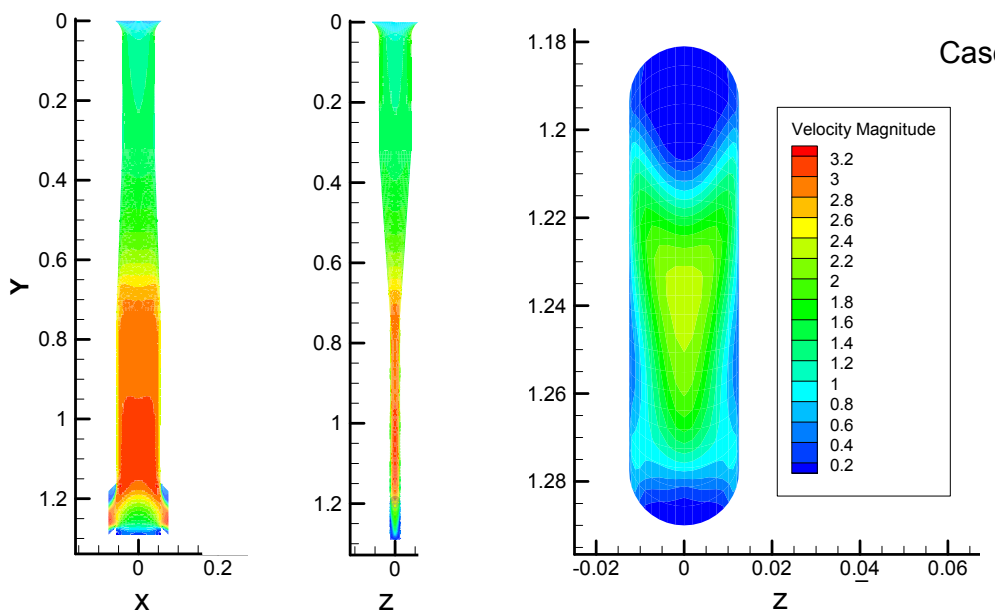
Casting speed (m/min)	3.3
Mold Width (mm)	6.87
Mold Thickness (mm)	90
Mold Length (mm)	2500
Steel density ρ_{steel} (kg/m^3)	7000
Slag density ρ_{slag} (kg/m^3)	3000
Steel viscosity μ (kg/m-s)	0.006
Electrical Conductivity σ (Ω-m)$^{-1}$	714,000
Gravity acceleration (m/s^2)	9.81

Investigation of EMBr & SEN depth

Case	SEN Depth (mm)	EMBr Setting (T)	FieldLocation
1*	350	0	Actual
2*	350	0.3550	Actual
3*	300	0	Actual
4*	300	0.3550	Actual
5*	250	0	Actual
6*	250	0.3550	Actual
7	200	0	Actual
8	200	0.3550	Actual
9	150	0	Actual
10	150	0.3550	Actual
11	100	0	Actual
12	100	0.3550	Actual
13	150	0.3550	**Raised**

* Kevin Cukierski, 2008

Nozzle Flow – Velocity Contours

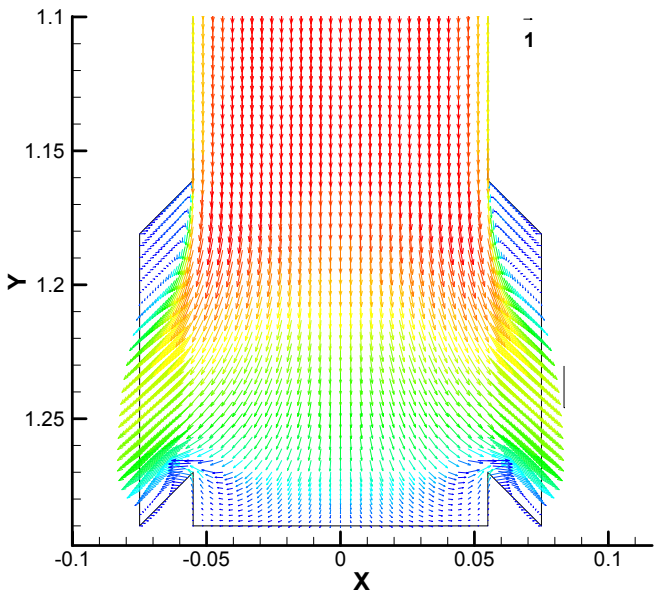


Front View

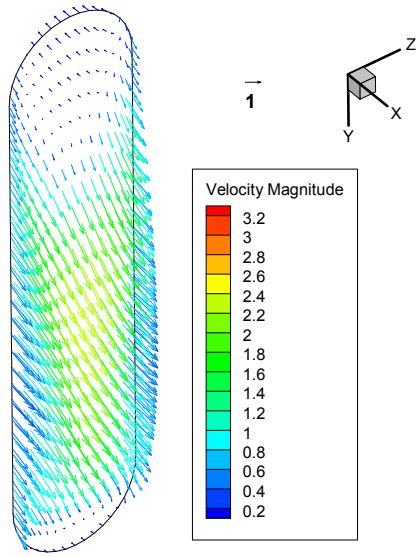
Side View
(looking into Port)

View into right port

Nozzle Flow – Velocity Vectors

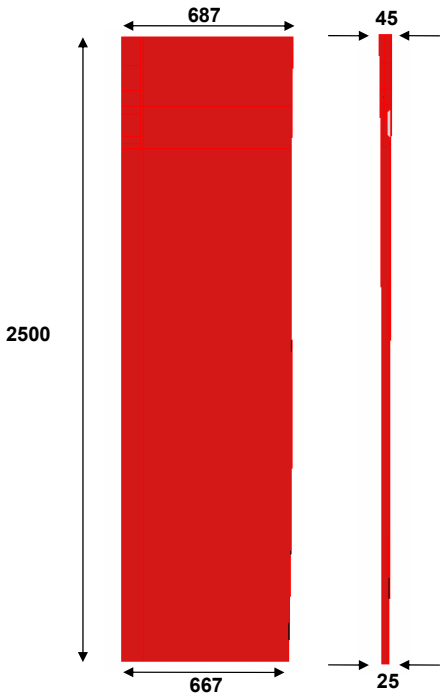


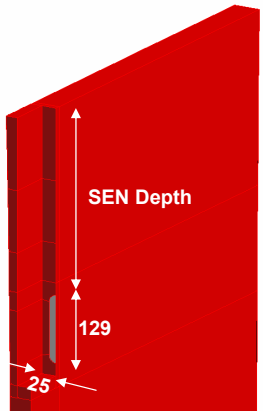
Front View
(Close-up)



3D View of Flow exiting port
(Close-up)

Mold Simulations



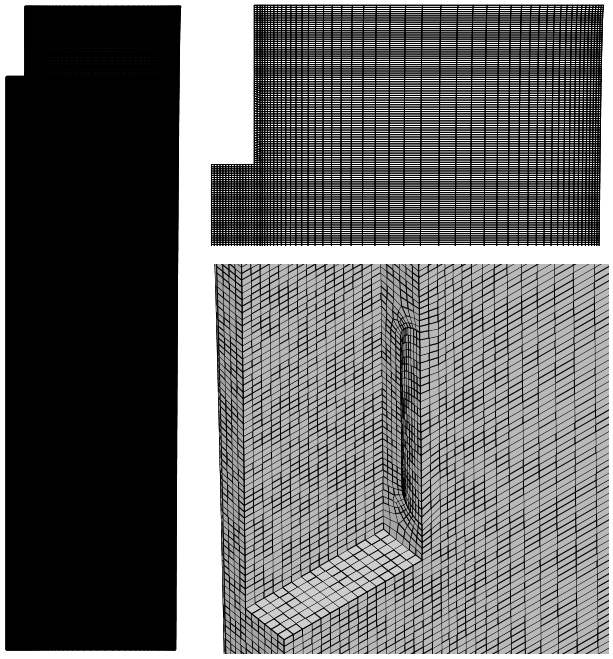


SEN Depths:

- •100mm •250mm
- •150mm •300mm
- •200mm •350mm

Cukierski & Thomas, Met Trans B, 2008

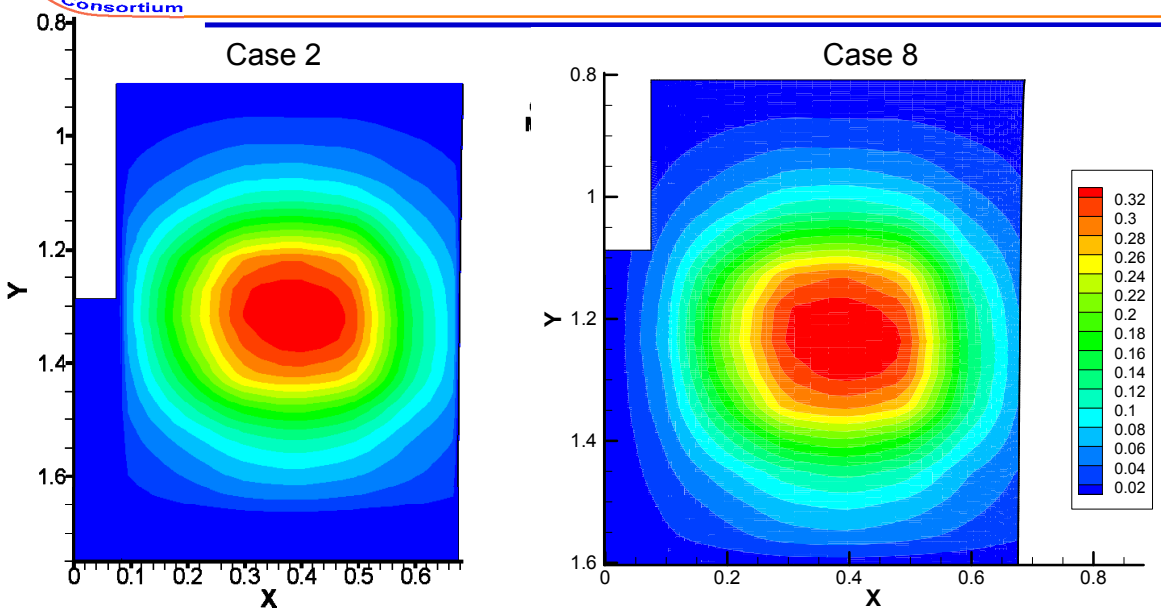
Mold Mesh



- Fluid Region (Case 9,10)
  - 422,620 hexahedral cells
- Wide Face Sink Side Sink for Shell Extraction simulation
  - Volume zone with 1 mm thickness behind the fluid region to the wide face side
  - 41,912 hexahedral cells
- Narrow Face Side Sink for Shell Extraction Simulation
  - Volume zone with 1 mm thickness behind the fluid region on the narrow side
  - 6,980 hexahedral cells
- Total : ~500,000 cells

