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Mold Flow with Argon Gas, EMBr and Evaluation using Nailboard Measurements

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Acknowledgements

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- Baosteel (Prediction Measurement and Optimization of Mold Fluid Flow in Continuous Slab Casting with FC Mold at Baosteel, UIUC Research Project)
- Baosteel (plant data, including geometry, nailboard measurements, SVC measurements)
- ABB (EMBr magnetic field data)

Overall Objectives

- Improve understanding of fluid flow in the BaoSteel slab-casting mold, including the effect of EMBr;
- Develop an off-line CFD model to accurately model multiphase fluid flow with EMBr (prediction of flow pattern, surface velocity, etc.);
- Apply model to optimize EMBr operation in commercial slab casters, evaluate the quality of flow pattern and to improve nozzle design.

Current Objectives

- Build RANS models of multiphase flow (Ar gas and molten steel) with EMBr in SEN and mold regions using FLUENT.
- Evaluate the differences between Eulerian-Eulerian model and Eulerian-Mixture model
- Investigate effect of EMBr settings on mold flow pattern and top surface velocity
- Compare predictions with results of nailboard and SVC experiments

Model Description

- Mesh created in ICEM CFD
- Continuity Equation

(1) $$\frac{\partial}{\partial t}\left(a_q \rho_q\right) + \nabla \cdot \left(a_q \rho_q \vec{v}_q\right) = S_q$$

Single Phase: $a_q = 1$ phase q volume fraction

Eulerian-Eulerian: q can be any phase

Eulerian-Mixture: $$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m}; \quad \rho_m = \sum_{k=1}^{n} \alpha_k \rho_k$$

Mixture Model, solve **ONLY** for Mixture Phase

- Steel momentum equation

(2) $$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + \nabla \cdot \left(\rho \vec{v}\vec{v}\right) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \rho \vec{g} + \vec{F}$$ [1]

- Magnetic Induction Method

(3) $$\frac{\partial \vec{b}}{\partial t} + \left(\vec{U} \cdot \nabla\right)\vec{b} = \frac{1}{\mu\sigma}\nabla^2 \vec{b} + \left(\left(\vec{B}_0 + \vec{b}\right) \cdot \nabla\right)\vec{U} - \left(\vec{U} \cdot \nabla\right)\vec{B}_0$$

σ electrical conductivity

μ magnetic permeability

$\vec{U}$ velocity field

$\vec{B}$ magnetic field

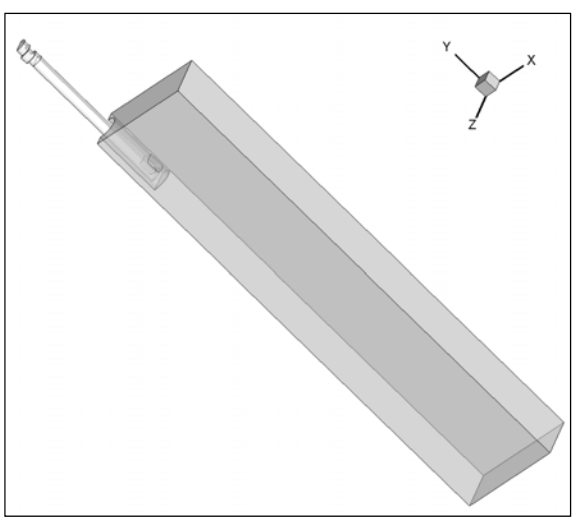
$\vec{B}_0$ imposed magnetic field

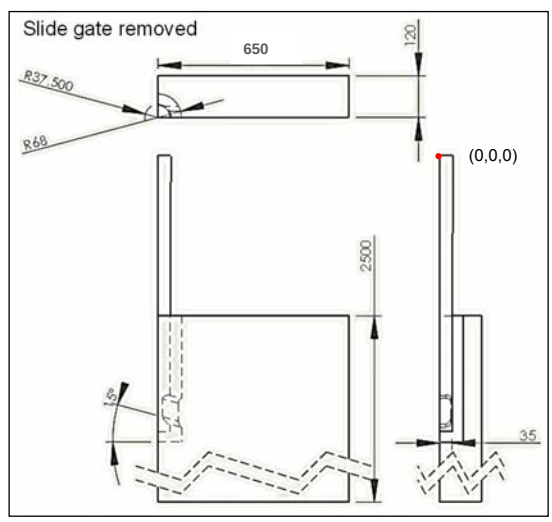
$\vec{b}$ induced field

- Steady-State *RANS* Turbulence Model (*k-ε*) with wall laws
- ½ of SEN, slide gate, and 2.5-m mold region

Geometry

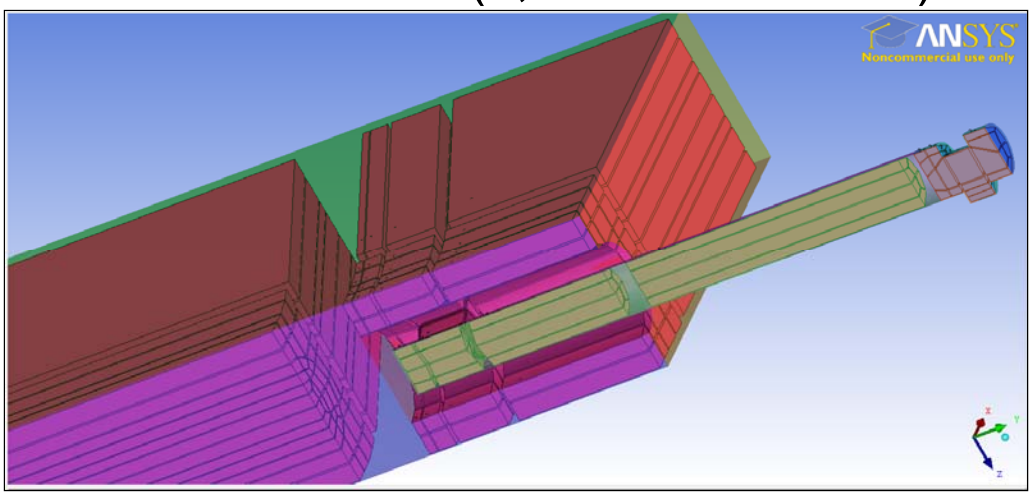
Mold Thickness(MT) (mm)	Mold Width(MW) (mm)	Slide Gate Opening (% Open)	Submergence depth (mm)	Casting Speed (m/min)
240	1300	70	160	1.2



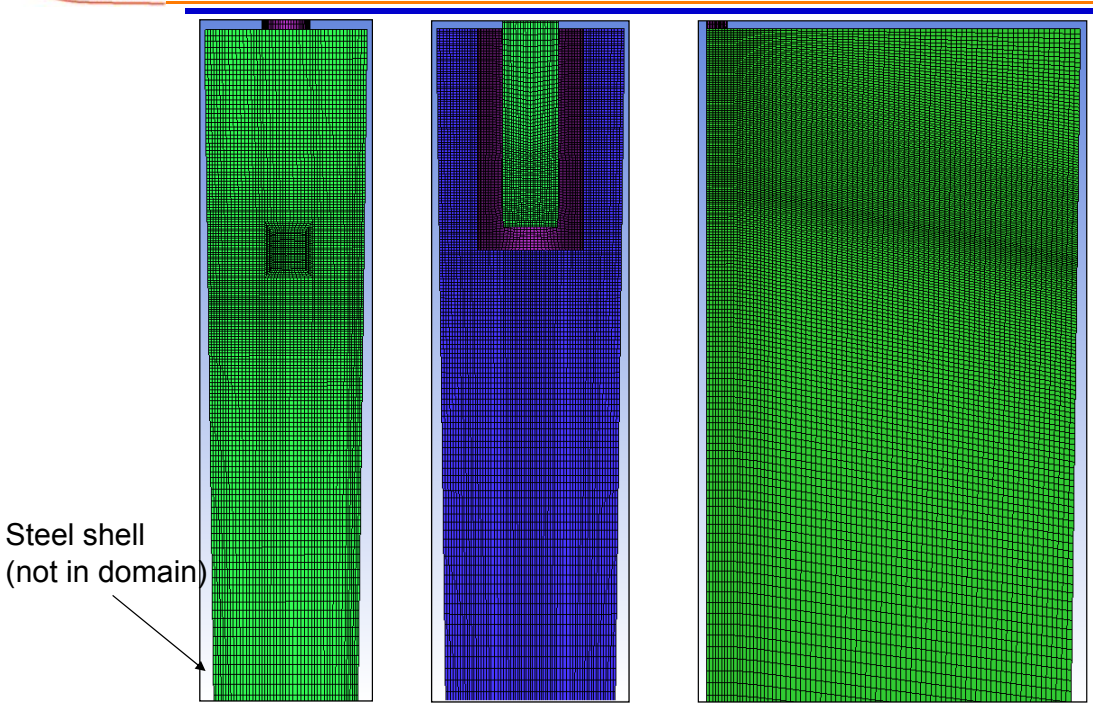


Mesh Information

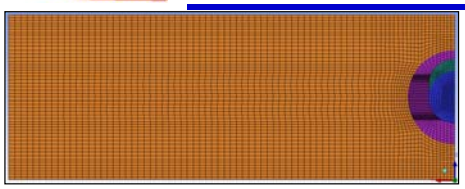
- Mesh of ½ SEN + ½ Mold + ½ Slide Gate
- Mapped hexahedron mesh, >220 blocks and ~1 million elements (1,000 million DOF)



