CCC Annual Report

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Effect of EMBr on Flow in SEN and Mold

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Objectives

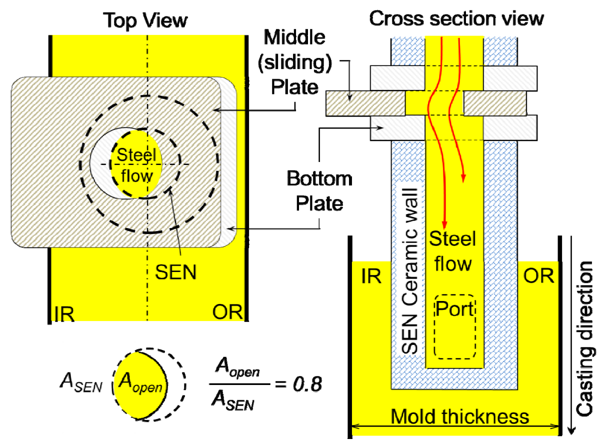
- Use high resolution LES model to study the effect of SEN submergence depth on the molten steel flow in mold
- Understand the transient molten steel flow and transient effect of double-ruler EMBr
- Investigate the effect of SEN submergence depth on EMBr braking efficiency
- Prepare flow field for inclusion transport and capture studies

Casting Conditions and Steel Properties

- Baosteel No. 4 caster, 230×1300mm strand
- Slide gate 80% open at V_c = 1.8m/min, steel first entering IR side
- SEN port downward angle 15º, port area 65×83 mm^2

Properties of Molten Steel	
Density ρ_l (kg/m^3)	7000
Dynamic Viscosity μ_l (kg/m-s)	0.0063
Electrical Conductivity σ (S/m)	714000[1]
Magnetic Permeability (h/m)	1.26×10^{-6}

Note: solid shell conductivity taken as 787000 S/m [1]



Schematic of slide gate configuration

Governing Equations For Fluids

- The Navier-Stokes equations in conservation form with LES model

$$\nabla \cdot (\rho \boldsymbol{u}) + \dot{s} = 0$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\nabla p + \nabla \cdot \left[(\mu + \mu_{sgs}) (\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) \right] + \boldsymbol{F}_L$$

$\dot{s}$ – Mass sink due to solidifying shell

$\boldsymbol{F}_L$ – Source from Lorentz force

- Sub-grid scale - Coherent-Structure Smagorinsky Model[2] (CSM)

$$\nu_{sgs} = C_s^2 (\Delta x \Delta y \Delta z)^{2/3} \sqrt{2 S_{ij} S_{ij}}$$

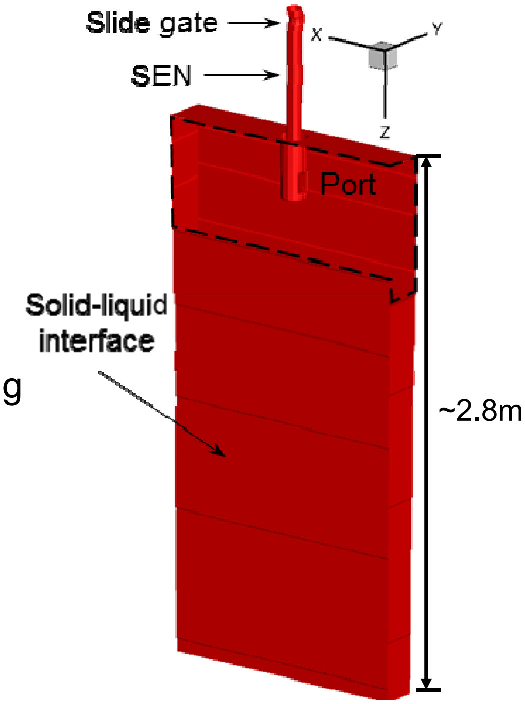
$$C_s^2 = C_{csm} |Q/E|^{3/2} (1 - Q/E)$$

$$Q = 1/2 (W_{ij} W_{ij} - S_{ij} S_{ij}) \qquad E = 1/2 (W_{ij} W_{ij} + S_{ij} S_{ij})$$

W_{ij} – vorticity tensor $\qquad$ S_{ij} – velocity-strain tensor

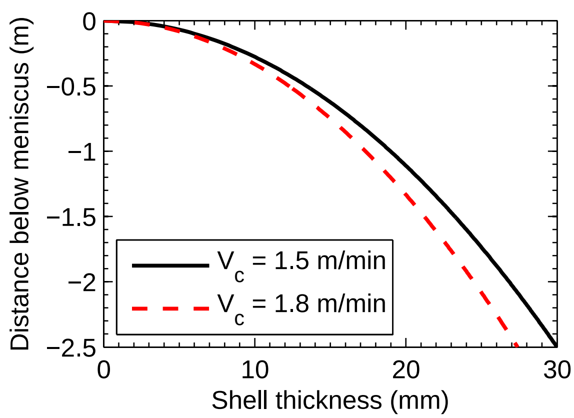
Computational Domain and Boundary Conditions

- Domain slide gate, SEN, mold region
- Cartesian grid ~16 million cells, hexahedral with edge length ~4mm
- Solid shells included
- Boundary Conditions
  - velocity inlet, 1.66m/s
  - top surface, no slid wall
  - shell-molten steel interface, moving wall 0.03m/s with mass sink
  - outside of shell insulated wall
  - outlet, zero derivative velocity