Case 7 to 13

Applied Magnetic Fields



350mm SEN Depth EMBr on

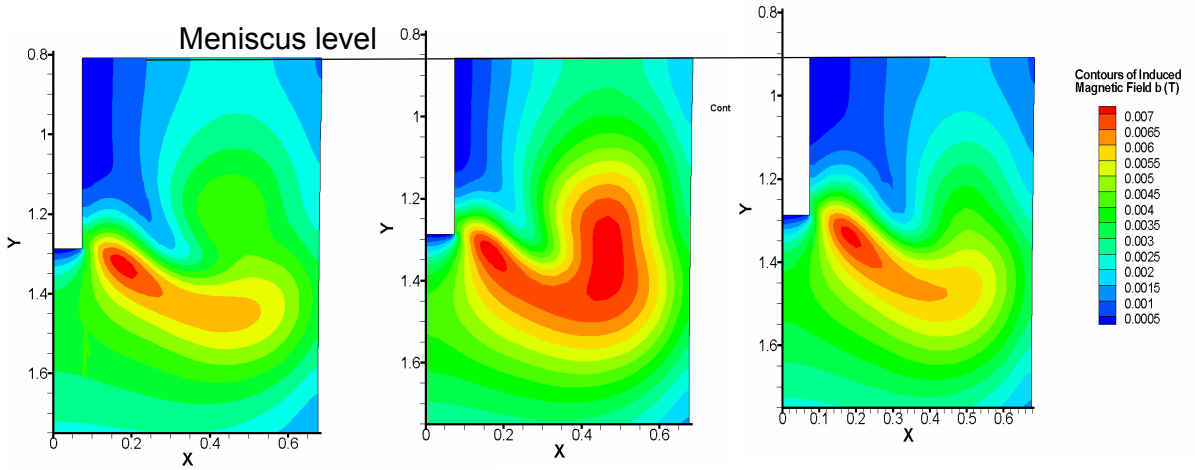
150mm SEN Depth EMBr on

Cukierski & Thomas, Met Trans B, 2008

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

Induced Magnetic Fields

Case 2, 4, 6



Case 2

350mm SEN
EMBr On

Case 4

250mm SEN
EMBr On

Case 6

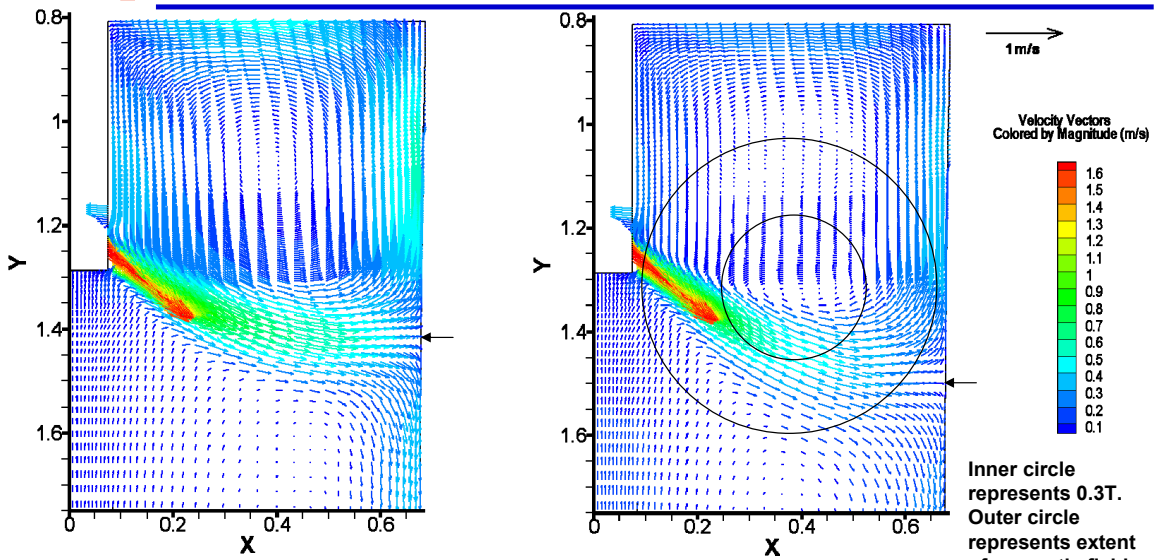
200mm SEN
EMBr On

(40x smaller than applied field)

Cukierski & Thomas, Met Trans B, 2008

Mold Flow – Deep SEN

Case 1 and 2



350 mm SEN Depth no EMBr – Jet impinges 620mm below meniscus

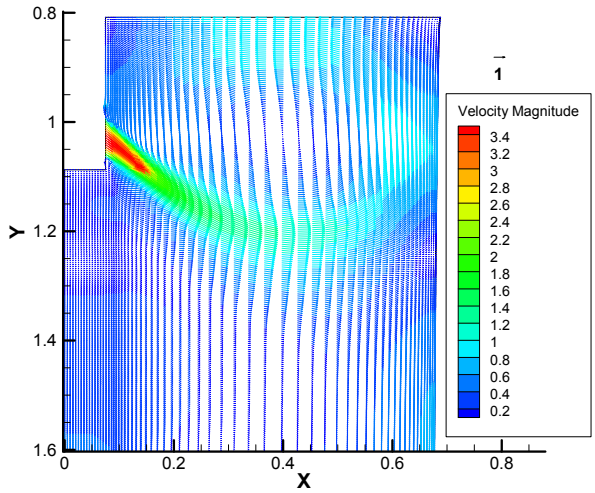
350 mm SEN Depth EMBr on – Jet impinges 705mm below meniscus

Inner circle represents 0.3T. Outer circle represents extent of magnetic field.

Cukierski & Thomas, Met Trans B, 2008

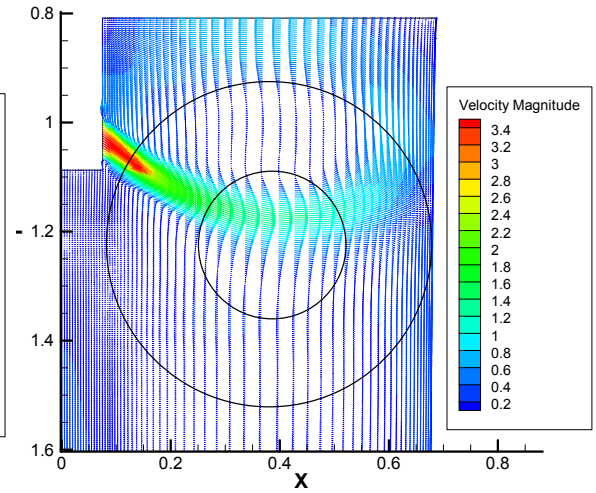
Mold Flow – Shallow SEN

Case 9 and 10



150mm SEN Depth

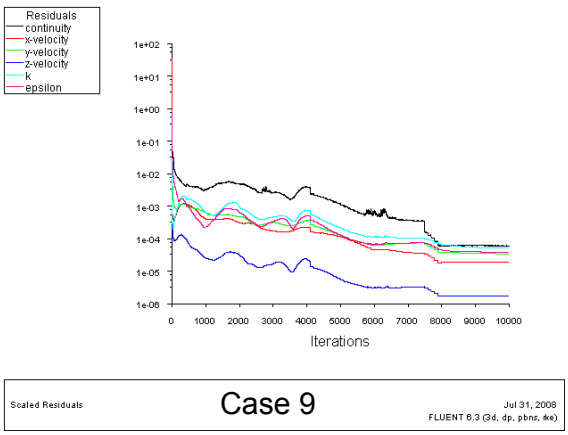
no EMBr



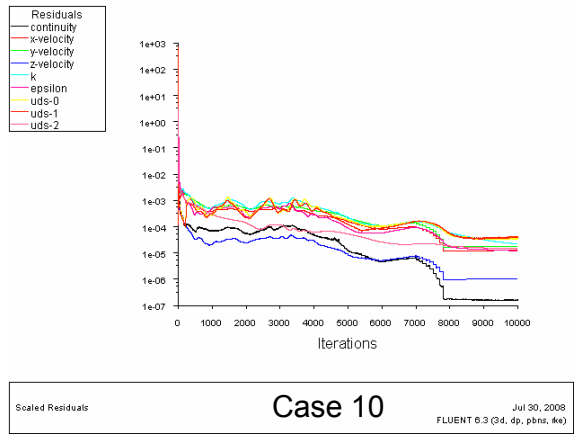
150mm SEN Depth

EMBr on

Residuals for Case 9 and 10



Case 9

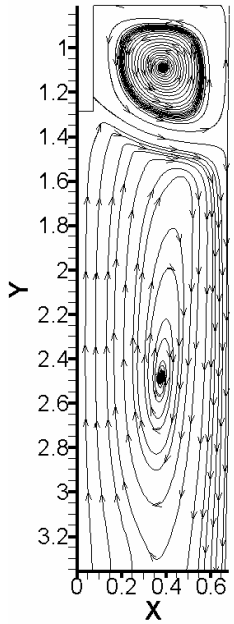


Case 10

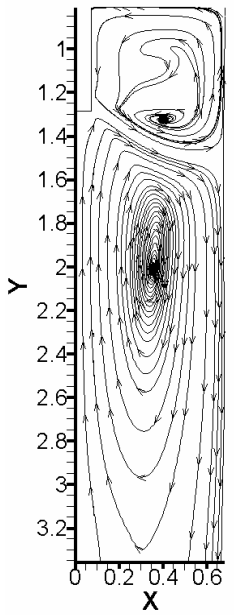
Solution is converged < 10^{-4} (residuals all cases < 10^{-3})

Lower Recirculation – Deep SEN

Case 1 and 2



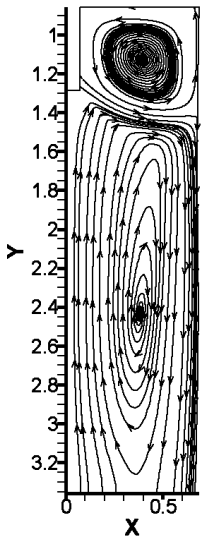
350 mm SEN Depth
no EMBr



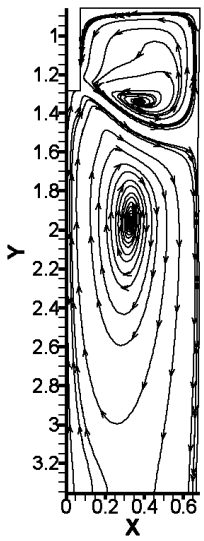
350 mm SEN Depth
EMBr on

Streamlines

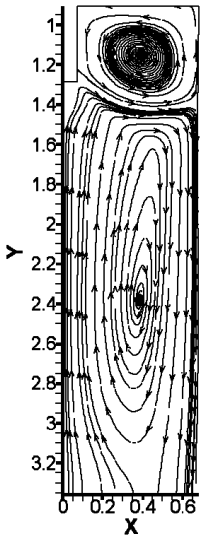
Case 3 through 6



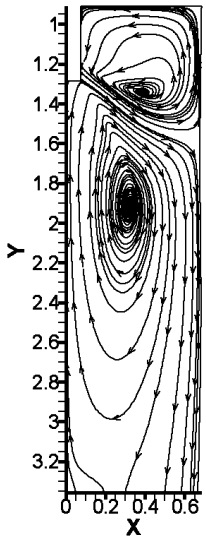
300 mm SEN Depth
no EMBr



300 mm SEN Depth
EMBr on



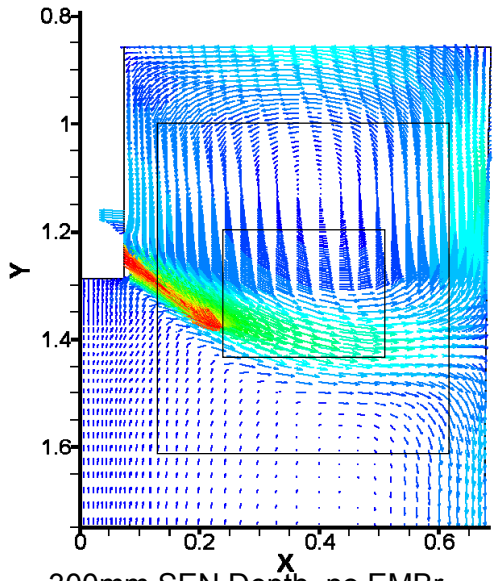
250 mm SEN Depth
no EMBr



250 mm SEN Depth
EMBr on

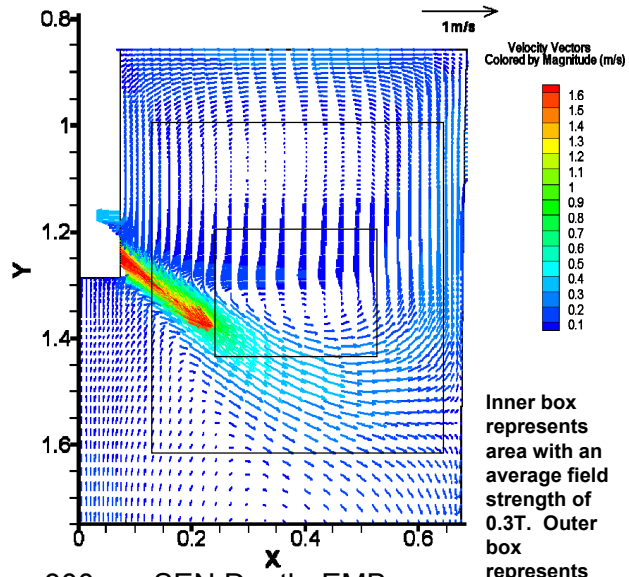
Cukierski & Thomas, Met Trans B, 2008

Velocity Magnitude, Case 3 and Case 4



300mm SEN Depth, no EMBr

– Jet impinges 560mm below meniscus



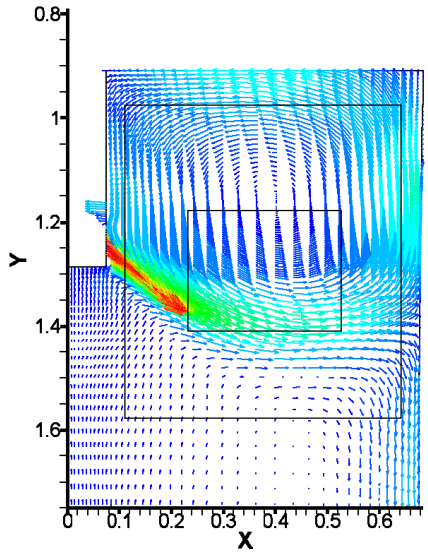
300mm SEN Depth, EMBr on

– Jet impinges 700mm below meniscus

Inner box represents area with an average field strength of 0.3T. Outer box represents approximate extent of magnetic field.