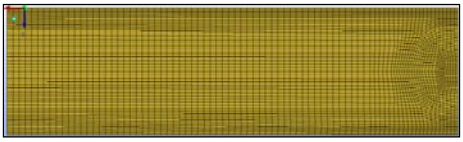
Mesh Slices



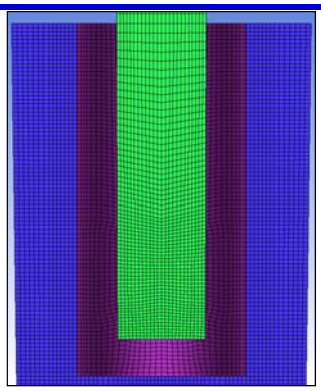
Mesh – Other Views



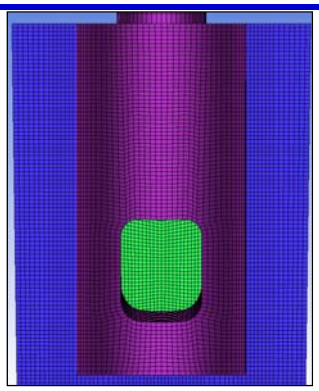
Top View



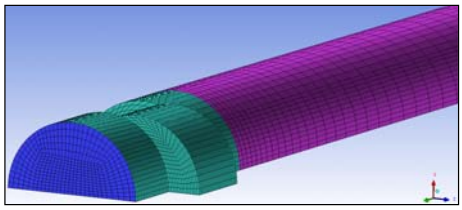
Bottom View



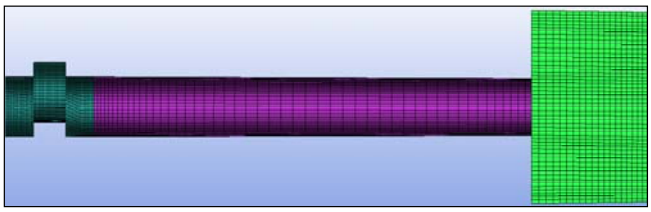
Symmetry Plane



Port (Inside Mold)



Gate and Nozzle – View 1



Gate and Nozzle – View 2

Shell Thickness Calculation

Based on plant observation, shell thickness at the mold exit is around ***19* mm**, with casting speed 1.2 m/min. So we can estimate the shell shape by using the equations below:

$$S = k\sqrt{t}$$

$$L_{moldexit} = 0.8\ m$$

$$S_{moldexit} = 19\ mm$$

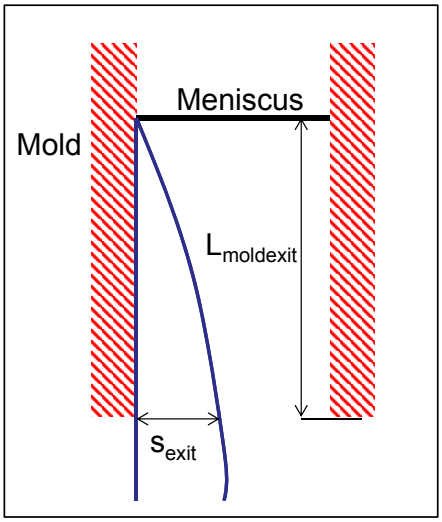
$$V_c = 1.2 m/\min = 0.02\ m/s$$

$$t_{exit} = \frac{L_{moldexit}}{V_c} = \frac{0.8m}{0.02m/s} = 40\ s$$

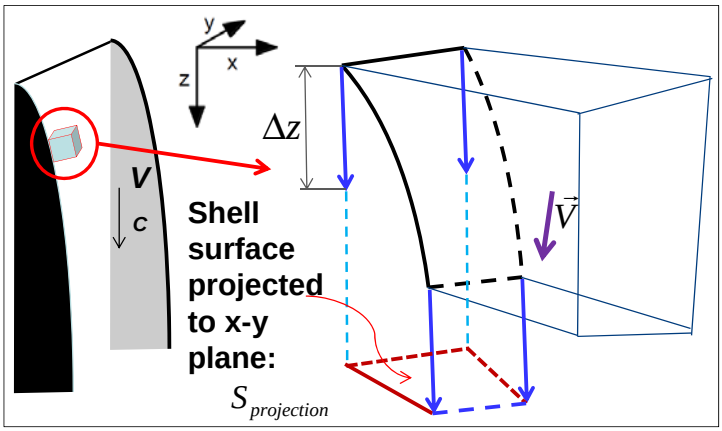
$$k = \frac{S_{moldexit}}{\sqrt{t_{exit}}} = \frac{19mm}{\sqrt{40s}} = 3.00\ mm \cdot s^{-\frac{1}{2}}$$

$$3.00mm \cdot s^{-\frac{1}{2}} = 3.00mm \cdot s^{-\frac{1}{2}} \cdot 0.03937 \frac{inch}{mm} \cdot \left(\frac{1}{60}\frac{\min}{s}\right)^{-\frac{1}{2}}$$

$$= 0.91\ inch \cdot \min^{-\frac{1}{2}}$$



SHELL EFFECT



Sinks on shell (adapted from Rui Liu, 2011[2])

ρ is the dansity of steel

V_c is casting speed

$S_{projection}$ is the area projected to V_c plane

$\vec{V}$ is the local steel velocity

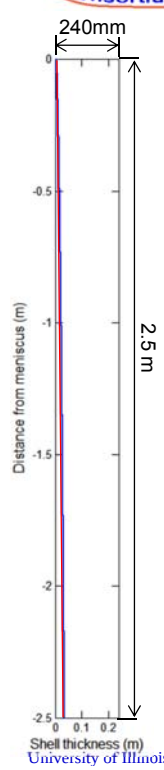
Δt is a very small time

Δm is the mass of steel solidified in time Δt

Corresponding Mass rate: $\dot{m} = \rho V_C S_{xy}$

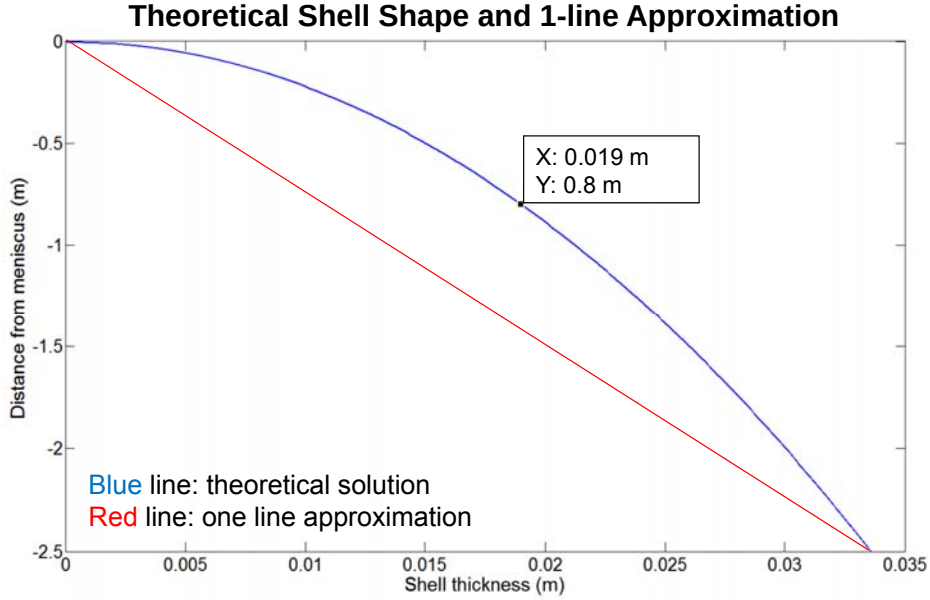
Corresponding rate of change of Momentum: $\dot{\vec{P}} = \dot{m}\vec{V}$

Shell Shape



- Left figure: Equal axis view
- Bottom figure: horizontal axis amplified

Theoretical Shell Shape and 1-line Approximation



Casting Conditions, Boundary Conditions and Material Properties

Casting Conditions	Value
Mold Thickness	240 mm
Mold Width	1300 mm
Submergence Depth	160 mm
Port Downward Angle	15 deg.
Casting Speed	1.2 m/min

Properties	Steel	Ar
Density (kg/m^3)	7,000	0.5
Viscosity (kg/m-s)	0.0063	2.12e-5
Electrical Conductivity (S/m)	714,000 [3]	1.0e-15 [4]
Magnetic Permeability (h/m)	1.26*10^{-6} [3]	4π*10^{-7}

Location	Boundary Condition
Inlet	V = 1.42 m/s
Outlet	Pressure 184kpa
Symmetry Plane	Symmetry
Top Surface (Meniscus)	No-slip wall
NF and WF	No-slip wall; with Steel Mass & Momentum sink
Other Places	No-slip wall

Simulation Overview

Simulation No.	Slide Gate	Ar Gas Conditions	EMBr Conditions (Amp)	Multiphase model
S1a	--	--	--	--
S1b	70%*	--	--	--
S2a	70%	--	T400 B600***	--
S2b	70%	--	T000 B600	--
S3a	70%	3mm, 10%V**	--	Eulerian-Eulerian
S3b	70%	3mm, 10%V	--	Eulerian-Mixture
S4a	70%	3mm, 10%V	T400 B600	Eulerian-Mixture