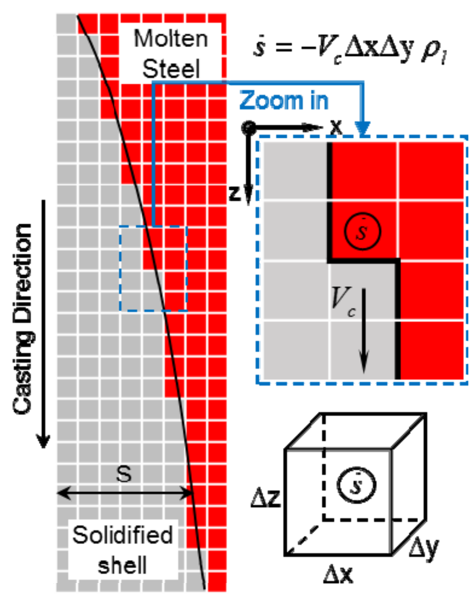


Shell Profile and Mass Sink

- Shell thickness $S = Kt^{1/2}$ with $K = 3mm \cdot s^{-1/2}$ (from a breaking shell)
- Mass sink added at some cells
- Cells in shell are solid cells with downward velocity equals V_c and electrical conductivity of 787000 S/m[1]



Shell Profile



Mass sink terms

Governing Equations for MHD

- By introducing the electric potential Φ and using Ohm's law, the current density is:

$$\boldsymbol{J} = \sigma\left(-\nabla\Phi + \boldsymbol{u}\times\boldsymbol{B}\right)$$

- A well conducting material the current conservation law

$$\nabla\cdot\boldsymbol{J} = 0$$

- Therefore, electric potential satisfies the Poisson equation

$$\nabla\cdot\left(\sigma\nabla\Phi\right) = \nabla\cdot\left[\sigma\left(\boldsymbol{u}\times\boldsymbol{B}\right)\right]$$

- The Lorentz force is obtained from

$$\boldsymbol{F}_L = \boldsymbol{J}\times\boldsymbol{B}$$

- Equations are solved on the entire domain (including the shell)

List of Simulations and EMBr Profile

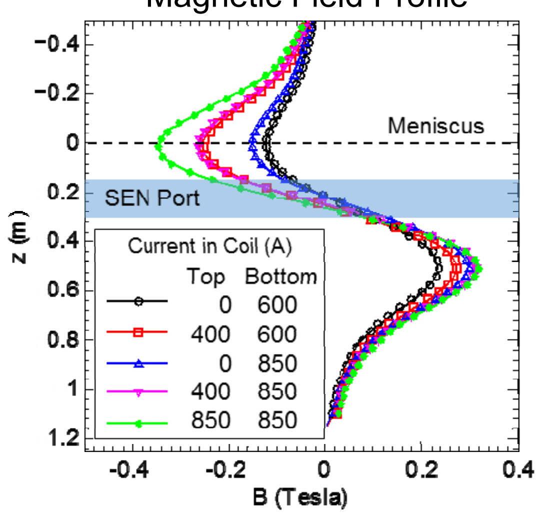
- Applied magnetic field ***B***, measured by ABB and Baosteel
- Investigate two submergence depth four different EMBr settings

List of Seven Simulations
(**230×1300mm**, slide gate **80%** open, $\boldsymbol{V_c}$ **= 1.8m/min**)

	SEN Submergence Depth (mm)	Top Coil Current (A)	Bottom Coil Current (A)
1	170	0	0
2	170	0	850
3	170	400	850
4	170	850	850
5	200	0	0
6	200	0	850
7	200	400	850

Addition Validation Case:
230×1200mm strand $\boldsymbol{V_c}$ **= 1.3m/min**, gate **70%** open area, no EMBr, no argon injection

Magnetic Field Profile



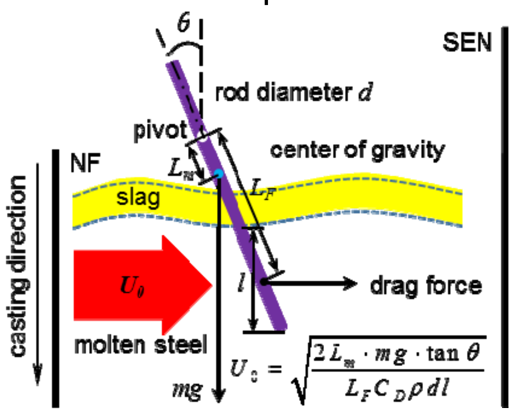
Solver and Computational Details

- Multi-GPU finite volume code CUFLOW written in CUDA Fortran
- Fractional step, 2nd order Adams-Bashforth explicit
- Poisson equations are solved by V-cycle multi-grid method with Red-Black Gauss-Seidel SOR

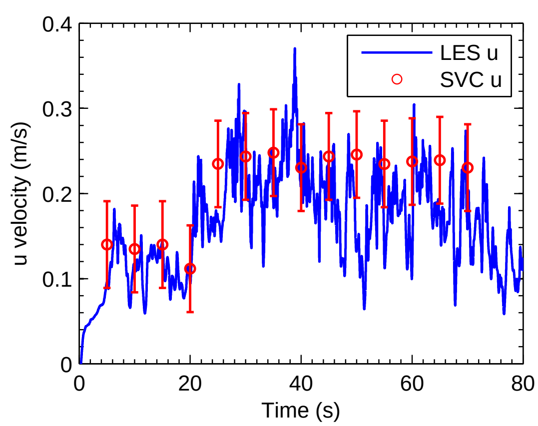
- Domain decomposed onto 6 GPUs (Nvidia K20) on BlueWaters
- Timesteps are taken as ~0.0002s
- 40s LES simulations (16million cells) takes ~2 days to finish
- Multi-Grid using 5 V-Cycle and 6 sweeps on Poisson equations for pressure and 8 V-Cycle and 8 sweeps for electric potential
- Sum or pressure residual reduced to $O(1\times10^{-8})$ at each timestep (sum of residuals drops 3 or 4 orders of magnitude)