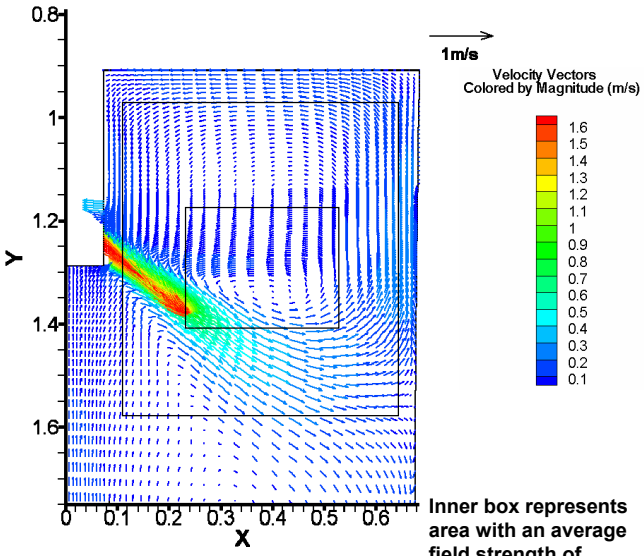
Cukierski & Thomas, Met Trans B, 2008

Velocity Magnitude, Case 5 and 6



300mm SEN Depth, no EMBr

– Jet impinges 490mm below meniscus



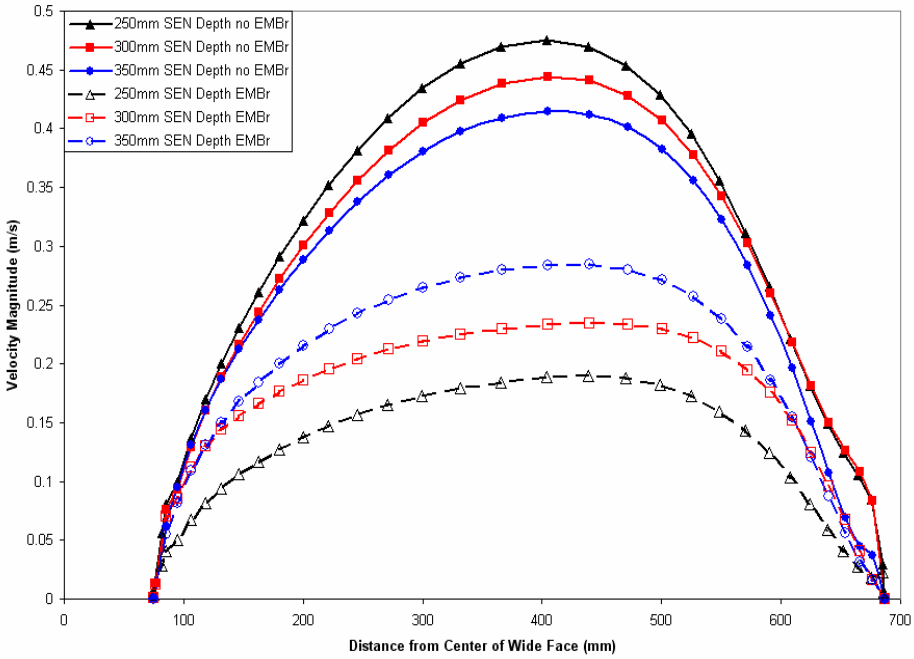
300mm SEN Depth, EMBr on

– Jet impinges 660mm below meniscus

Inner box represents area with an average field strength of 0.3T. Outer box represents approximate extent of magnetic field.

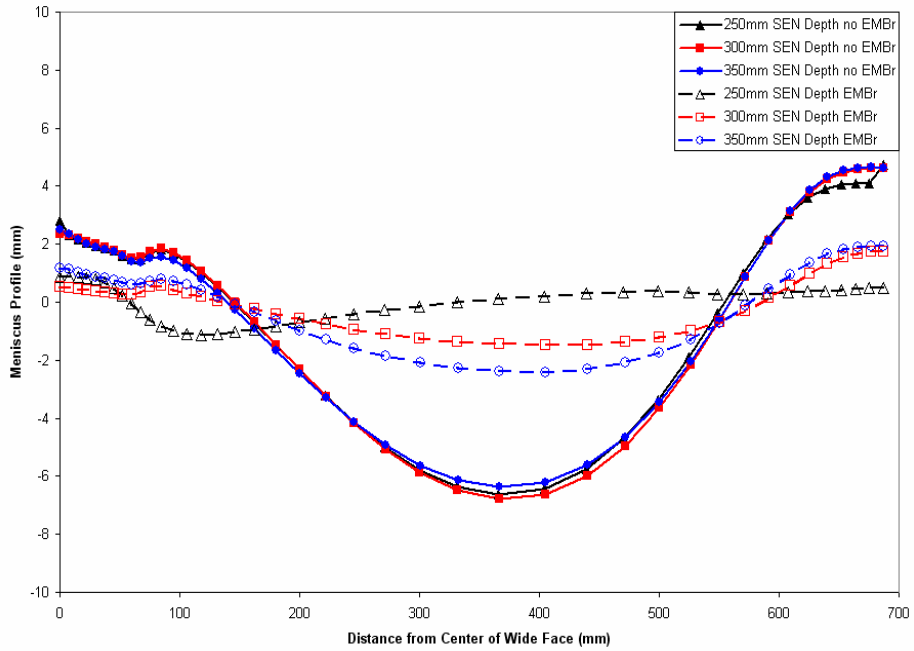
Cukierski & Thomas, Met Trans B, 2008

Meniscus Velocities – Deep SEN
Cases 1 to 6



Cukierski & Thomas, Met Trans B, 2008

Meniscus Profiles – Deep SEN
Case 1 to 6

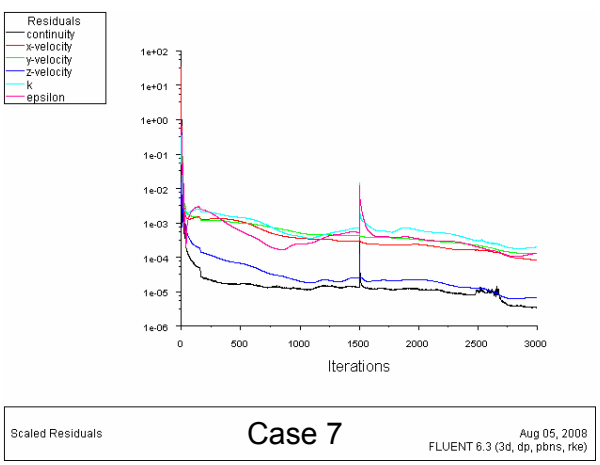


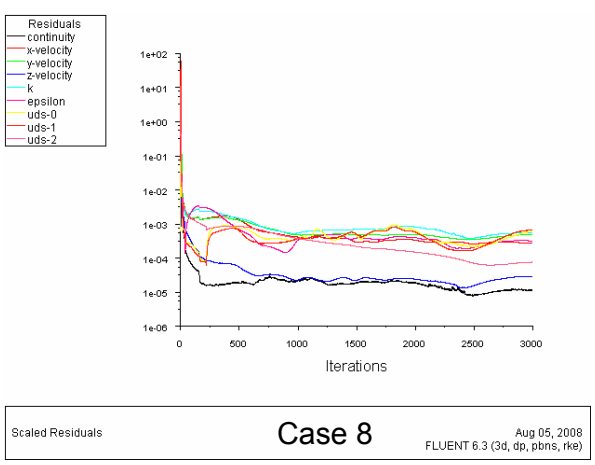
Cukierski & Thomas, Met Trans B, 2008

Effect of EMBr with Deep SEN

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

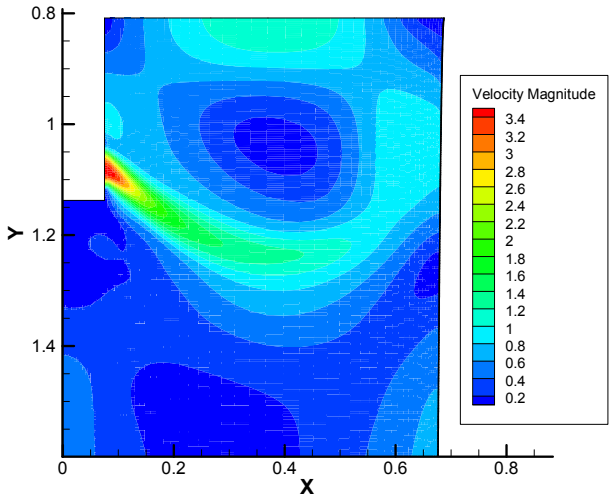
Residuals for Case 7 and 8



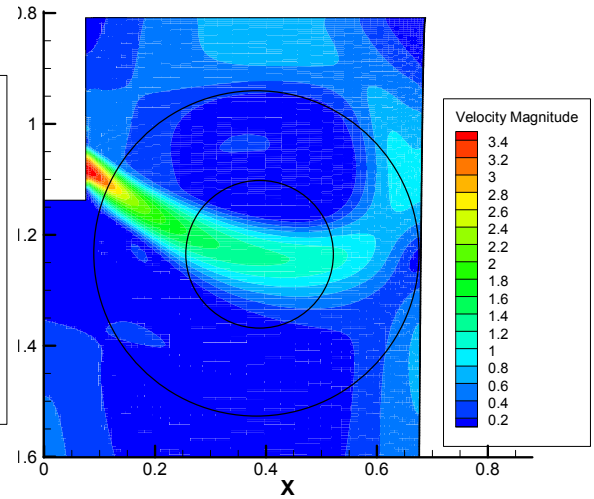


Solution is converged (residuals < 10^{-3})