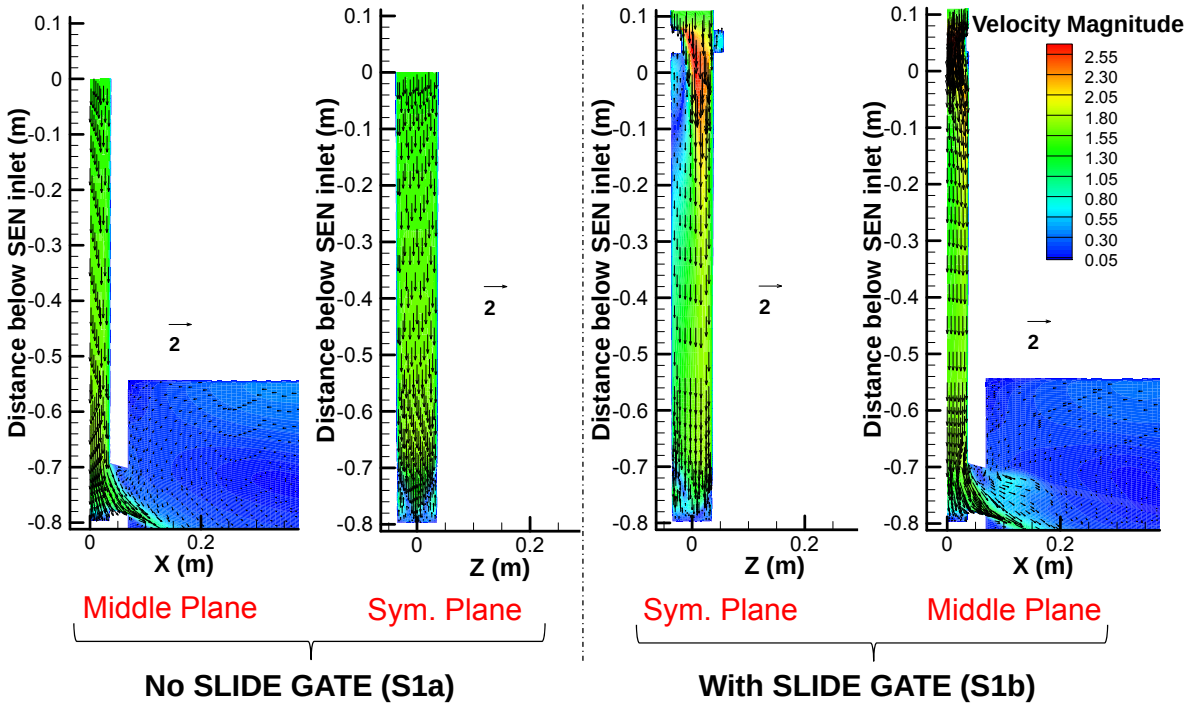
$$Ar\ Flow\ Rate = Ar\ Injection\ Rate \times Expension\ Factor \times \%Enter\ SEN = 15L/\min \times 4 \times 70\% = 0.042m^3/\min$$

$$Steel\ Flow\ Rate = CastingSpeed \times V_c \times MoldWidth = 1.2m/\min \times 0.24m \times 1.3m \approx 0.37m/\min$$

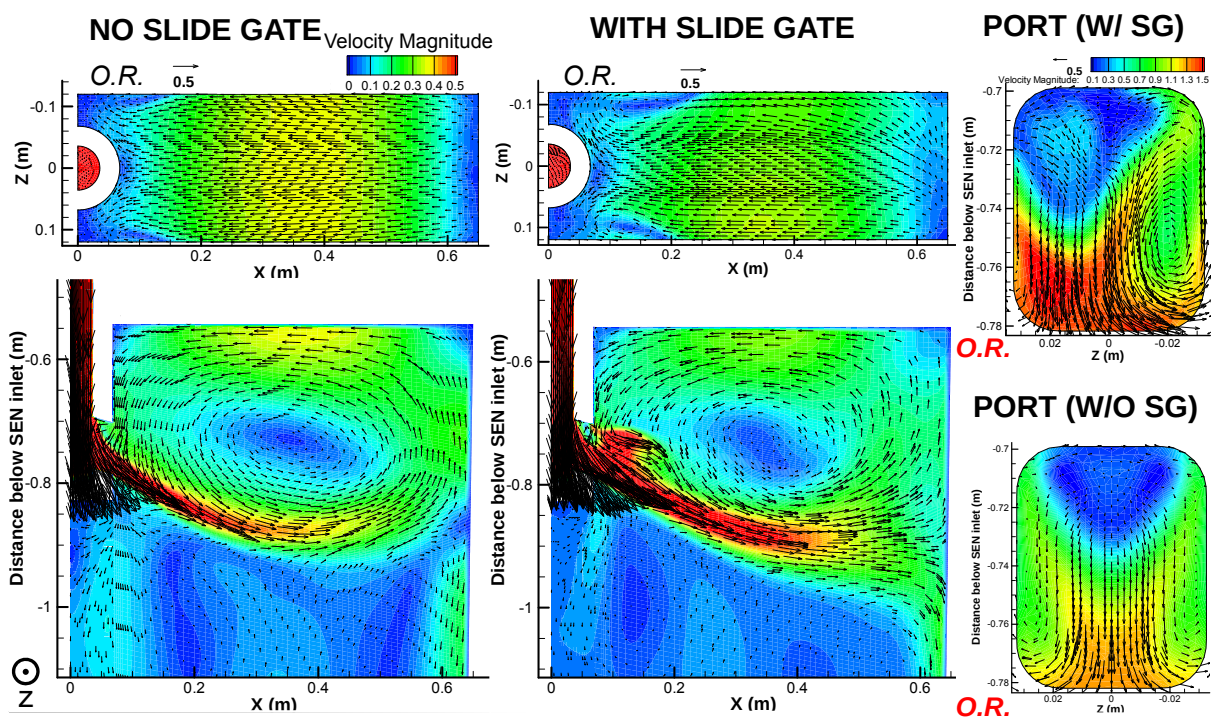
$$Ar\ Volume\ Fraction = \frac{Ar\ Flow\ Rate}{Ar\ Flow\ Rate + Steel\ Flow\ Rate} \approx 0.10$$

NOTE:
** 70% Open*
*** Bubble Diameter is 3mm, Ar volume fraction 10%.*
**** Top coil current 400Amp, bottom coil current 600Amp*

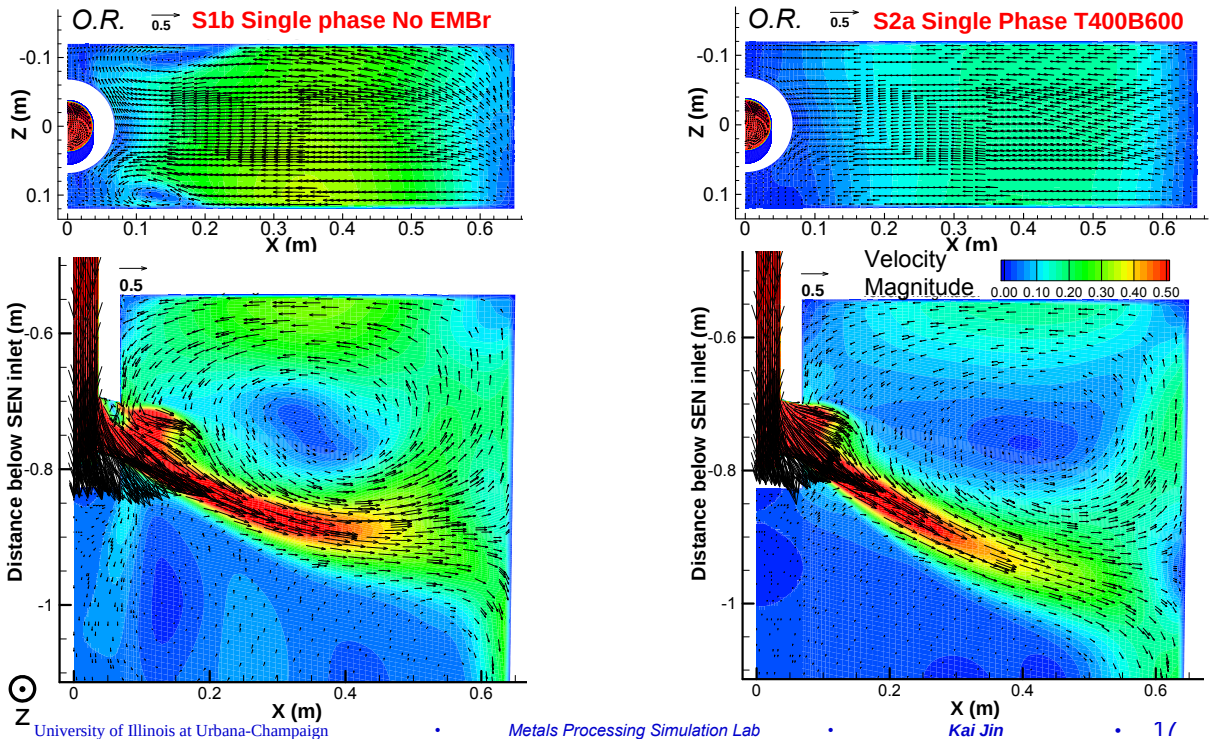
S1 Result – Effect of Slide Gate (SG) – Flow in SEN



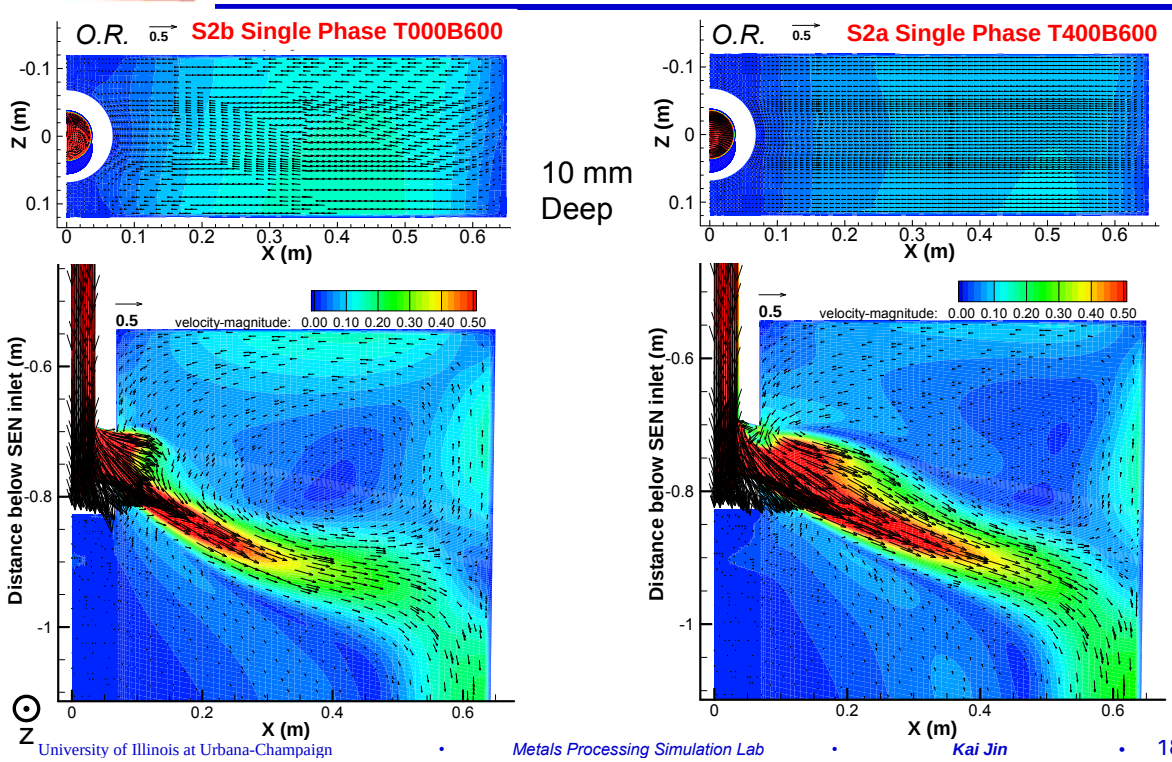
S1 (S1a &S1b) Result – Effect of Slide Gate (SG) – Single-Phase Flow in Mold (no EMBr) (Middle Plane, Plane 10 mm below top surface and Port)