Validation – Compare Predicted Velocity with Plant SVC Results

- SVC[3] measurement provided by Baosteel: No. 4 caster with 230×1200mm strand and a lower casting speed of 1.3m/min, no EMBr, no argon injection
- LES simulations carried out with the same conditions, u velocity (along WF) in the quarter mold center plane and 1cm below top surface are compared with SVC data points



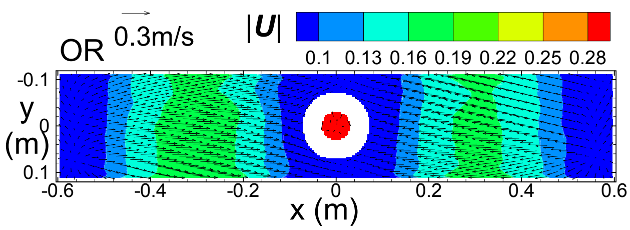
Schematic of SVC measurements

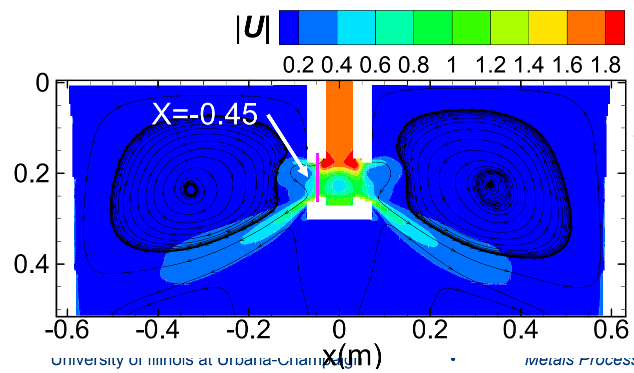


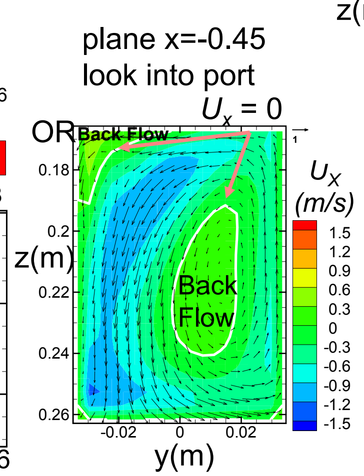
Compare u velocity from LES with SVC

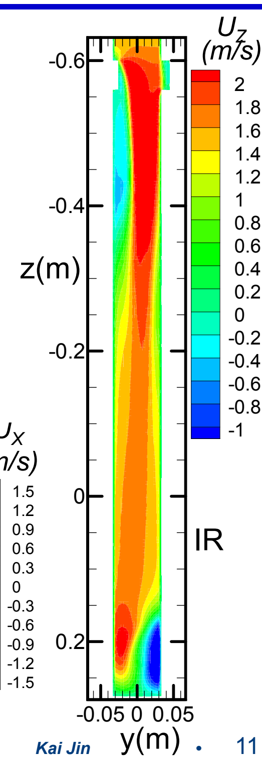
Mean Velocity (Validation Case)

- Time averaged velocity magnitude $|\boldsymbol{U}| = (U_x^2+U_y^2+U_z^2)^{1/2}$
- Back flow - reversal going into the port (towards inside SEN)
- A big swirl at bottom of SEN



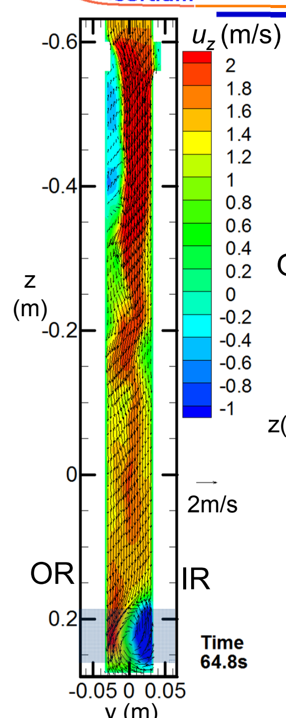




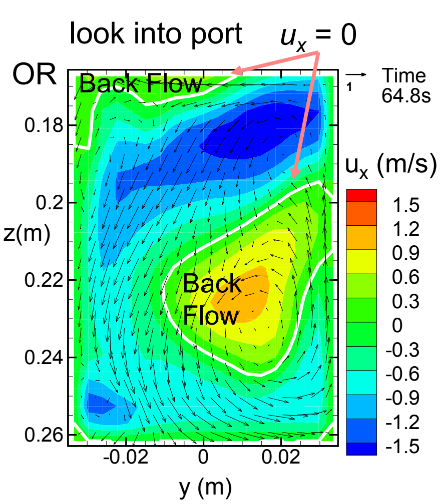


Transient Flow in SEN, Port and Shape of the Jet Exiting Port (Validation Case)

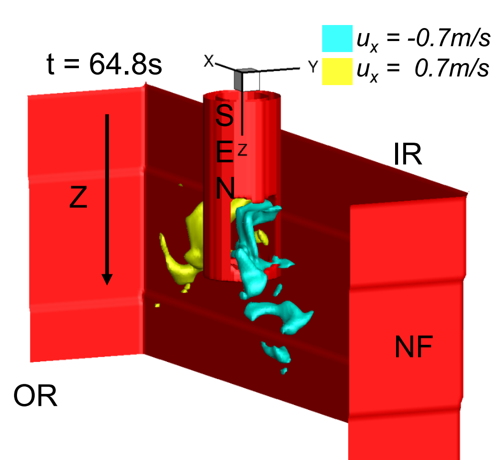
Large circulation in SEN bottom causes low pressure in the circulation center and suck in fluid in the mid of port, instantaneous velocity $\boldsymbol{u} = (u_x, u_y, u_z)$