EMBr Field and Mold Velocity – Shallow SEN
Case 7 and 8



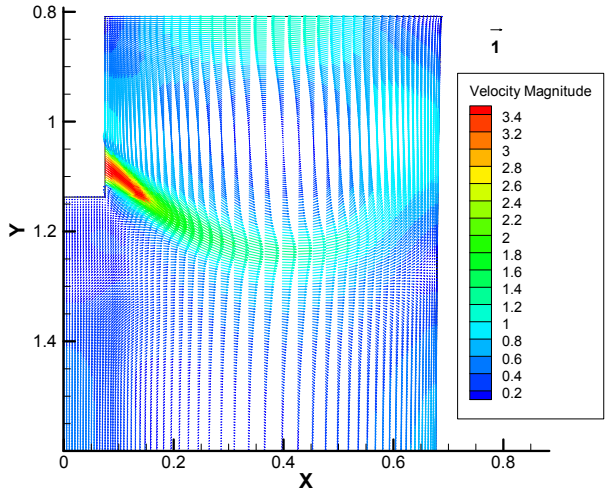
200 mm SEN Depth
no EMBr



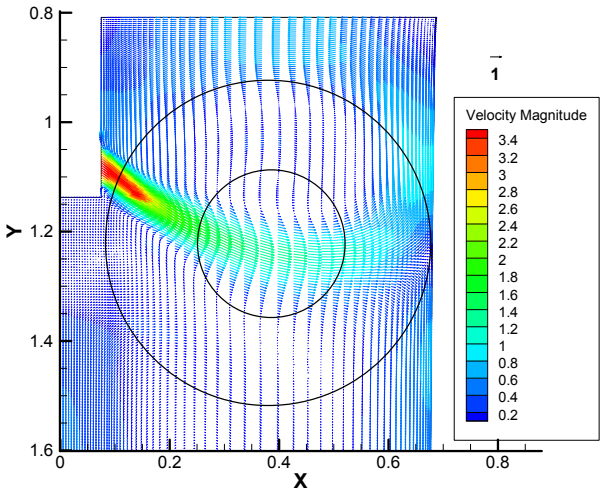
200 mm SEN Depth
EMBr on

Inner circle represents 0.3T. Outer circle represents extent of magnetic field

Mold Flow
Case 7 and 8

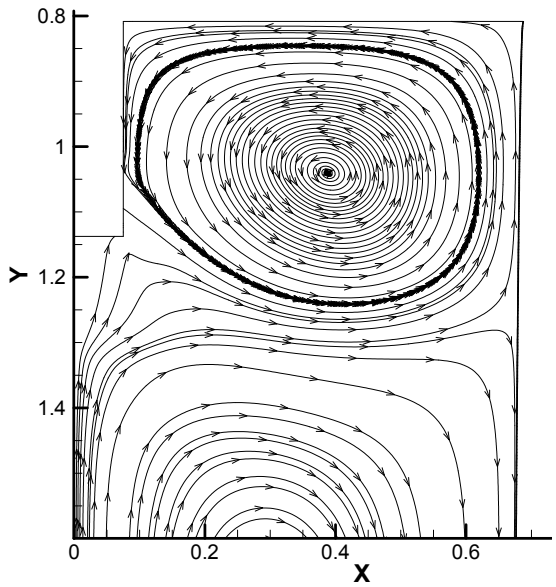


200 mm SEN Depth
no EMBr

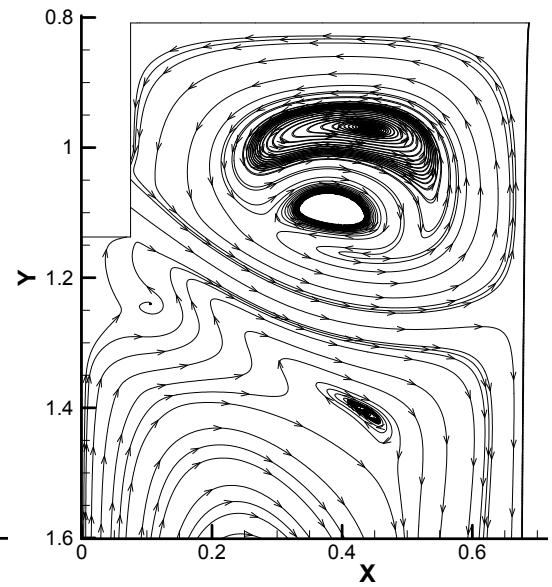


200 mm SEN Depth
EMBr on

Streamlines
Case 7 and 8

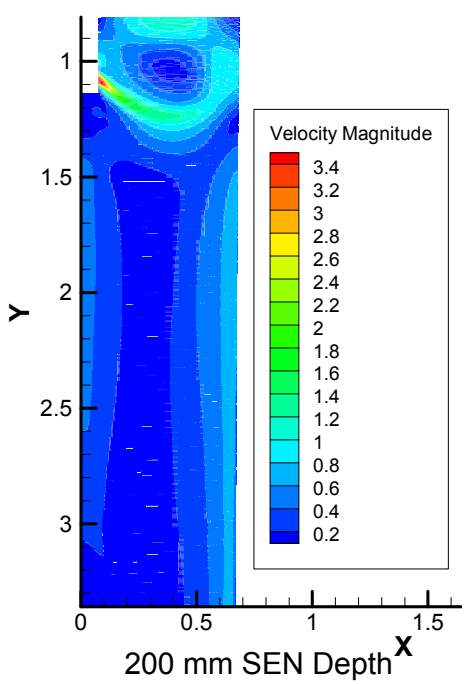


200 mm SEN Depth
no EMBr

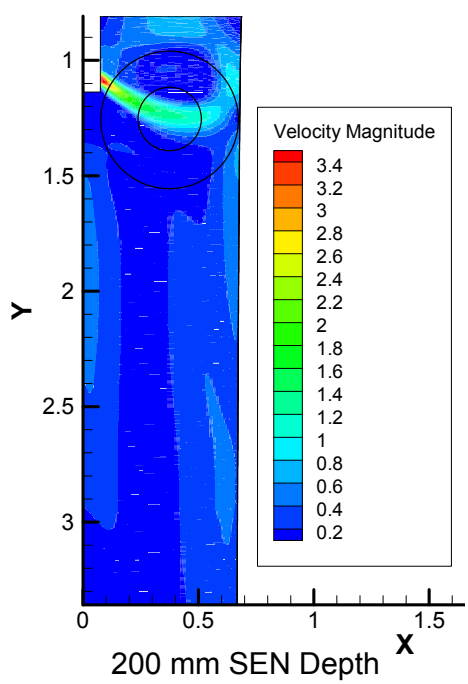


200 mm SEN Depth
EMBr on

Velocity in Lower Recirculation –
Shallow SEN (Case 7 and 8)

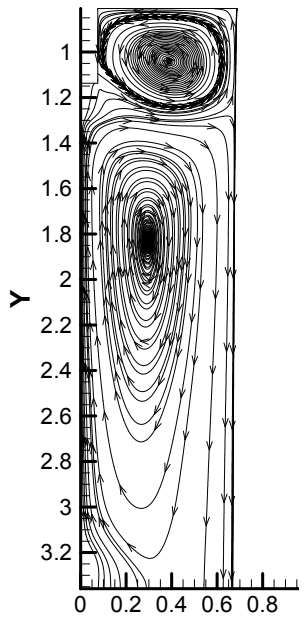


200 mm SEN Depth
No EMBr

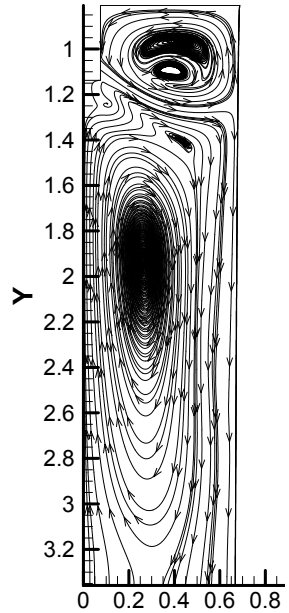


200 mm SEN Depth
EMBr on

Streamlines
Case 7 and 8

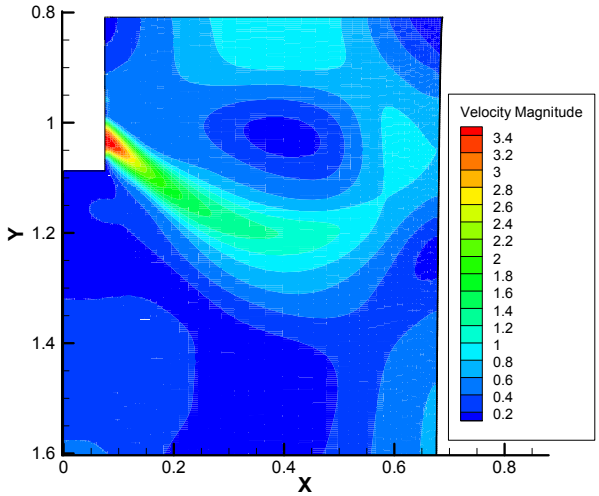


200 mm SEN Depth
no EMBr

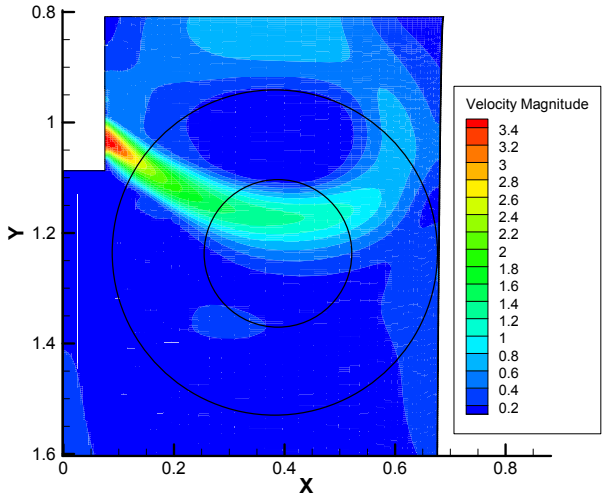


200 mm SEN Depth
EMBr on

EMBr Field and Mold Velocity – Shallow SEN
Case 9 and 10



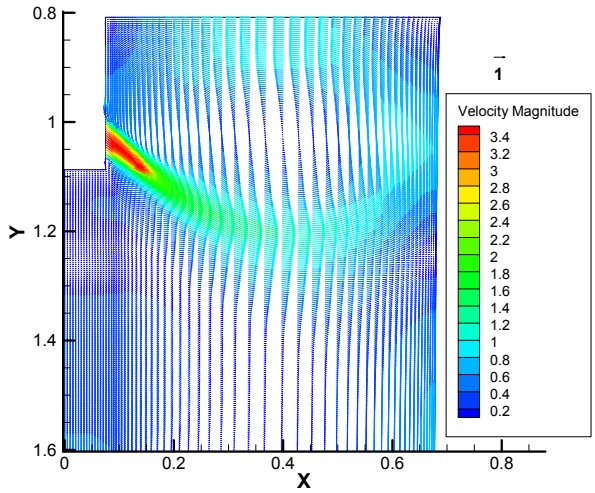
150 mm SEN Depth
no EMBr



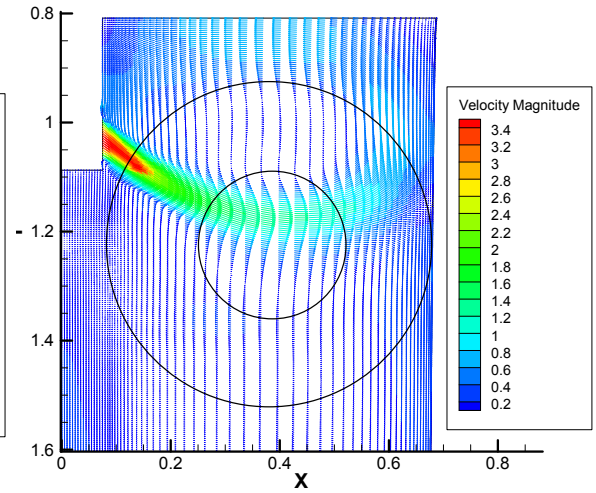
150 mm SEN Depth
EMBr on

Mold Flow

Case 9 and 10



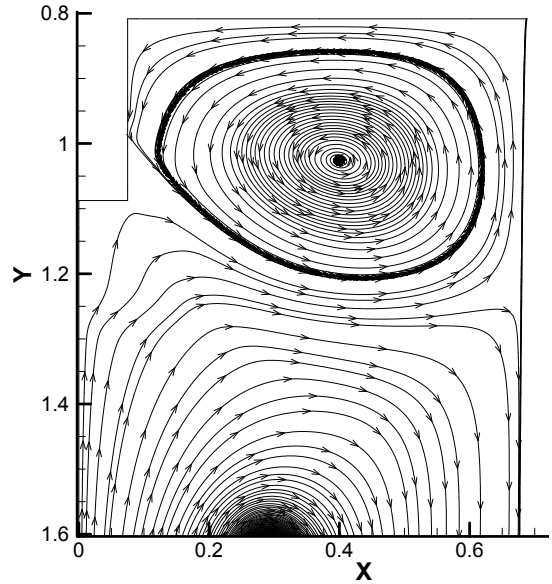
150 mm SEN Depth
no EMBr



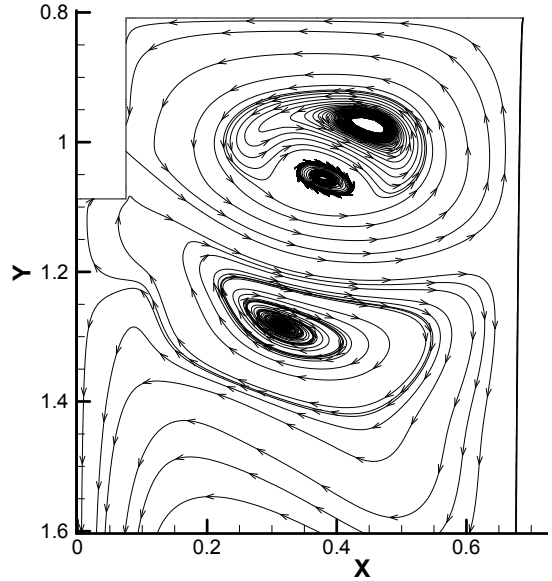
150 mm SEN Depth
EMBr on

Streamlines- Shallow SEN

Case 9 and 10

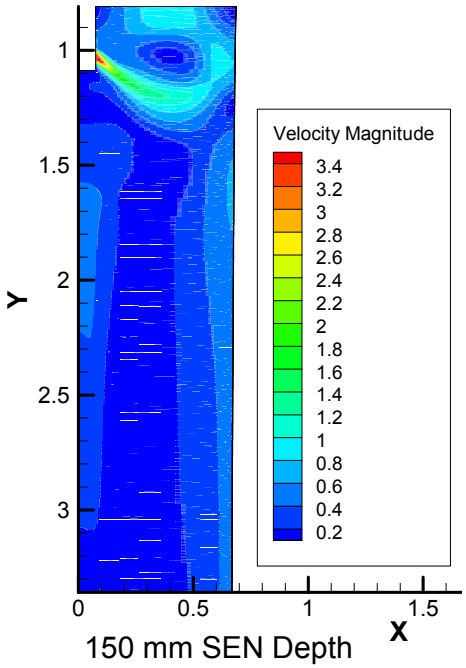


150 mm SEN Depth
no EMBr

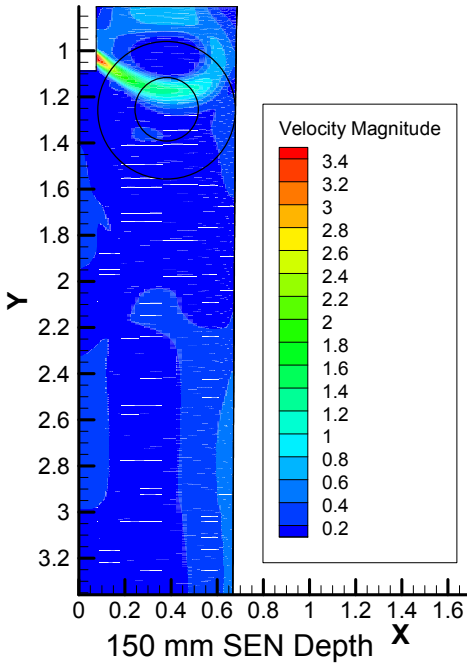


150 mm SEN Depth
EMBr on

Velocity in Lower Recirculation – Shallow SEN (Case 9 and 10)