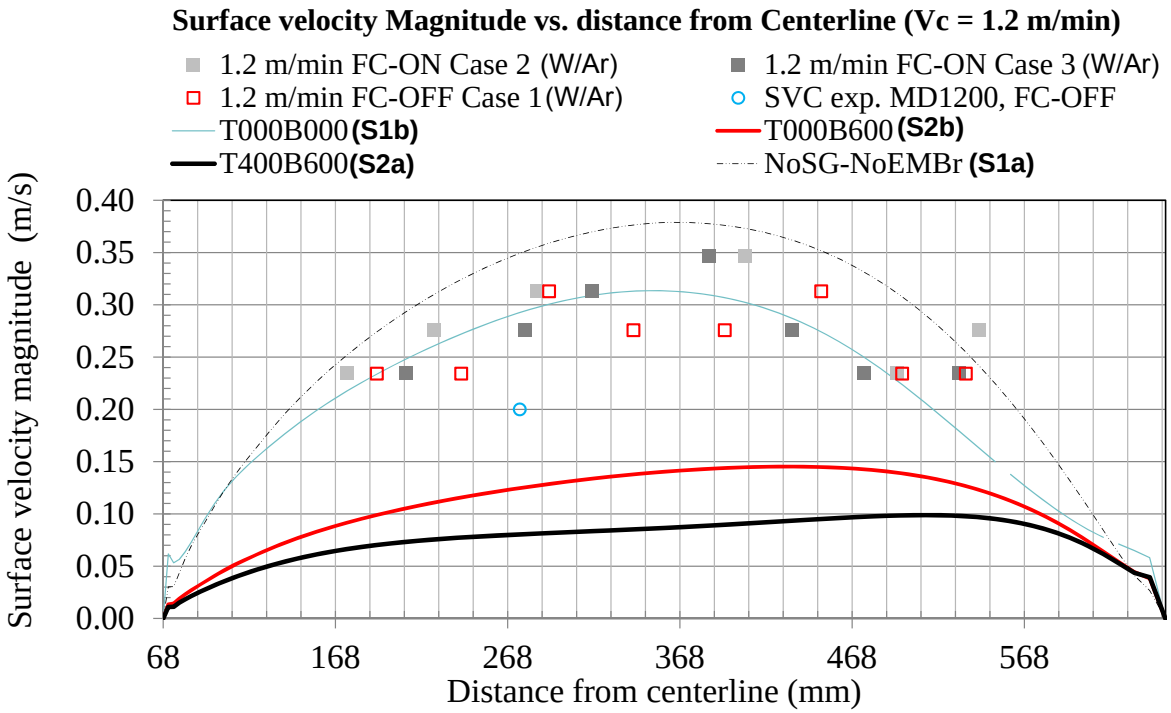
EMBr Effect on Single-Phase Flow - S2a Result



EMBr Effect on Single-Phase Flow - S2b Result



Single-Phase Flow Surface Veocity Comparison (S1&S2)



Single-Phase Flow Simulation Conclusions

- Slide gate can generate asymmetric flow in nozzle and affects symmetry of flow through port, but little effect on surface cross-flow with single-phase flow;
- Double roll pattern is observed in all single-phase simulations: EMBr has little effect on flow pattern; the large asymmetric behavior observed in the nailboard experiments is not due to EMBr;
- EMBr can significantly reduce flow speed in mold region: maximum surface velocity drops from ~0.35 m/s to ~0.18 m/s comparing S1b (no EMBr=T0 B0) and S2a (T400 B600), (constant 1.2m/min);
- No simulation matches with experiments data, the surface velocity direction is GREATLY DIFERENT from plant measurement;

Eulerian-Eulerian Model Euqations

- Eulerian-Eulerian Momentum Equation for Phase q [1]

(4)
$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right)+\nabla\cdot\left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right)=-\alpha_q \nabla p+\nabla\cdot\bar{\bar{\tau}}_q+\alpha_q \rho_q \vec{g}+\sum_{p=1}^{n}\left(\vec{R}_{pq}+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp}\right)+\vec{F}$$

(5)
$$\sum_{p=1}^{n}\vec{R}_{pq}=\sum_{p=1}^{n}K_{pq}\left(\vec{v}_p-\vec{v}_q\right)$$

Interphase momentum exchange coef.

$$K_{pq}=\frac{\alpha_q \alpha_p \rho_p f_{drag}}{\tau_p}$$

$\vec{R}_{pq}$ is interaction force between phases

$\dot{m}_{pq}$ is phase p mass being transferred to q

$\vec{v}_{pq}$ is interphase velocity

τ_p is particulate relaxation time (Eqn.12)

f_{drag} is drag function (Eqn.14)

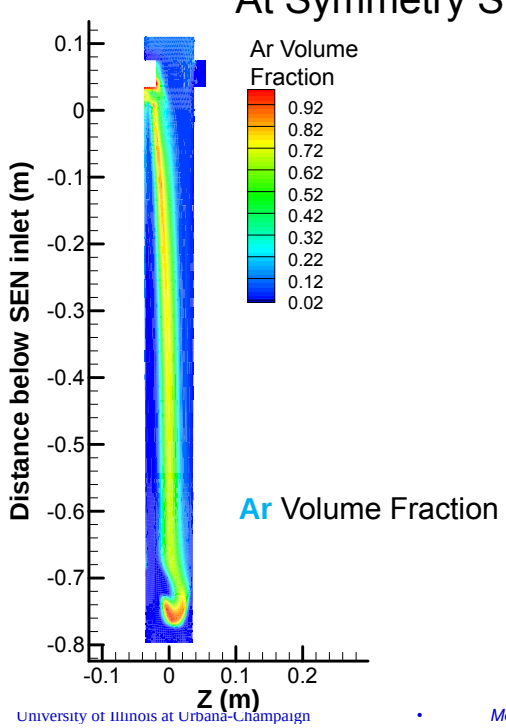
- **If Mixture Model**, solve **ONLY** for Mixture Phase:

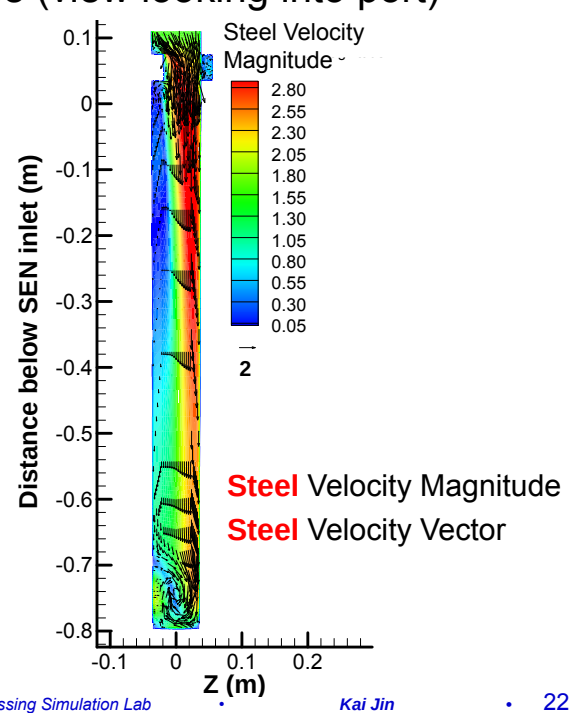
(6)
$$\frac{\partial}{\partial t}\left(\rho_m \vec{v}_m\right)+\nabla\cdot\left(\rho_m \vec{v}_m \vec{v}_m\right)=-\nabla p+\nabla\cdot\left[\mu_m\left(\nabla\vec{v}_m+\nabla\vec{v}_m^T\right)\right]+\nabla\cdot\left(\sum_{k=1}^{n}\alpha_k \rho_k \vec{v}_{dr,k}\vec{v}_{dr,k}\right)+\rho_m \vec{g}+\vec{F}$$

$$\mu_m=\sum_{k=1}^{n}\alpha_k \mu_k \;; \qquad \vec{v}_{dr,k}=\vec{v}_k-\vec{v}_m$$