Velocity in SEN



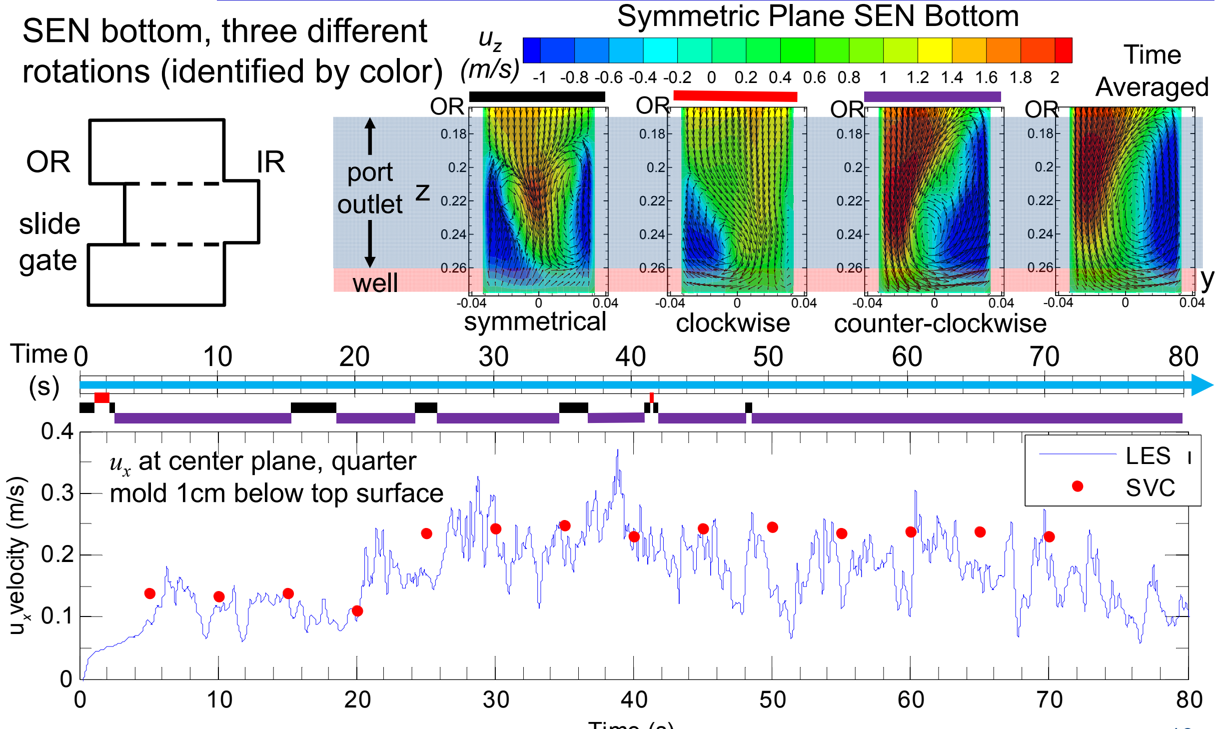
Velocity in port



Iso-surface of u

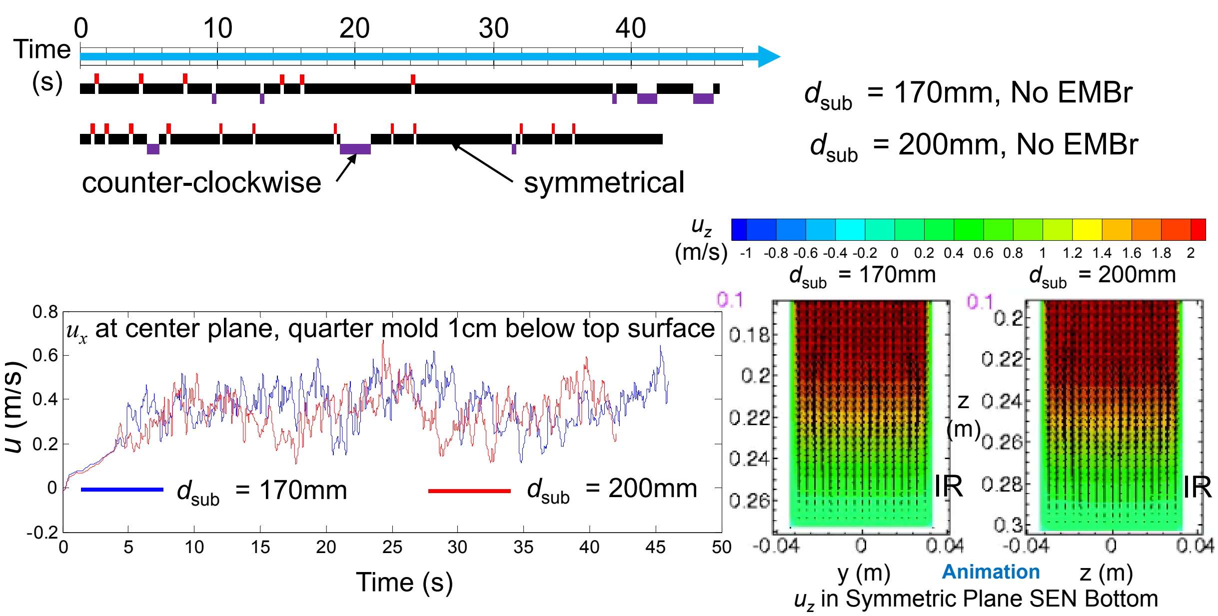
Flow Rotation at SEN Bottom and Top Surface Velocity (Validation Case)