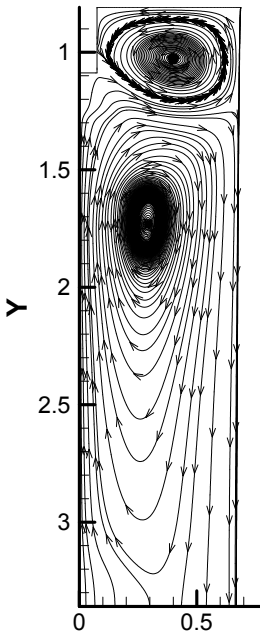


150 mm SEN Depth
no EMBr

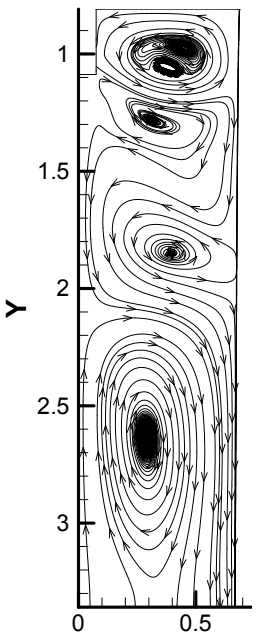


150 mm SEN Depth
EMBr on

Streamlines in Lower Recirculation – Shallow SEN (Case 9 and 10)

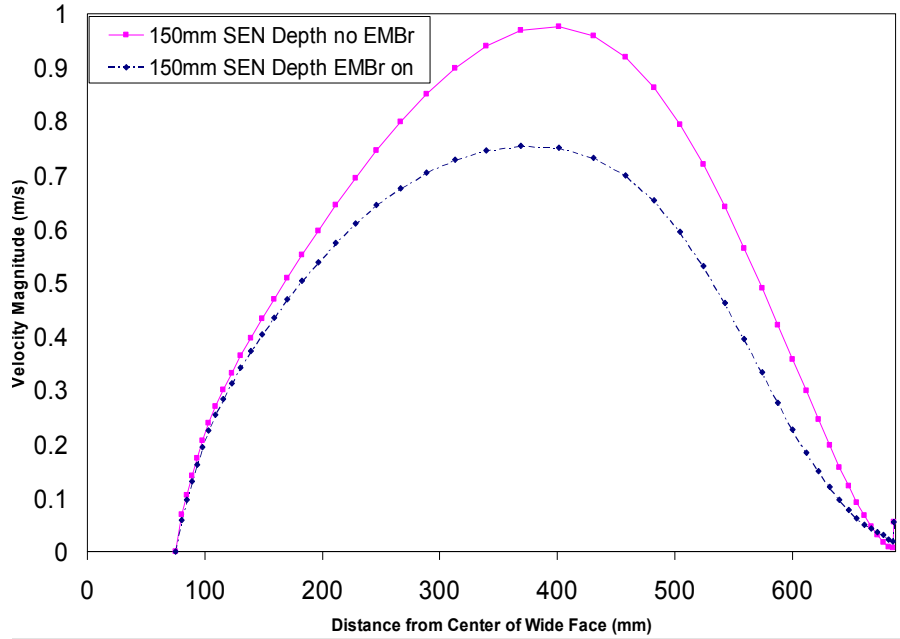


150 mm SEN Depth
no EMBr



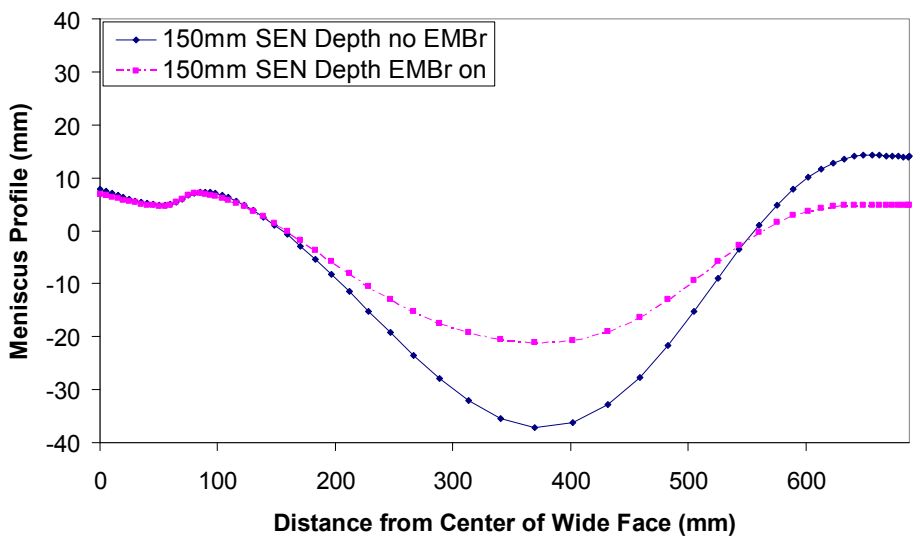
150 mm SEN Depth
EMBr on

Meniscus Velocity
Case 9 and 10



Comparison of velocity magnitude measured 10mm below top surface centerline

Meniscus Profile
Case 9 and 10



Comparison of magnitude profiles calculated Using the following equation

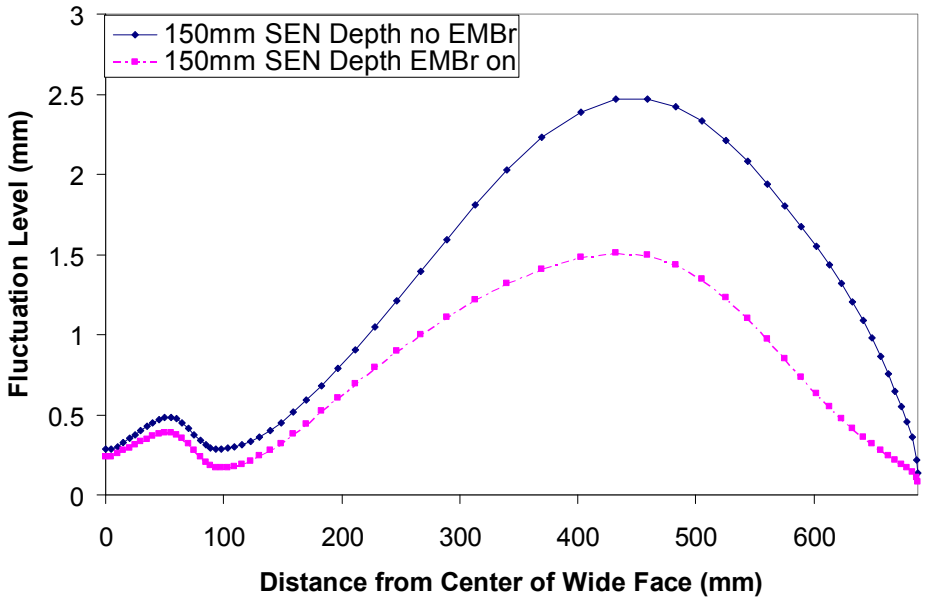
$$Meniscus\ Height = \frac{P_{static} - \overline{P}_{static}}{\rho_{steel} * g}$$

•Time averaged

•Pressures measured along top surface shell

Surface Level Fluctuation

Case 9 and 10



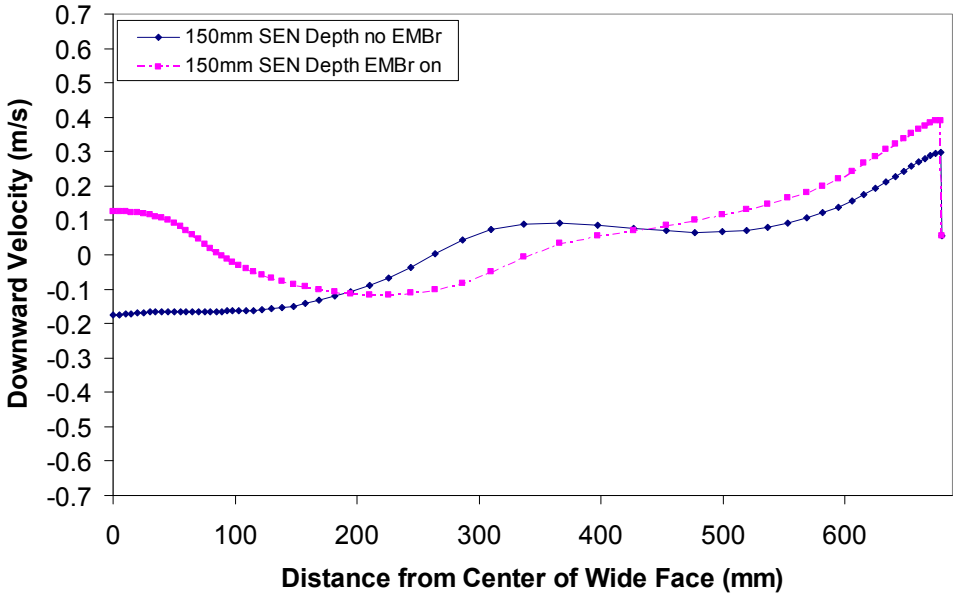
Fluctuations (h) ~ turbulent kinetic energy

$$0.5(\rho_{steel} - \rho_{slag})gh = \rho_{steel}K$$

Huang and B.G. Thomas, 1998

Downward Velocity Comparison

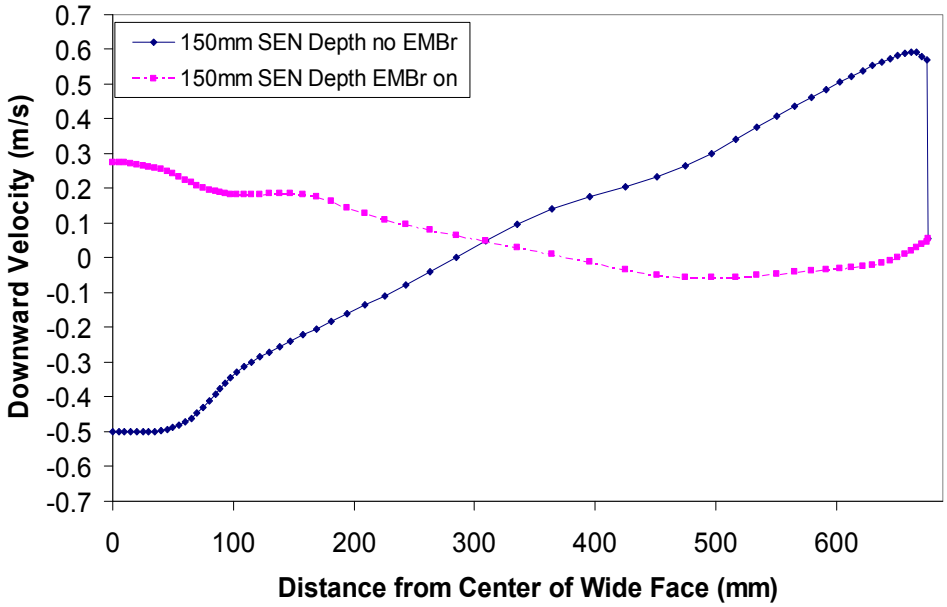
Case 9 and 10



Comparison of velocities 500mm Below Meniscus across the center of the wide face

Downward Velocity Comparison

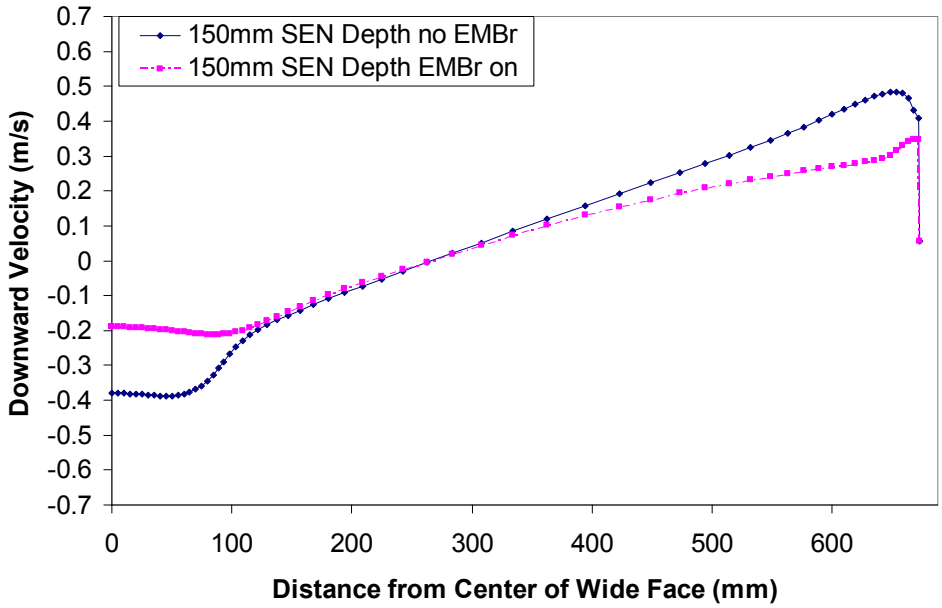
Case 9 and 10



Comparison of velocities 1000mm Below Meniscus across the center of the wide face