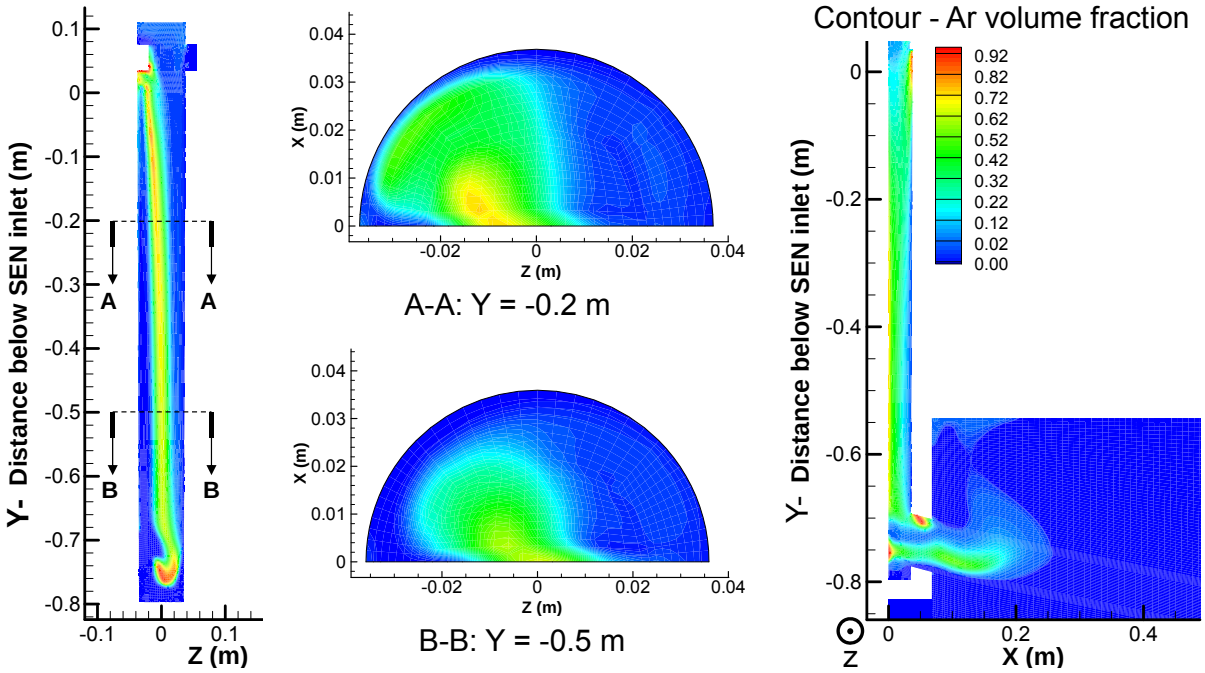
S3a Result in SEN (Sym. plane)

At Symmetry Surface (view looking into port)





S3a Ar Volume Fraction in SEN

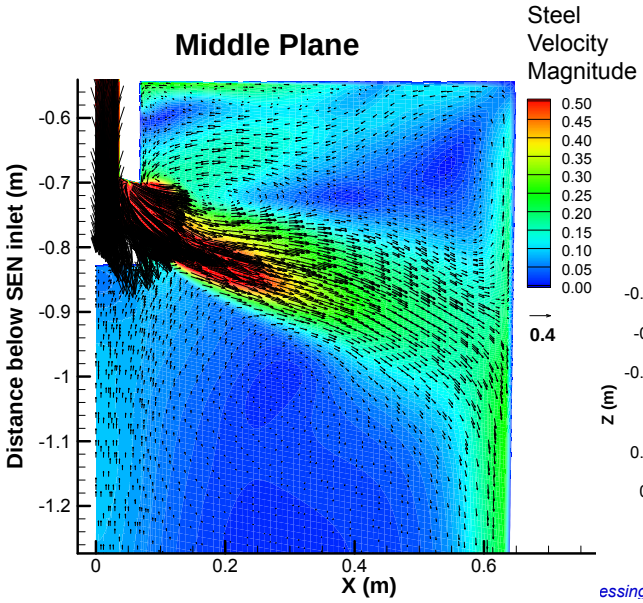


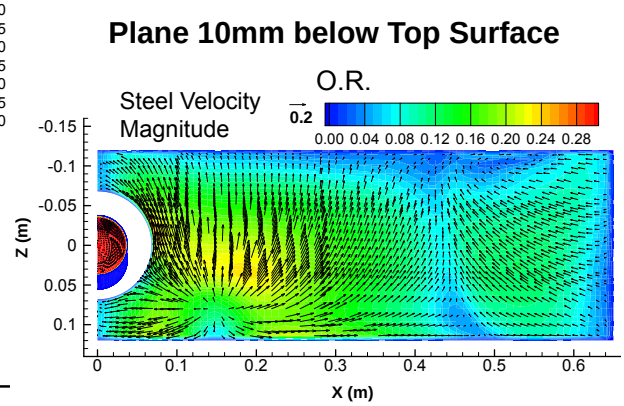
- Sym. Plane
- 2 Slices
- Middle Plane

S3a Velocity at Middle Plane and 10 mm belwo top surface

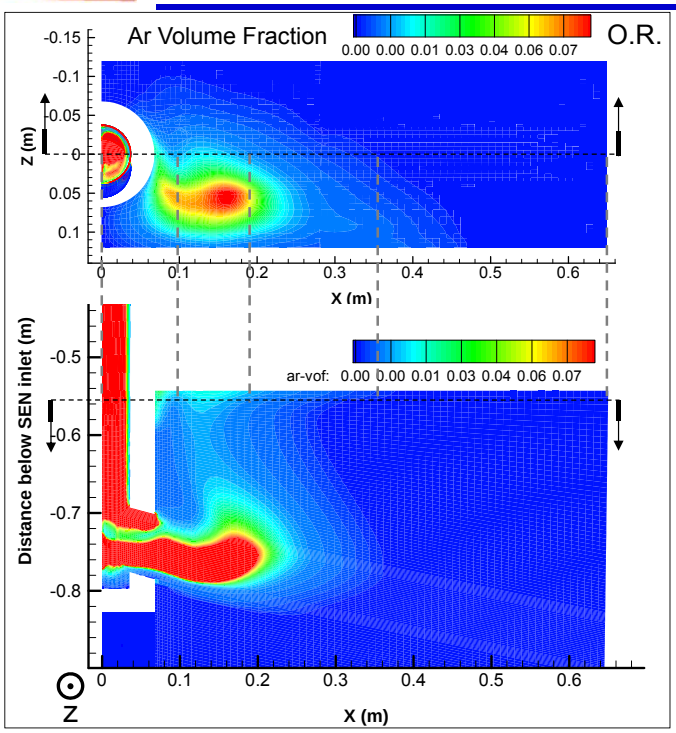
- Steel Velocity Magnitude Contour
- Steel Velocity Vector

- Huge cross flow captured just below top surface;
- Flow pattern changed (both in the middle plane and the region beneath top surface.





S3a Mold Ar Volume Fraction

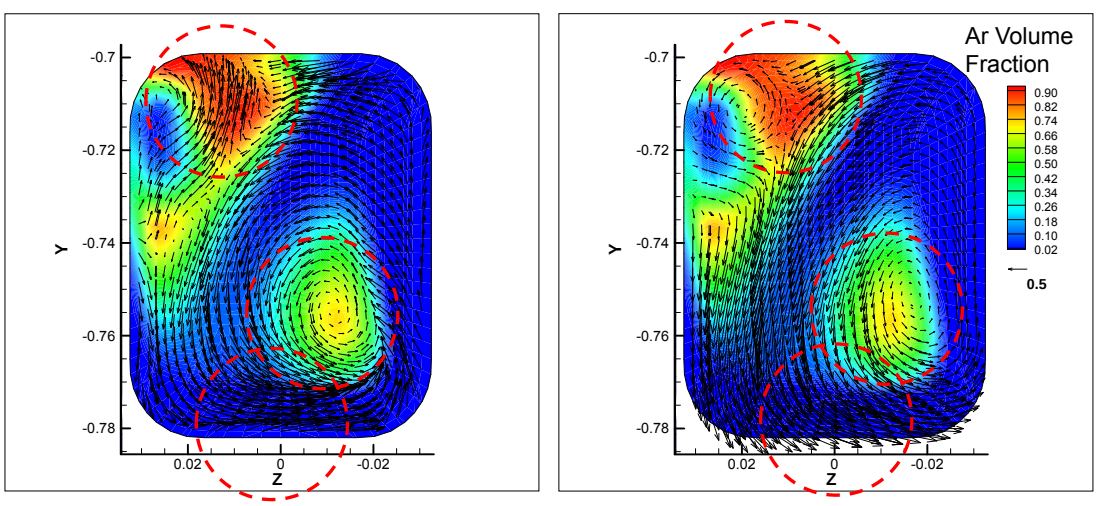


- Top view (10 mm below top surface)
- Side view (middle plane)

S3a Eulerian Model Result - Port View

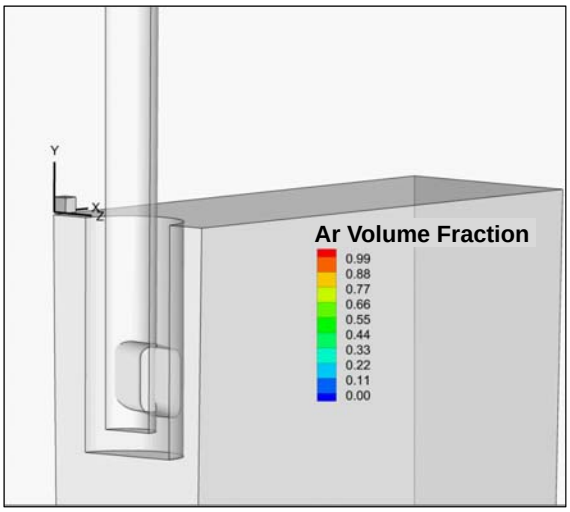
Ar and Steel Velocity May Have Large Different Port View (looking into port)