SEN bottom, three different rotations (identified by color)



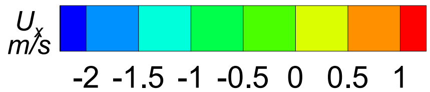
Swirls at SEN Bottom and Top Surface Velocity (without EMBr)

- 230×1300mm strand, V_c = 1.8m/min, submergence depth d_{sub} of 170mm and 200mm, No EMBr → two circulations at SEN bottom

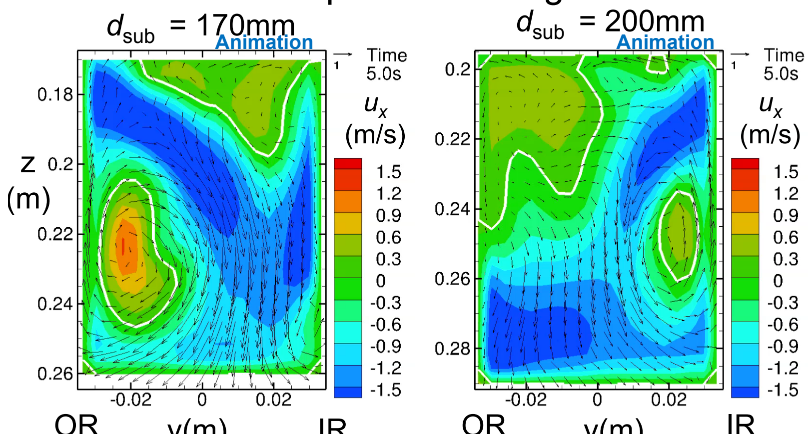


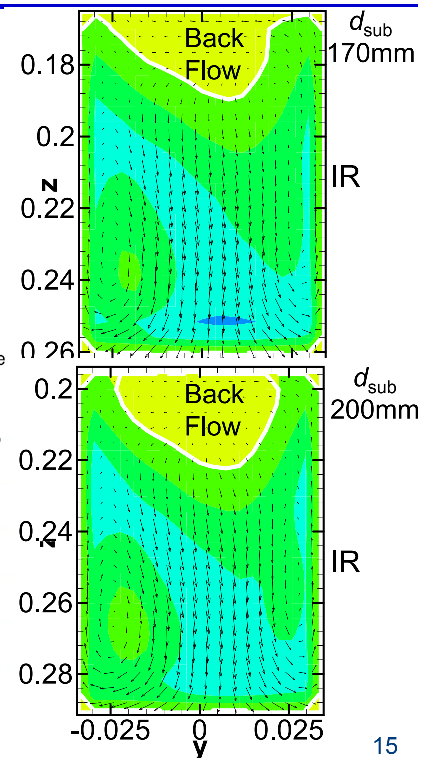
Flow in Port (without EMBr) Submergence depth 170 and 200mm

- At x=-0.045



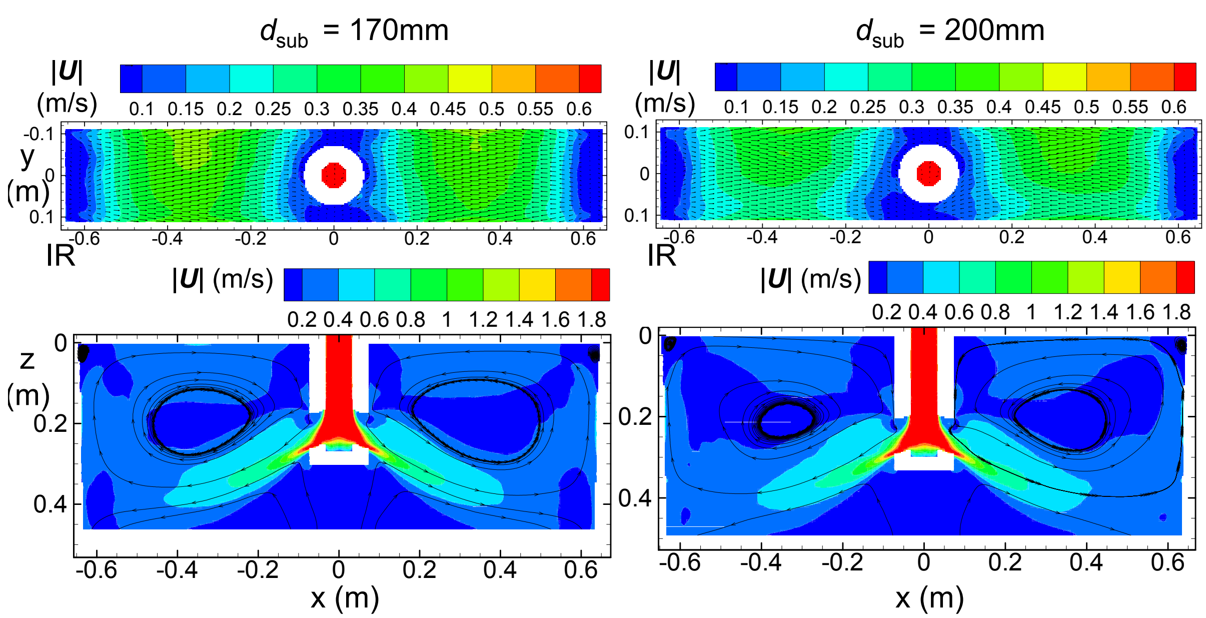
- Negative u_x → flow exiting port into mold
  Positive u_x → backflow
- White lines show where u_x = 0
- Backflow at top 1/4 – 1/3 region