Downward Velocity Comparison

Case 9 and 10

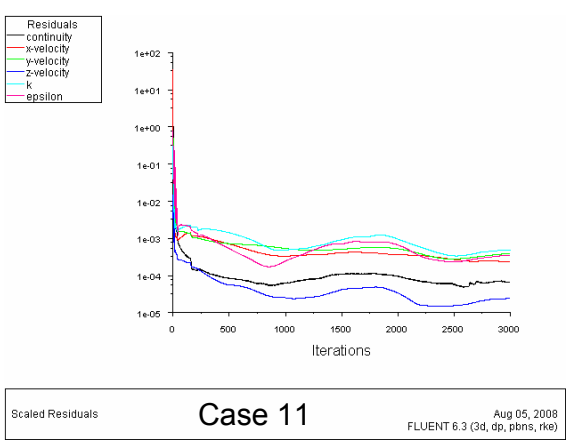


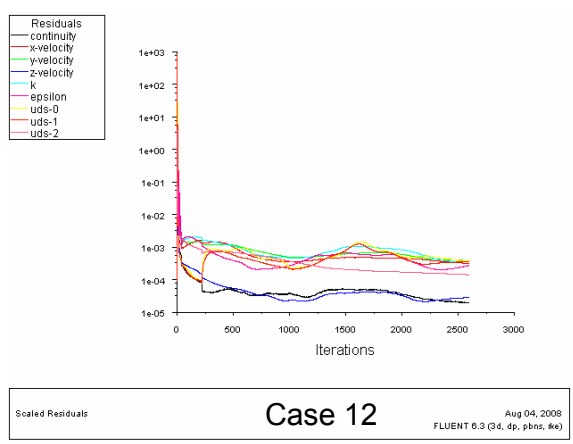
Comparison of velocities 1500mm Below Meniscus across the center of the wide face

Effect of EMBr with shallow SEN depth (150 and 200 mm SEN Depth)

- With the strongest magnetic field almost directly in the main path of the exiting jet:
  - Jet slows slightly
  - Jet deflects upward toward meniscus
- Result of EMBr is therefore:
  - meniscus velocity is reduced
  - meniscus profile is flatter
  - Level fluctuations are smaller
  - Velocity down narrow face is generally lower
  - Lower recirculation zone becomes more complex (150mm)

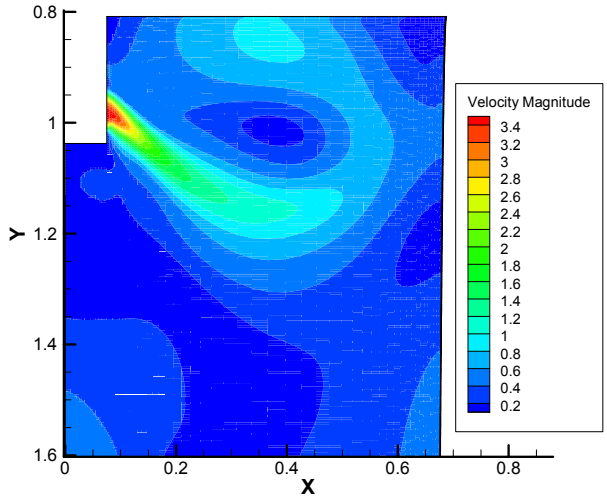
Residuals for Case 11 and 12



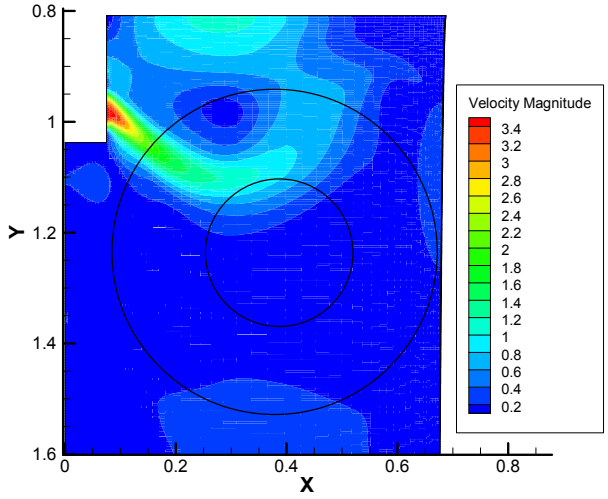


Solution is converged (residuals < 10^{-3})