Ar Velocity Vectors **Steel Velocity Vectors**

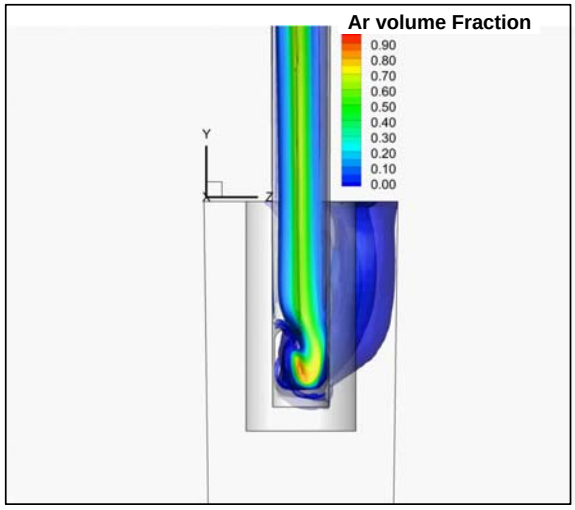


S3a ISO Surface Animations

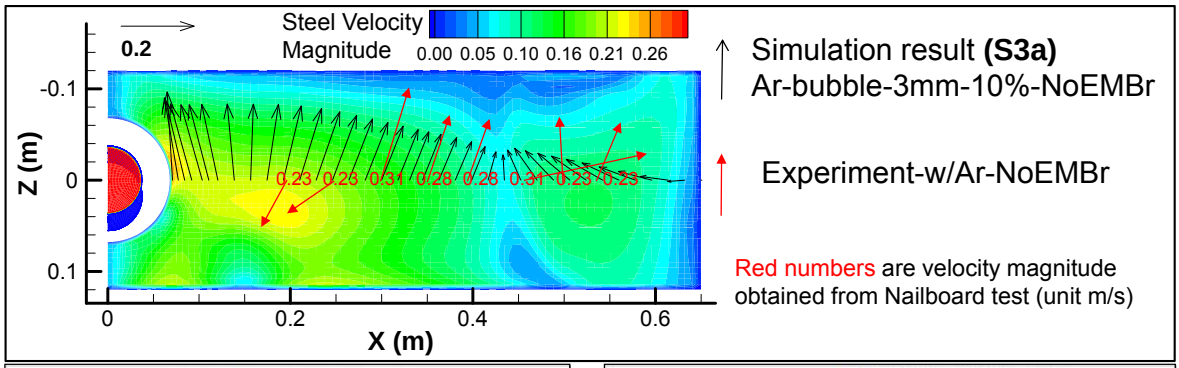
ISO-Surfaces of Ar VOF

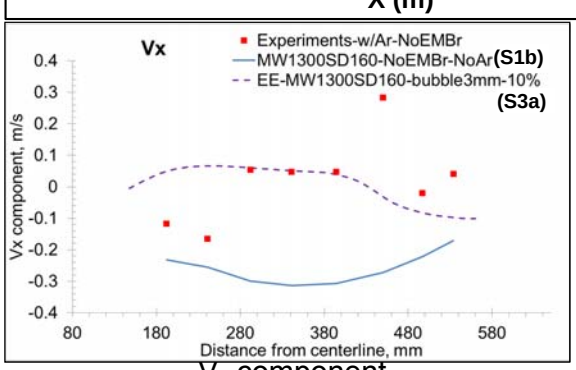


Rotating Ar Gas ISO Surface

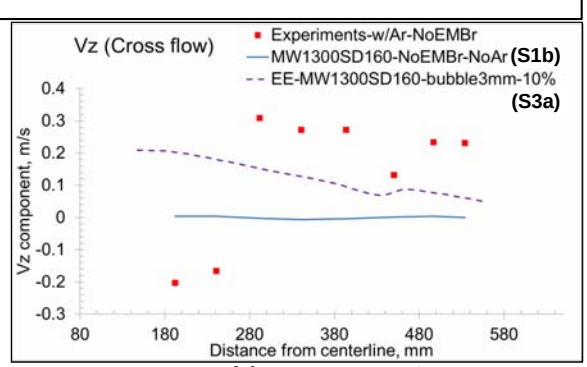


Compare Velocity Components





V_x component



V_z component

Eulerian-Mixture Model Equations

- Algebraic slip mixture model(Slip velocity)

(7)
$$\vec{v}_{pq} = \vec{a}\frac{\tau_p}{f_{drag}}\frac{(\rho_p - \rho_m)}{\rho_p} - \frac{\eta_t}{\sigma_t}\left(\frac{\nabla\alpha_p}{\alpha_p} - \frac{\nabla\alpha_q}{\alpha_q}\right)$$

- Particle relaxation time & Secondary-phase particle's acceleration

(12)
$$\tau_p = \frac{\rho_p d_p^2}{18\mu_q}$$

(13)
$$\vec{a} = \vec{g} - (\vec{v}_m \cdot \nabla)\vec{v}_m - \frac{\partial \vec{v}_m}{\partial t}$$

- Schiller-Naumann drag function

(14)
$$f_{drag} = \begin{cases} 1 + 0.15\,\mathrm{Re}^{0.687} & \mathrm{Re} \le 1000 \\ 0.0183\,\mathrm{Re} & \mathrm{Re} > 1000 \end{cases}$$

Prandtl/Schmidt number $\sigma_t = 0.5$

Turbulent diffusivity

(8)
$$\eta_t = C_\mu \frac{k^2}{\varepsilon}\frac{\gamma_y}{1+\gamma_y}\left(1 + C_\beta \zeta_\gamma^2\right)^{-0.5}$$

(9)
$$\zeta_\gamma = \frac{|\vec{v}_{pq}|}{\sqrt{2/3k}}$$
$$C_\beta = 1.8 - 1.35\cos^2(\theta)$$
$$\cos(\theta) = \frac{\vec{v}_{pq}\cdot\vec{v}_p}{|\vec{v}_{pq}||\vec{v}_p|}$$

(10)
$$\vec{v}_{pq} = \vec{v}_p - \vec{v}_q$$

Drift velocity

(11)
$$\vec{v}_{dr,p} = \vec{v}_{pq} - \sum_{k=1}^{n} c_k \vec{v}_{qk}$$

γ_y is time ratio between time scale of energetic turbulent eddies affected by crossing-trajectories effect and τ_p

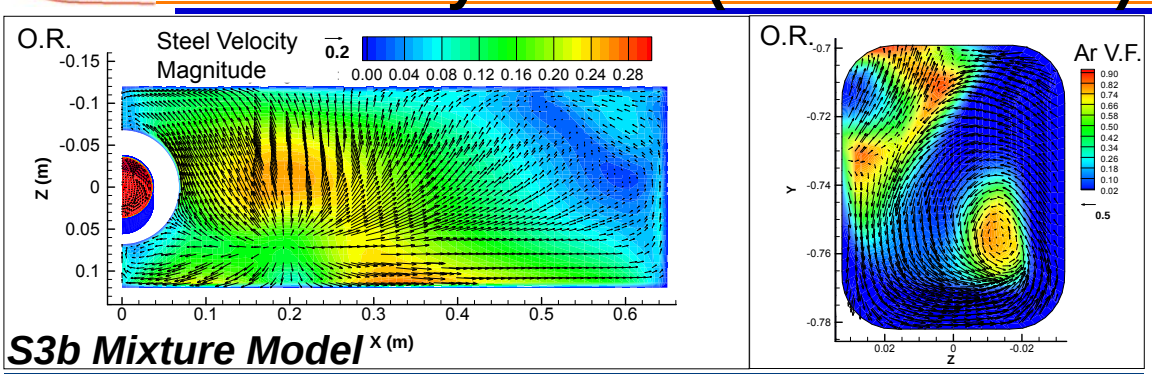
- Volume Fraction Equation

(15)
$$\frac{\partial}{\partial t}(\alpha_p\rho_p) + \nabla\cdot(\alpha_p\rho_p\vec{v}_m) = -\nabla\cdot(\alpha_p\rho_p\vec{v}_{dr,p}) + \sum_{q=1}^{n}(\dot{m}_{qp} - \dot{m}_{pq})$$

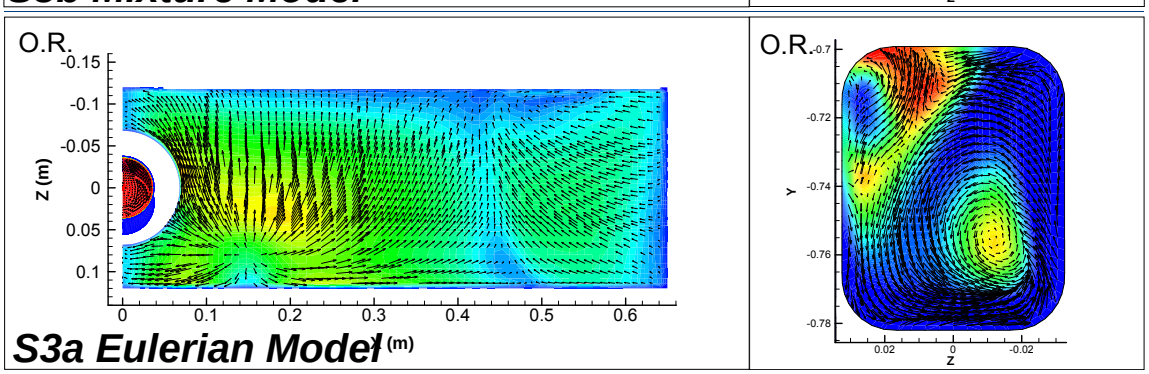
phase k mass fraction

(16)
$$c_k = \frac{\alpha_k\rho_k}{\rho_m}$$

Steel Velocity – 10 mm below TF. Ar Velocity at Port (look into Port)