Effect of Submergence Depth on Flow in Top Surface and Mold Time-averaged (Without EMBr)

- Contour of |***U***| in middle plane and on top surface (1cm below)



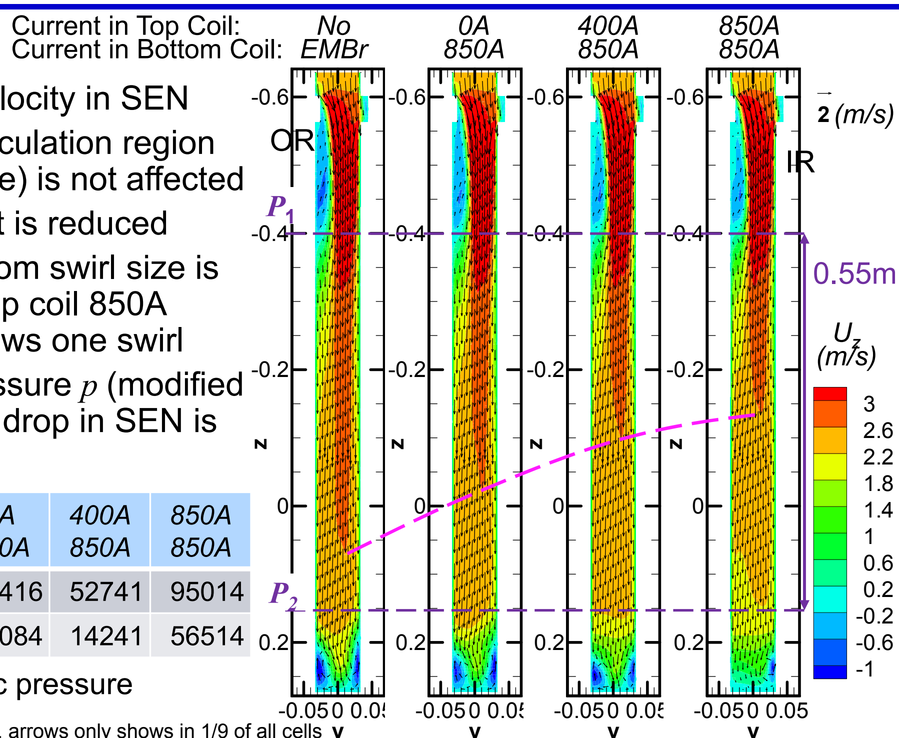
Note: arrows only shows 1/9 of all cells

Effect of EMBr (in SEN Centerplane Time-averaged; d_{sub} = 170mm)

- Contour of *w* velocity in SEN
- Size of the recirculation region (below slide gate) is not affected
- Length of the jet is reduced
- With EMBr Bottom swirl size is reduced; with top coil 850A bottom only shows one swirl
- With EMBr, pressure p (modified static pressure) drop in SEN is increased

Pressure (Pa)	No EMBr	0A 850A	400A 850A	850A 850A
$P_1 - P_2$	-8065	11416	52741	95014
$P_1^* - P_2^*$	-46565	-27084	14241	56514

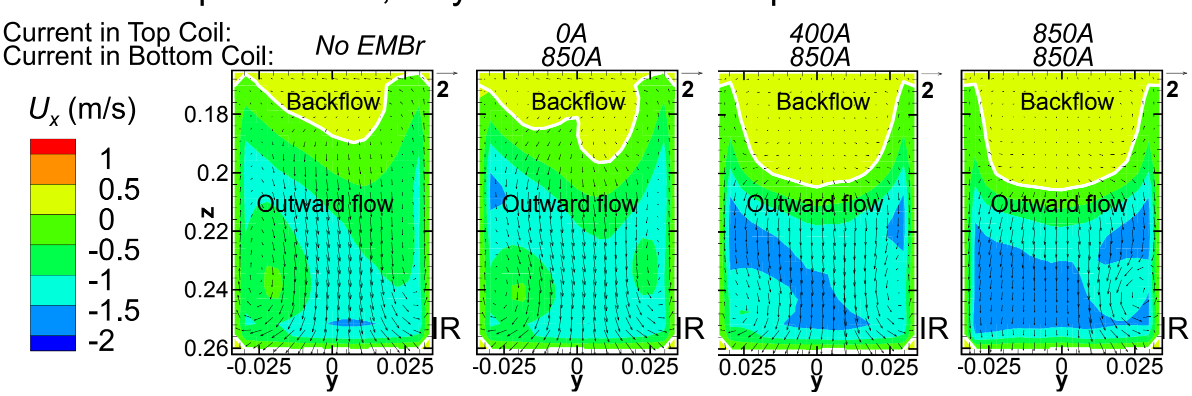
*Including ferrostatic pressure



Note: to make figure clearer, arrows only shows in 1/9 of all cells

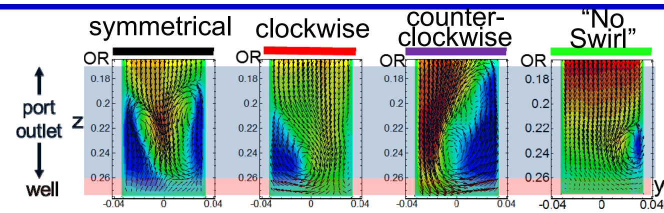
Effect of EMBr on Flow (in Port; Time-Averaged; d_{sub}=170mm)