EMBr Field and Mold Velocity
Case 11 and 12

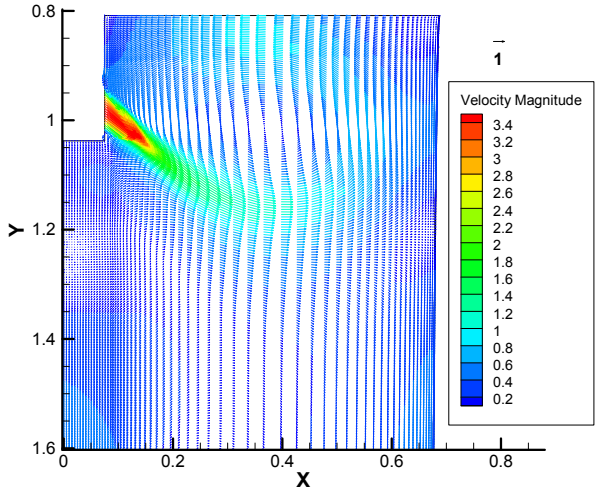


100 mm SEN Depth
no EMBr

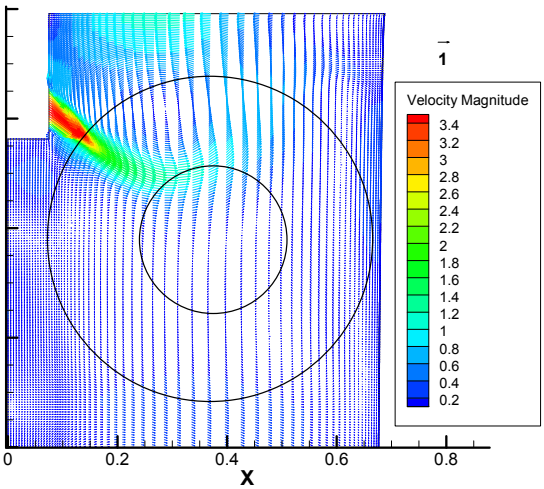


100 mm SEN Depth
EMBr on

Mold Flow
Case 11 and 12

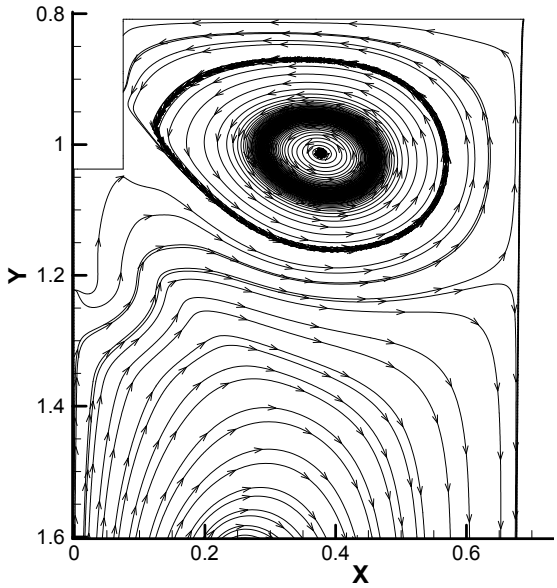


100 mm SEN Depth
no EMBr

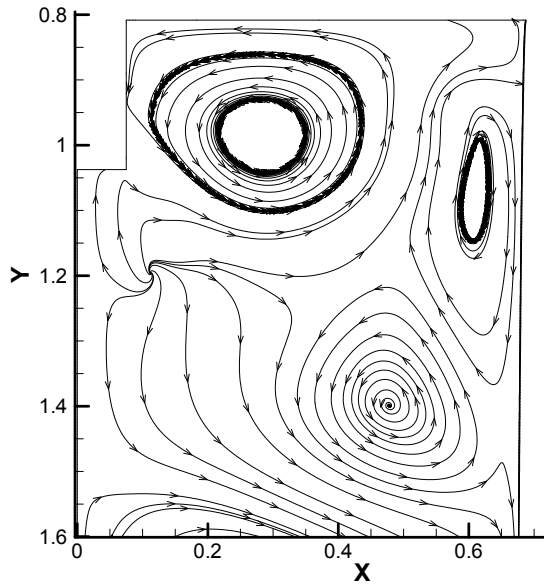


100 mm SEN Depth
EMBr on

Streamlines
Case 11 and 12

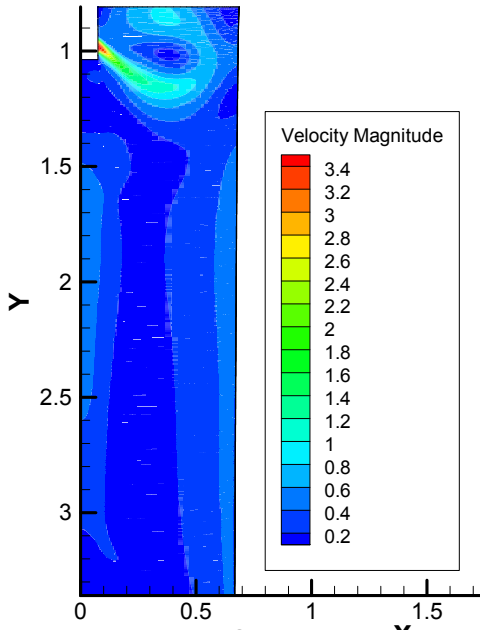


100 mm SEN Depth
no EMBr

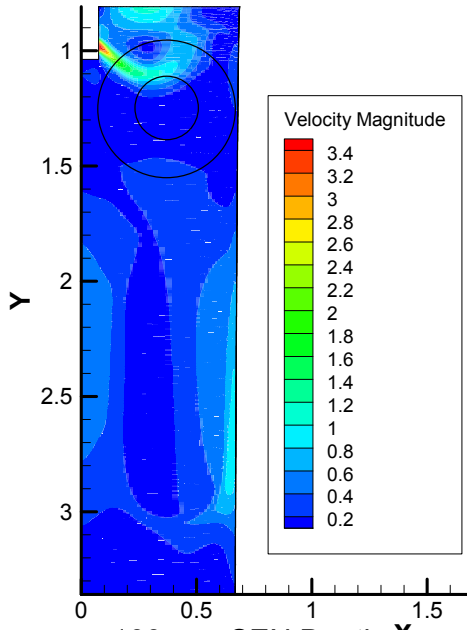


100 mm SEN Depth
EMBr on

Velocity Contour
Case 11 and 12

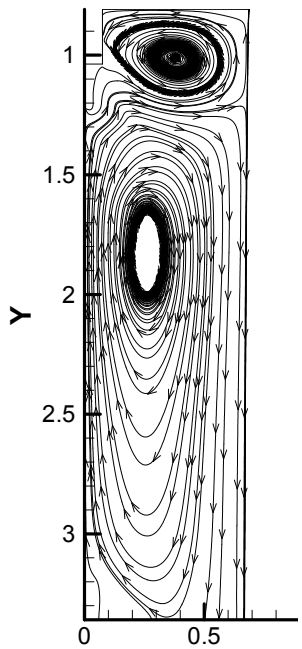


100 mm SEN Depth
no EMBr

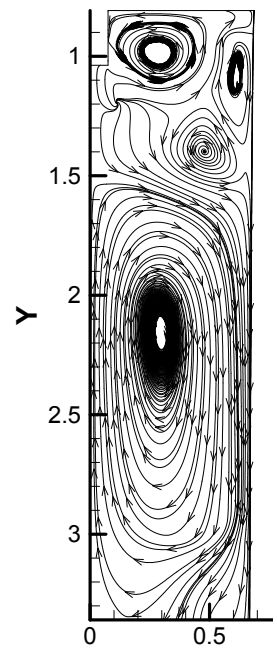


100 mm SEN Depth
EMBr on

Streamlines
Case 11 and 12

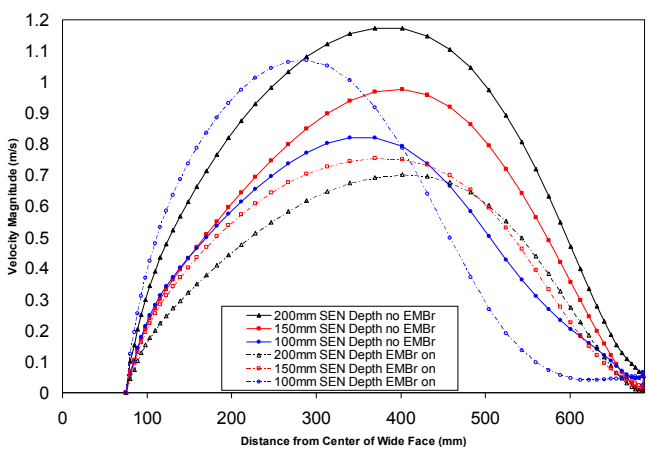


100 mm SEN Depth no EMBr

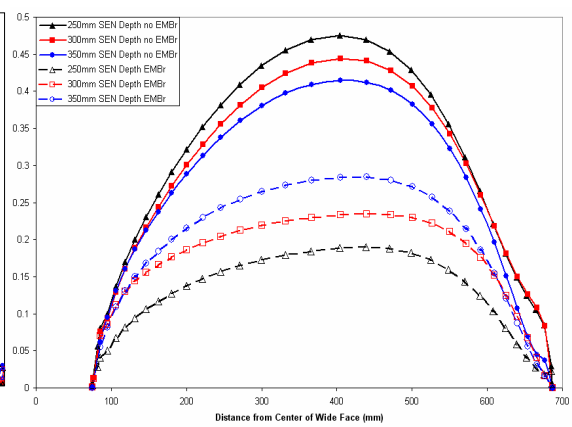


100 mm SEN Depth EMBr on

Meniscus Velocities – All cases



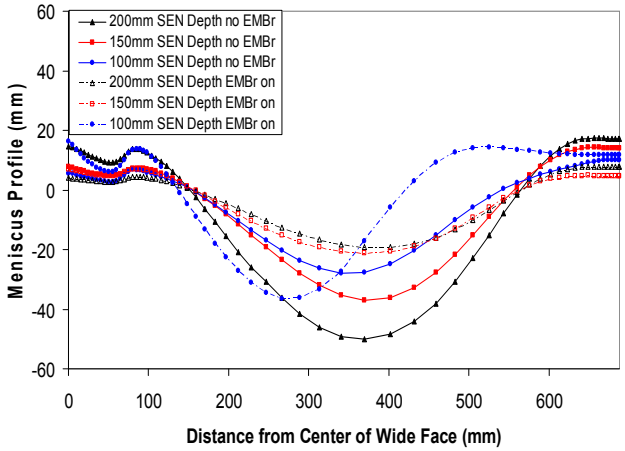
Case 7 to 12



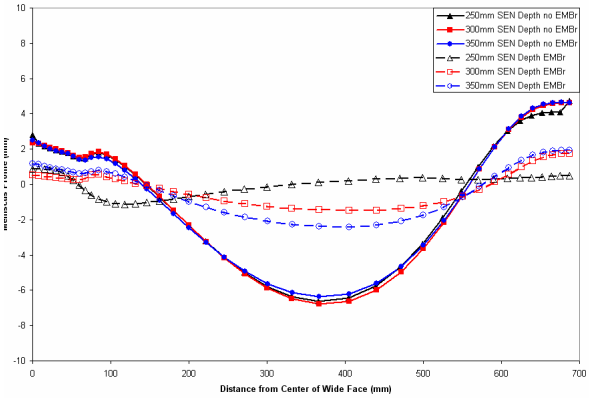
Case 1 to 6

Comparison of velocity magnitude measured 10mm below top surface centerline

Meniscus Profiles – All cases

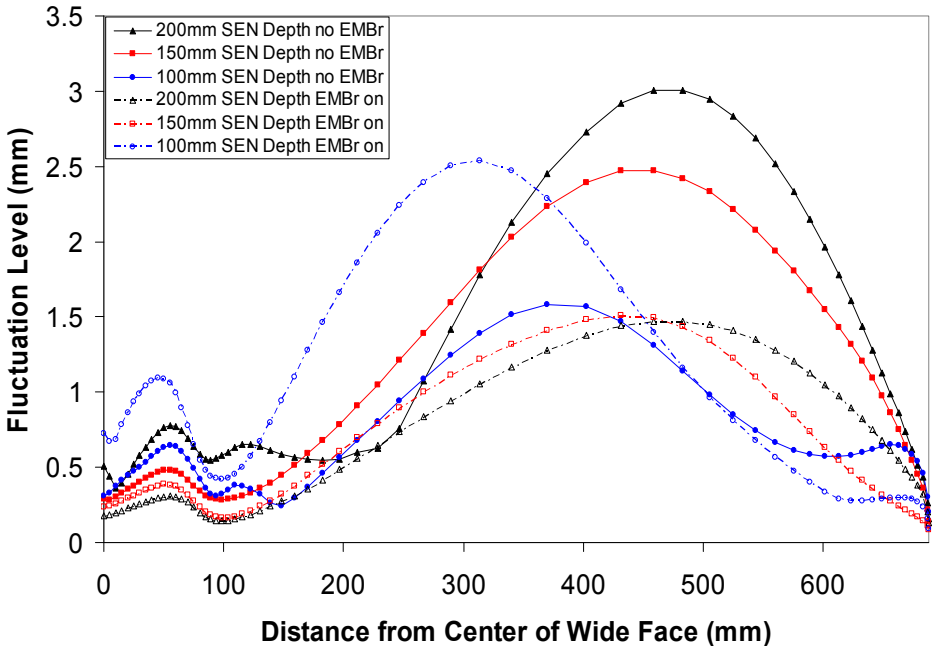


Case 7 to 12



Case 1 to 6

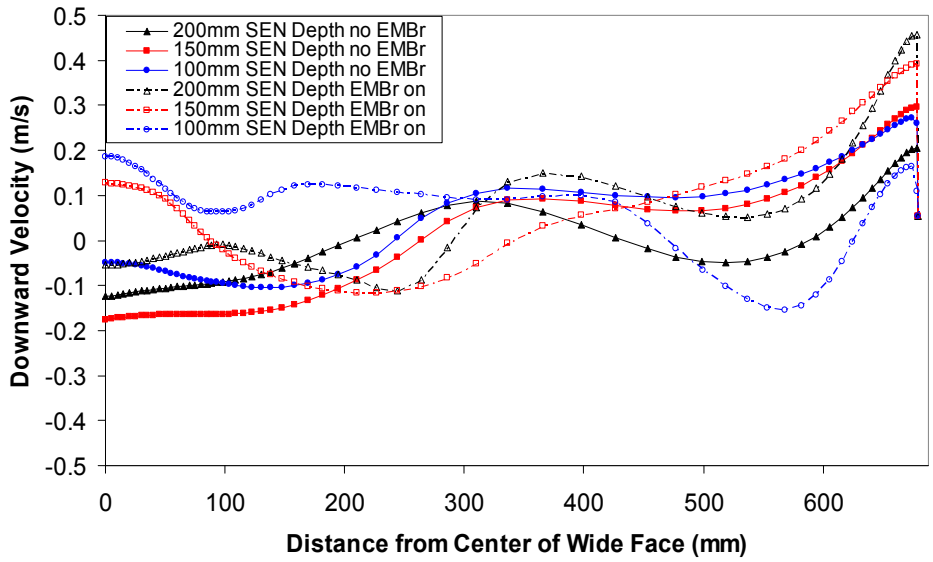
Surface level Fluctuations Case 7 to 12



$$\rho_{steel} K = 0.5(\rho_{steel} - \rho_{slag}) g h$$

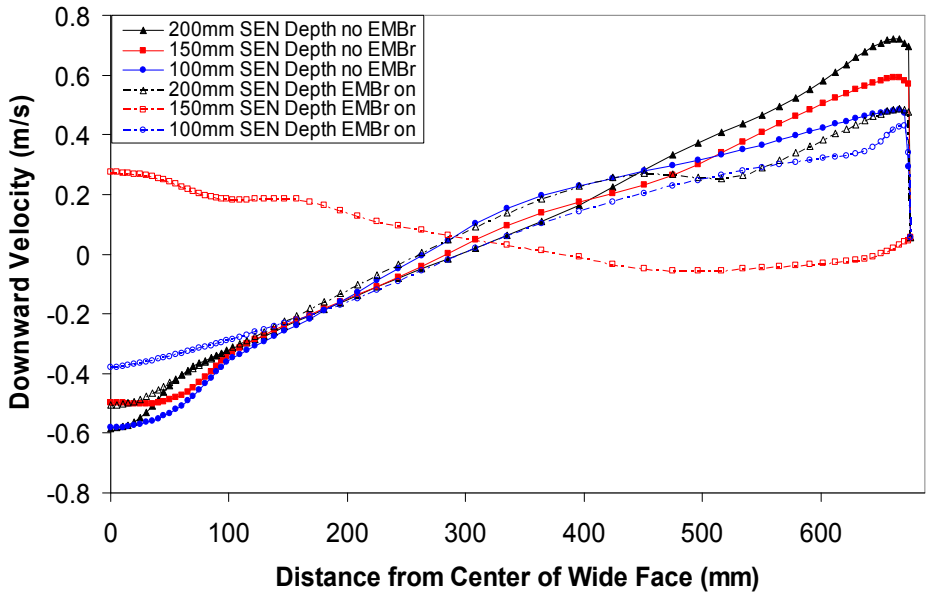
Huang and B.G. Thomas, Can Met Quart., 1998

Downward Velocities
Case 7 to 12



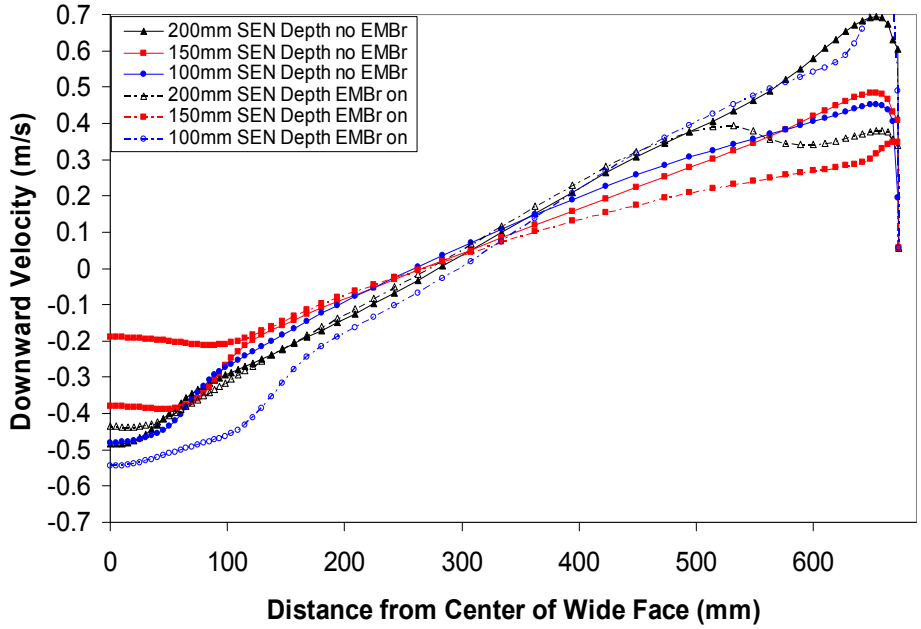
Comparison of velocites 500mm below meniscus across the center of the wide face

Downward Velocities
Case 7 to 12



Comparison of velocites 1000mm below meniscus across the center of the wide face

Downward Velocities
Case 7 to 12



Comparison of velocites 1500mm below meniscus across the center of the wide face

Effect of EMBr with 100 mm SEN Depth

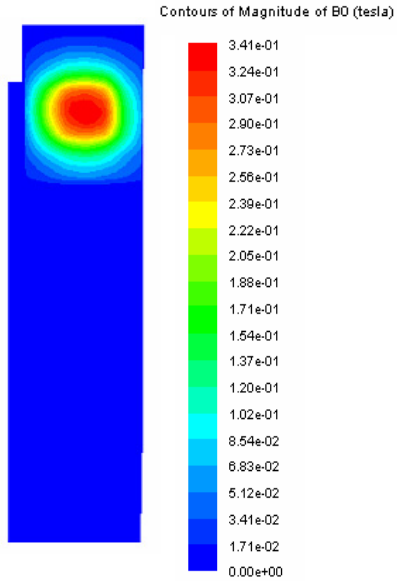
- With the strongest magnetic field below the main path of the exiting jet:
  - Jet deflects sharply impinging NF very near meniscus
  - Jet circulation thus moves toward SEN
- Result of EMBr is therefore:
  - meniscus velocity is reduced near the narrow face
  - meniscus profile and level fluctuation is higher toward the center.
  - Velocity down narrow face is lower
  - Lower recirculation zone becomes more complex as the magnetic field gets closer to meniscus

Effect of Raising Magnetic Field

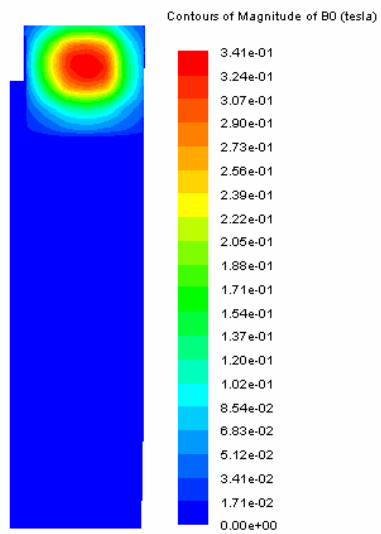
- Entire actual magnetic field was raised (towards meniscus) by 200mm
- Compare results for 150mm SEN depth: actual (case 10) vs. raised (case 13).