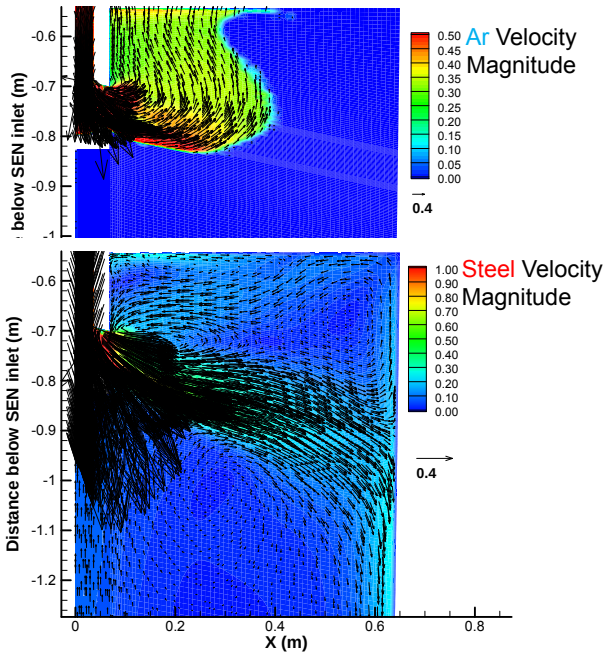
S3b Mixture Model



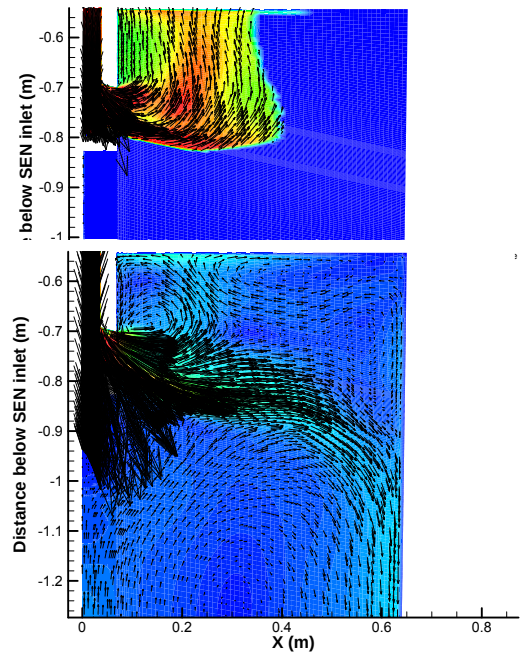
S3a Eulerian Model

Middle Plane Ar Volume Fraction

S3a - Eulerian Model

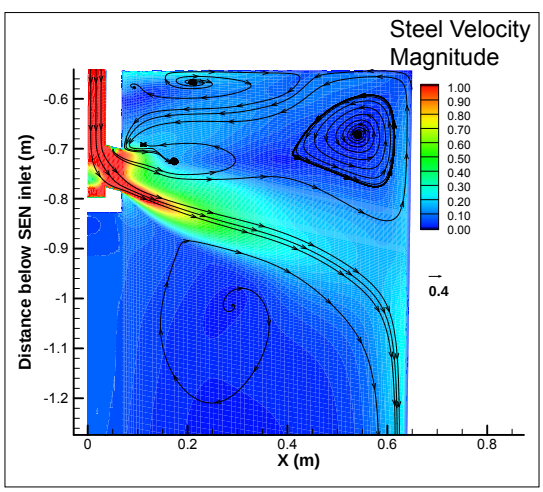


S3b - Mixture Model

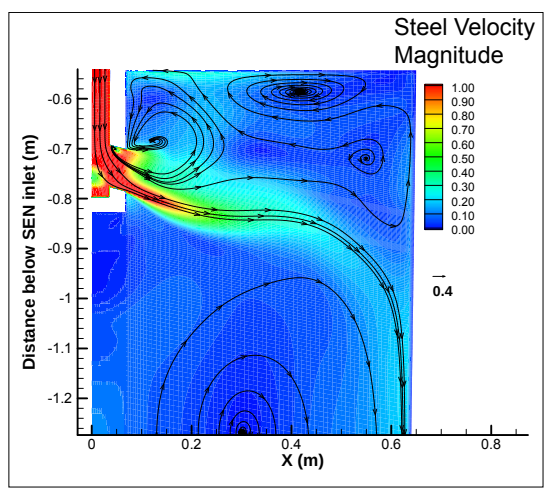


Middle Plane Streamline

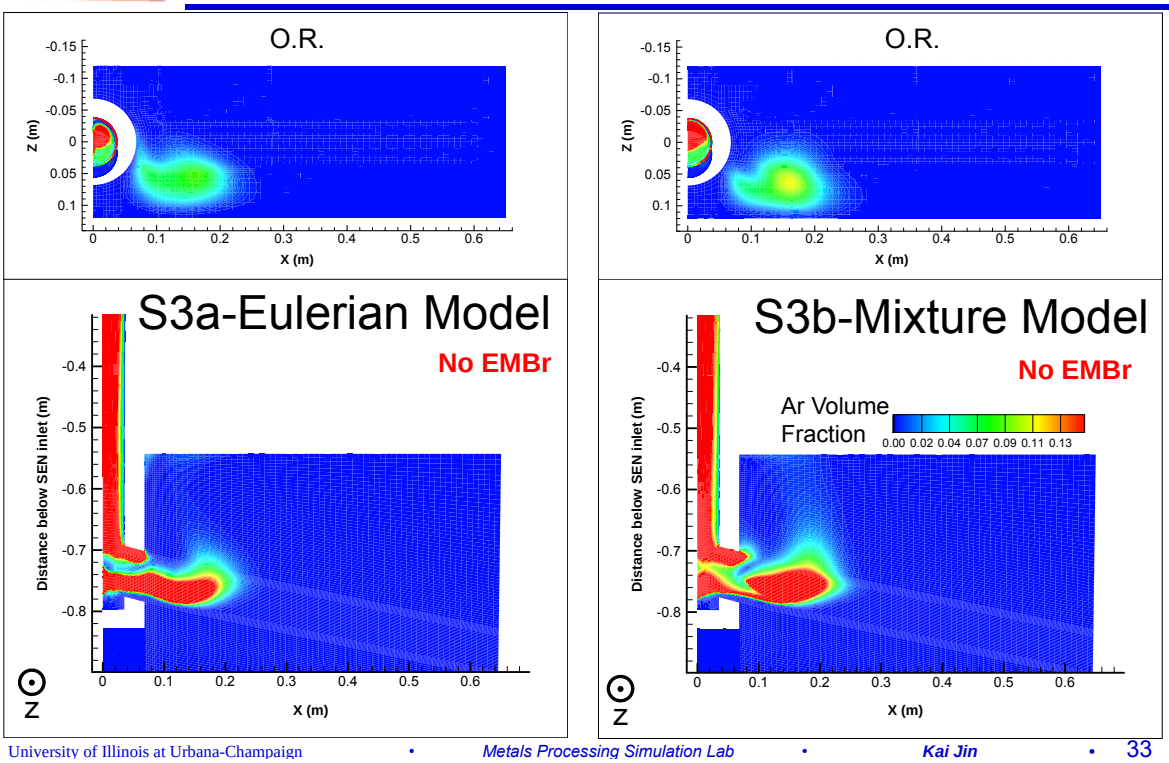
Eulerian Model



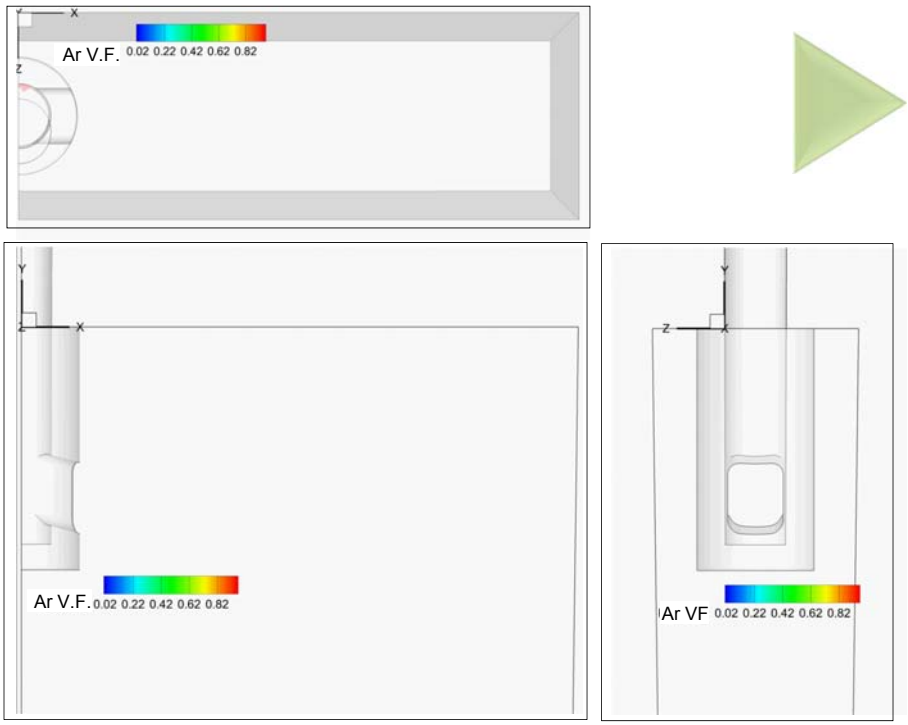
Mixture Model



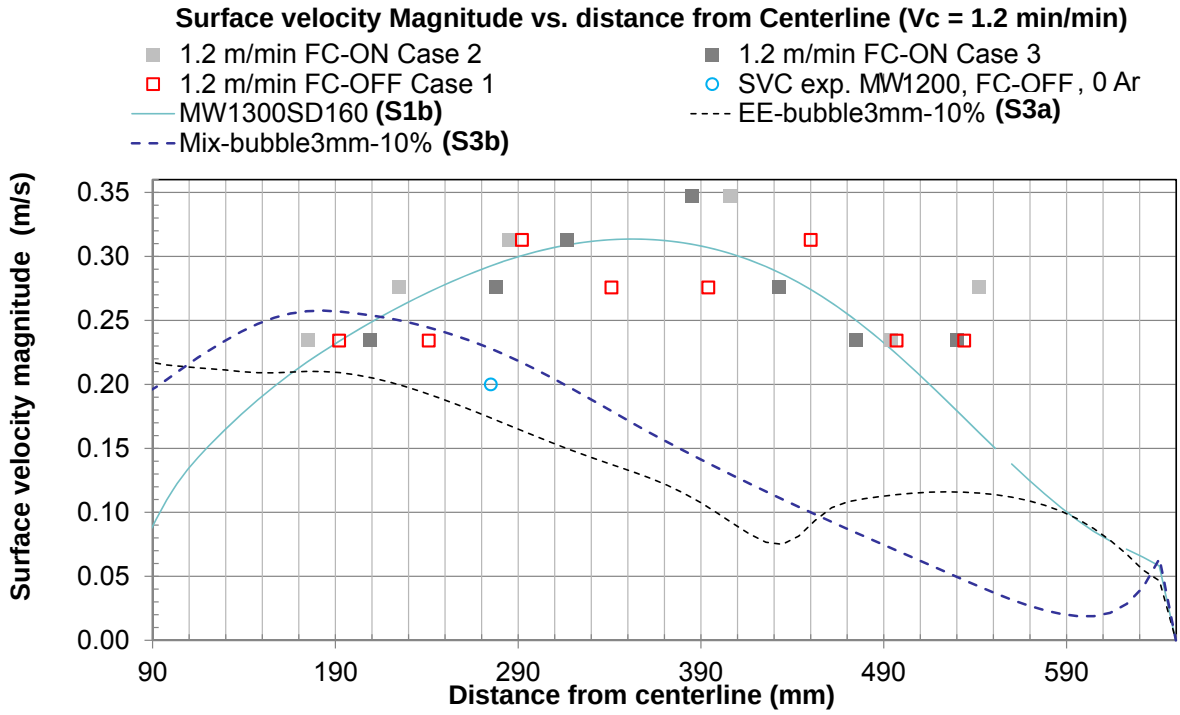
Compare Ar Volume Fraction Mid. Plane, Surface 1cm below TP.