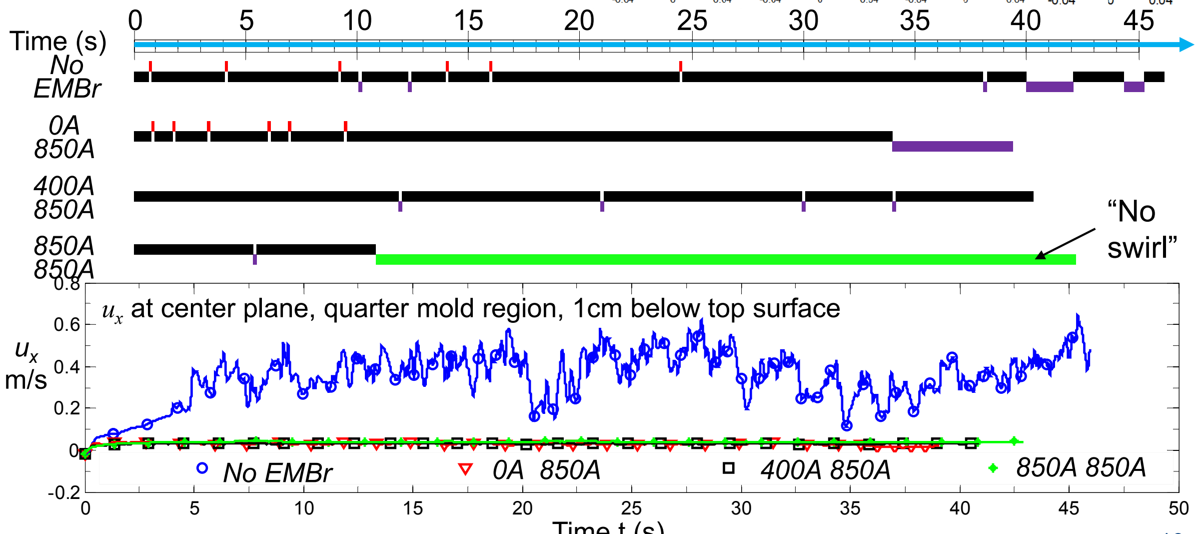
- Contour of U_x in middle of port, x = - 0.045,
- White line shows where U_x = 0
- Increasing ***B*** leads to:
  - More flow exiting at bottom of the port
  - Area of back flow region at top of port increases
  - Size of the swirls in port reduce
- With top coil 850A, only one circulation at port bottom IR side



Effect of EMBr on Swirl at SEN Bottom and Mold Top Surface Velocity (Transient; d_{sub}=170mm)

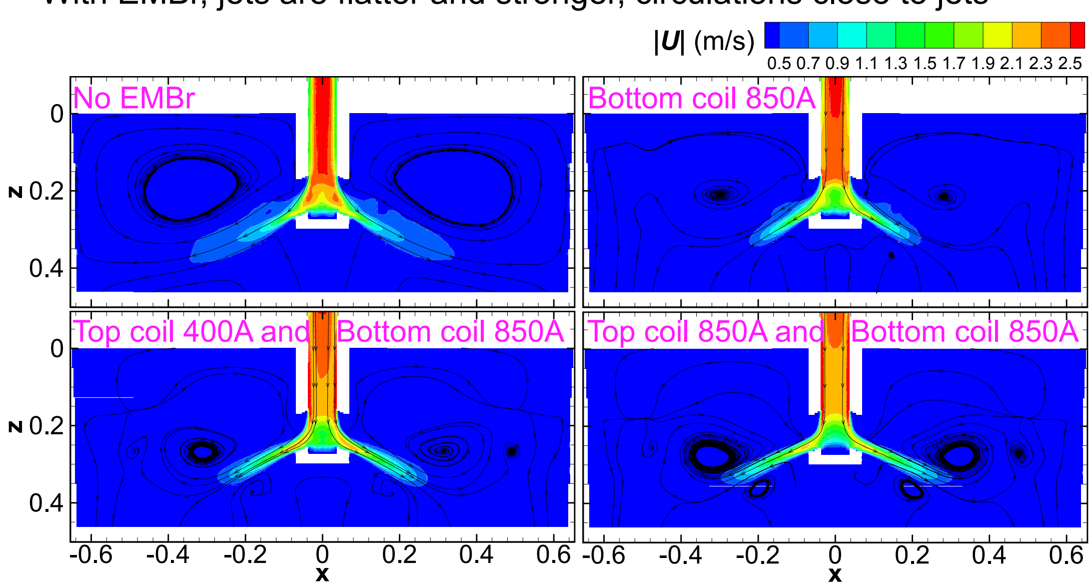
- Rotation at bottom of SEN
- With EMBr, flow velocity on top surface is too small (~0.05m/s)





Effect of EMBr on Flow in Mold (Time Averaged; d_{sub}=170mm)

- Nozzle flow – EMBr makes flow inside SEN more uniform, with strong EMBr → increases downward velocity along NF walls in SEN (M-shape profile, only seen in front view, perpendicular to field)
- With EMBr, jets are flatter and stronger, circulations close to jets