Location of Magnetic Field

Case 10 and 13

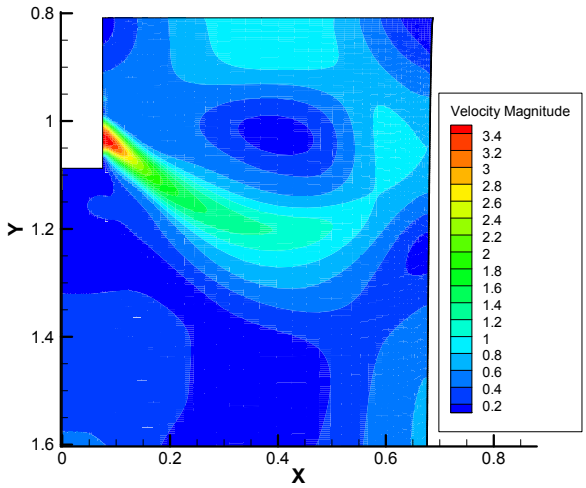


150 mm SEN Depth EMBr on

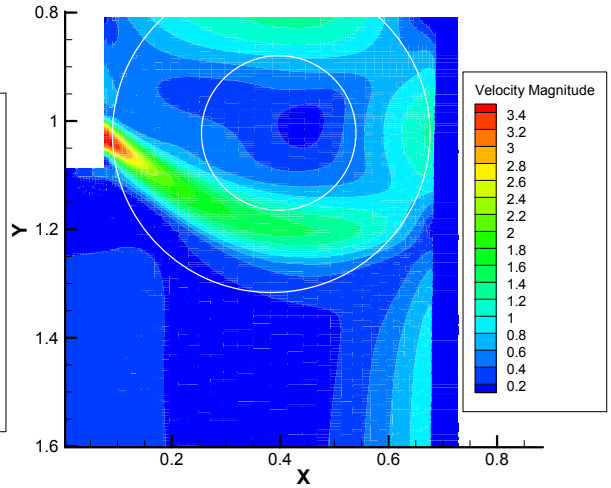


150 mm SEN Depth EMBr on, Raised Field

Velocity Contour Close-up,
Case 9 and 13

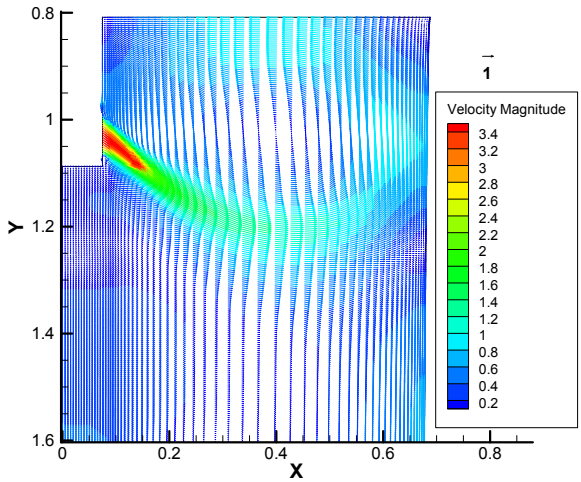


150 mm SEN Depth
No EMBr

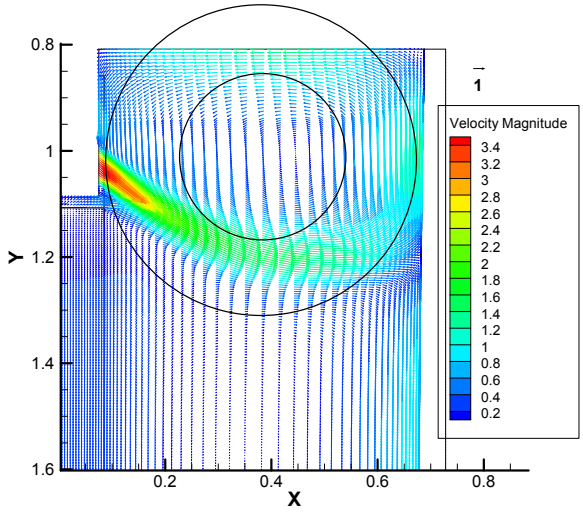


150 mm SEN Depth
EMBr on, Raised Field

Velocity Magnitude, Close-up,
Case 9 and 13



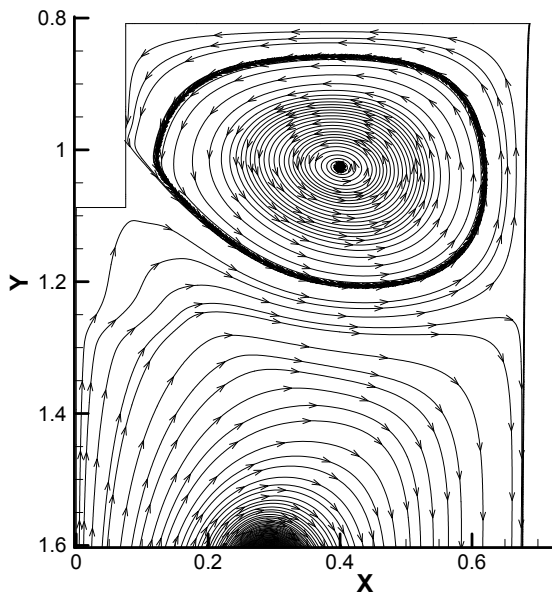
150 mm SEN Depth
No EMBr



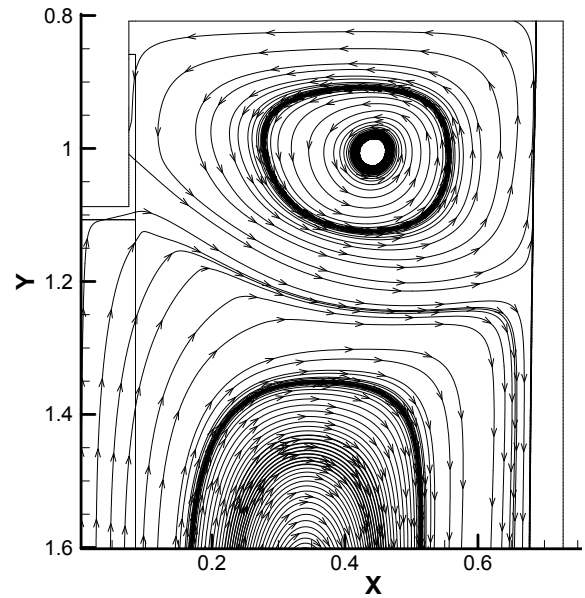
150 mm SEN Depth
EMBr on, Raised Field

Stream Line, Close-up,

Case 9 and 13



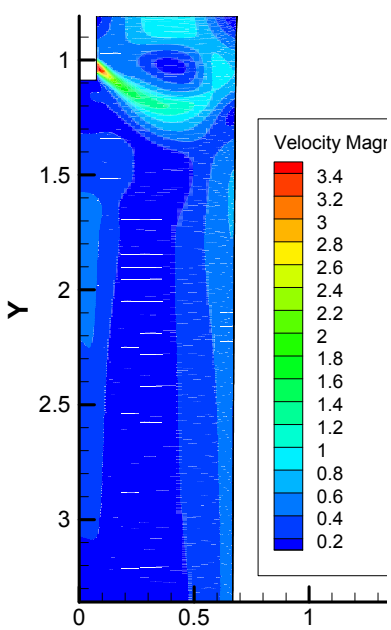
150 mm SEN Depth
No EMBr



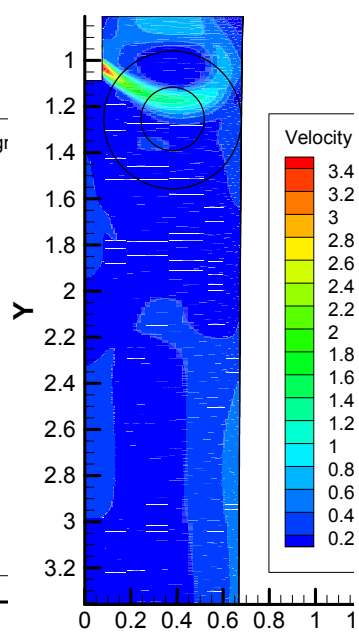
150 mm SEN Depth
EMBr on, Raised Field

Velocity Contours

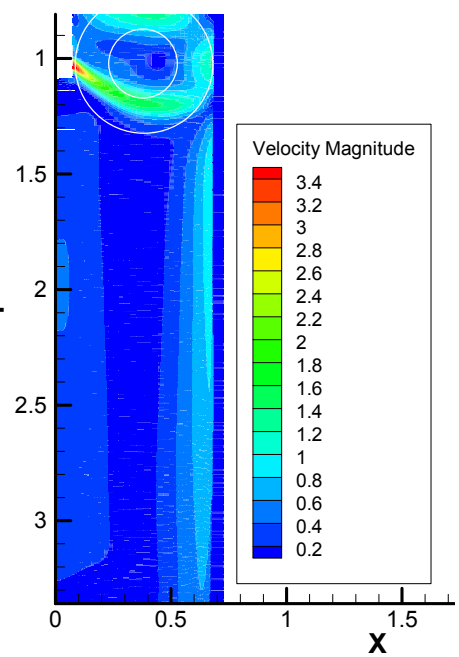
Case 9, 10 and 13



150 mm SEN Depth
No EMBr



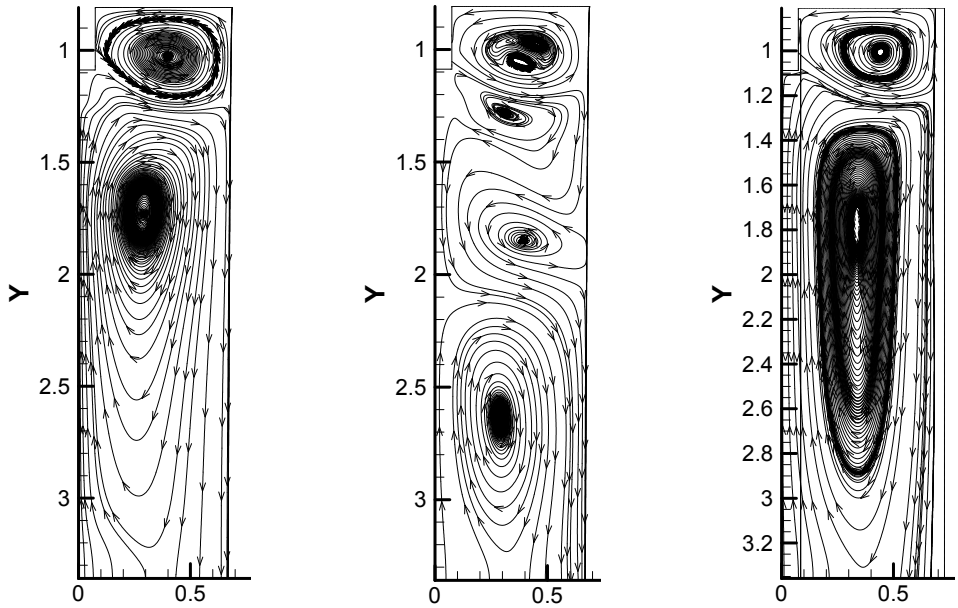
150 mm SEN Depth
EMBr on



150 mm SEN Depth
EMBr on, Raised Field

Streamlines

Case 9, 10 and 13



150 mm SEN Depth
No EMBr

150 mm SEN Depth
EMBr on

150 mm SEN Depth
EMBr on, Raised Field

Effect of Raising Magnetic Field

- Case 9 (no field) similar to case 13 (raised field)
- Case 10 has changed flow pattern with lower velocities
- Thus: raising field to center of the eye of the upper recirculation zone makes the field have almost no effect.

Summary

- For deep SEN depth, increasing SEN Depth causes:
  - EMBr off:
    - Decrease in meniscus velocity
    - Deeper jet impingement
    - Smaller meniscus wave (profile variations)
  - EMBr On:
    - Increase in meniscus velocity
    - Shallower jet impingement
    - Larger meniscus wave

Summary

- For shallow SEN depth, increasing SEN Depth causes:
  - EMBr off:
    - Increase in meniscus velocity
    - Larger meniscus wave
    - Increase in surface level fluctuation near the narrow face
  - EMBr On:
    - Decrease in meniscus velocity
    - Smaller meniscus wave
    - Decrease in surface level fluctuation near the narrow face