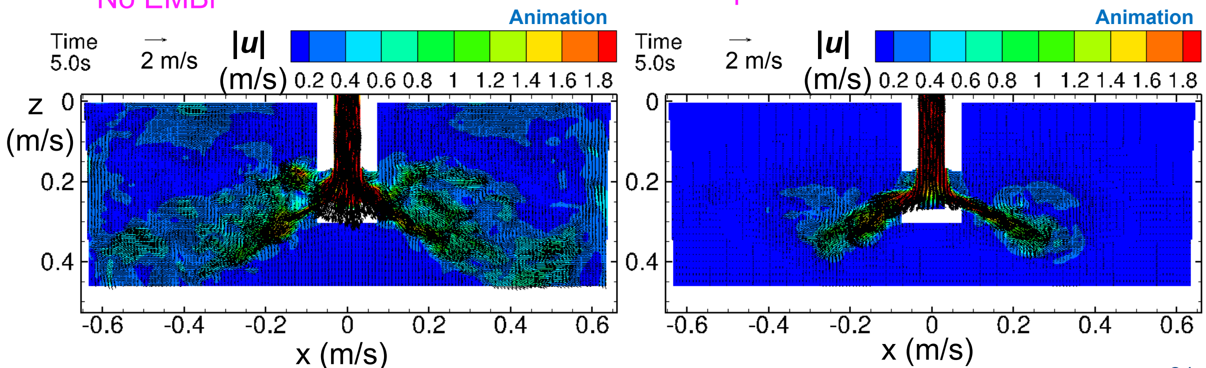


Effect of EMBr on Flow in Mold (Transient; d_{sub} = 170mm)

- Contour of velocity magnitude |***u***|
- With EMBr: velocity in mold is reduced; less fluctuations
- Without EMBr, jet travels further to NF. With EMBr, jets only reach quarter mold region
- With EMBr, shedding vortex from jet (at port outlet region) with frequency ~1Hz, those vortex die out quickly

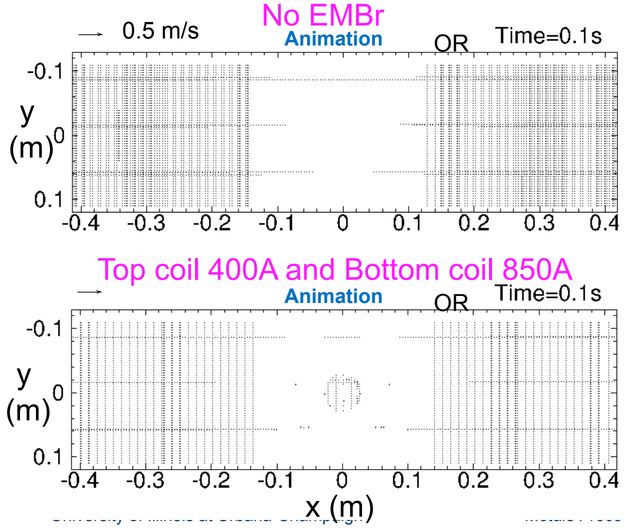
No EMBr

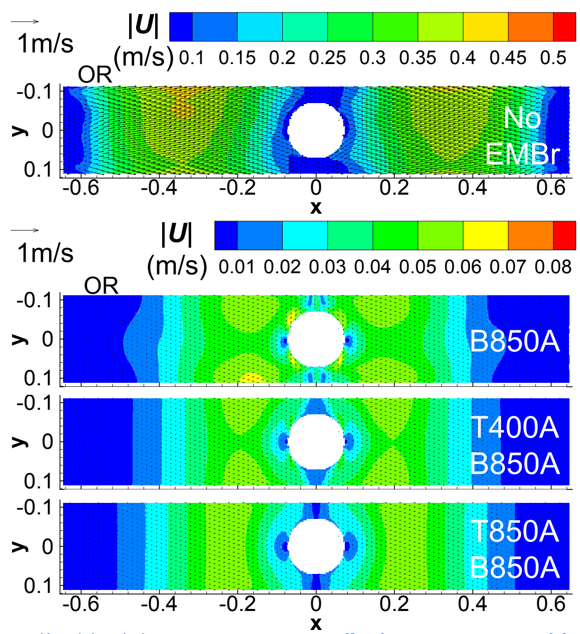
Top coil 400A and Bottom coil 850A



Effect of EMBr on Top Surface Stability and Vortex Motion (d_{sub} = 170mm)

- Without EMBr, top surface velocity 0.1~0.45 m/s
- With EMBr, top surface velocity around 0.03~0.07m/s
- EMBr reduces vortex on top surface, more stable





Conclusions

- Swirl exiting SEN depends on casting speed, gate position, and EMBr (in addition to geometry)
- Stronger port swirl with smaller slide gate opening fraction (which also accompanies lower casting speed);
- With no EMBr, strong asymmetric flow inside SEN due to slide gate causes big swirl in port bottom (especially with bottom well), & at port exit
- EMBr makes flow inside SEN more uniform, and even increases downward velocity along NF walls (with strong EMBr)
- EMBr causes tighter faster jet, which exits more towards lower region of port with accompanying larger back-flow in top;
- With EMBr, vortex shedding from upside of jet in the mold at ~1Hz
- With EMBr, jets only penetrates to quarter region of mold; recirculation regions become tighter and closer to jet and new smaller vortices form
- Even with this high casting speed, 1.8m/min: with no argon, EMBr lowers top surface velocity too much (~0.04m/s).

Acknowledgments

- Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, SSAB, ANSYS/ Fluent)
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References

[1] Ramnik Singh, Brian G. Thomas, and Surya P. Vanka, “Large Eddy Simulations of Double-Ruler Electromagnetic Field Effect on Transient Flow during Continuous Casting,” Metall. Mater. Trans. B, 2014, vol. 45, pp. 1098–1115.

[2] Hiromichi Kobayashi, “The Subgrid-Scale Models Based on Coherent Structures for Rotating Homogeneous Turbulence and Turbulent Channel Flow,” Phys. Fluids 1994-Present, 2005, vol. 17, p. 045104.

[3] Rui Liu, J Sengupta, D Crosbie, S Chung, M Trinh, and B. G Thomas: in Sens. Sampl. Simul. Process Control, “Measurement of Molten Steel Surface Velocity with SVC and Nail Dipping during Continuous Casting Process,” John Wiley & Sons, San Diego, 2011.