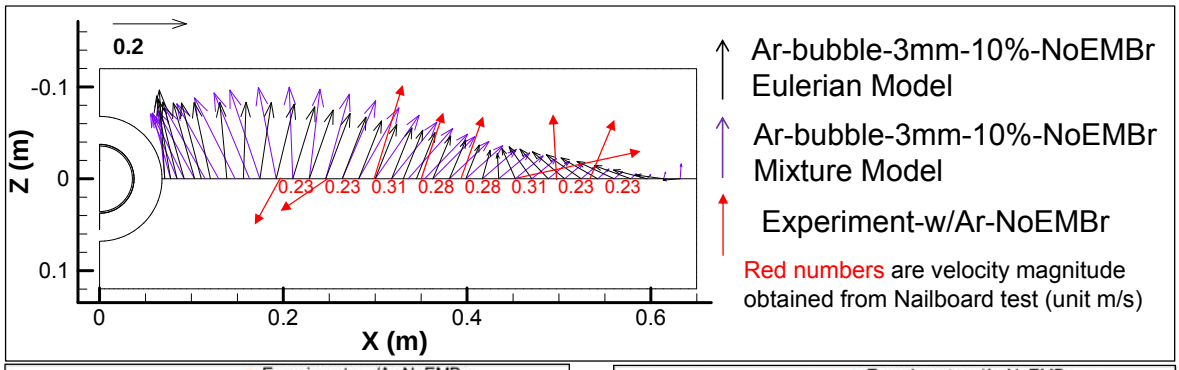
Animation of ISO Surface Developing (S3b)

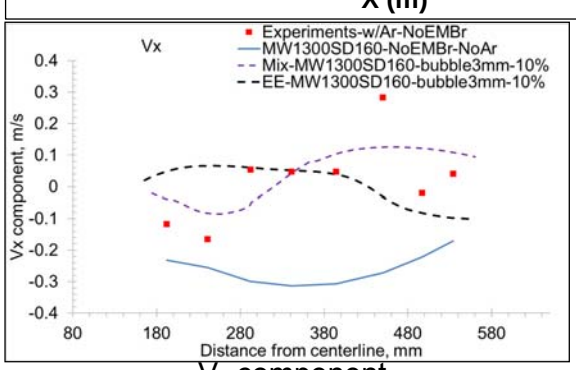


Mixture/Eulerian Model Compare with Measurements

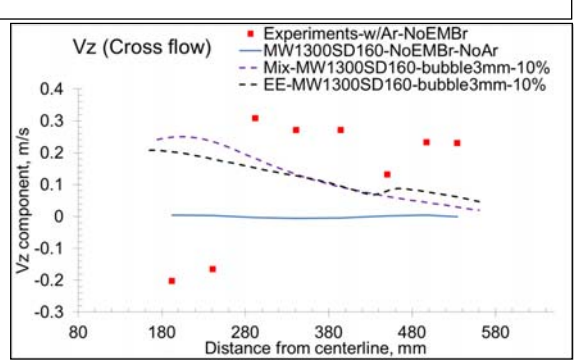


Compare Velocity Components Mixture Model (Surface 1cm below TS.)



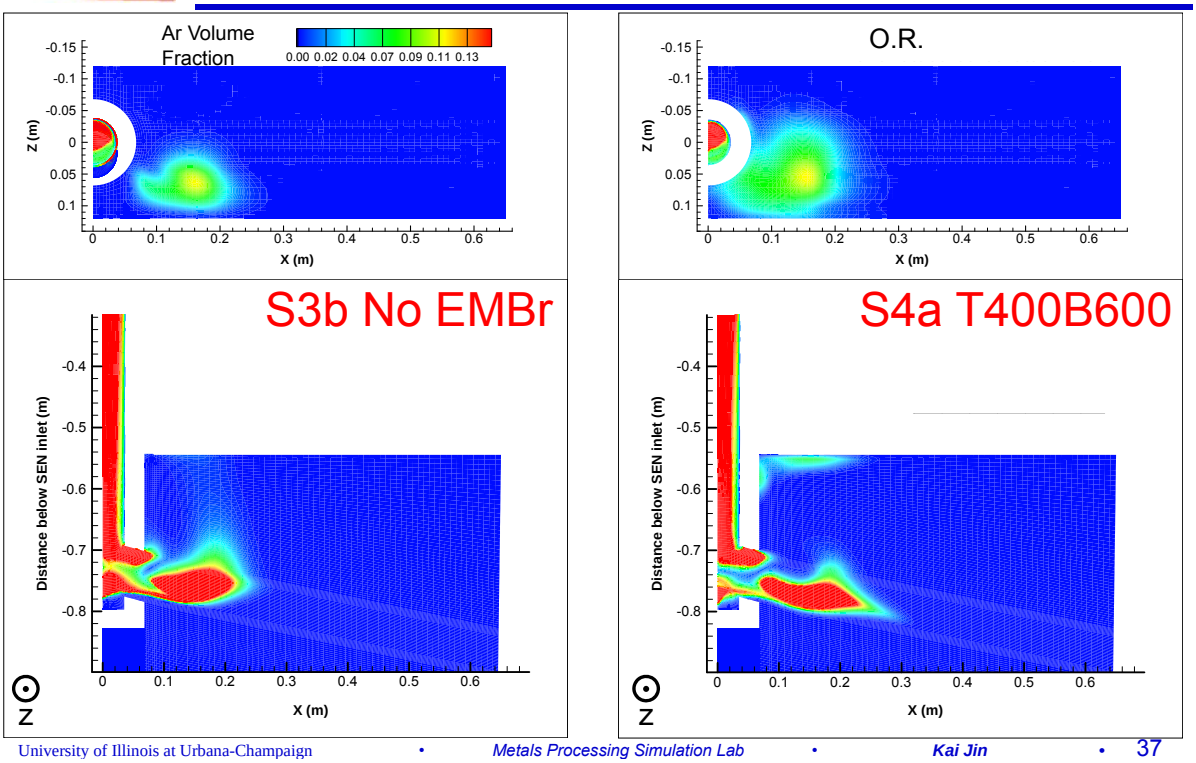


V_x component

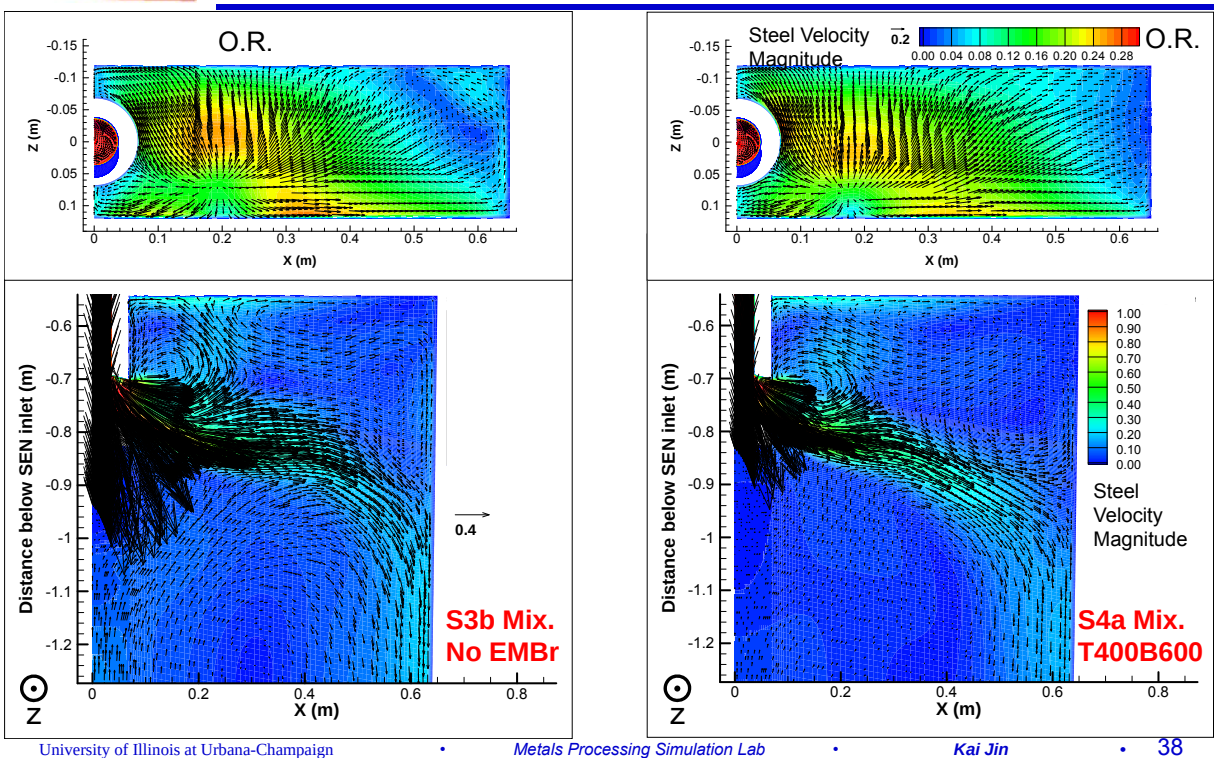


V_z component

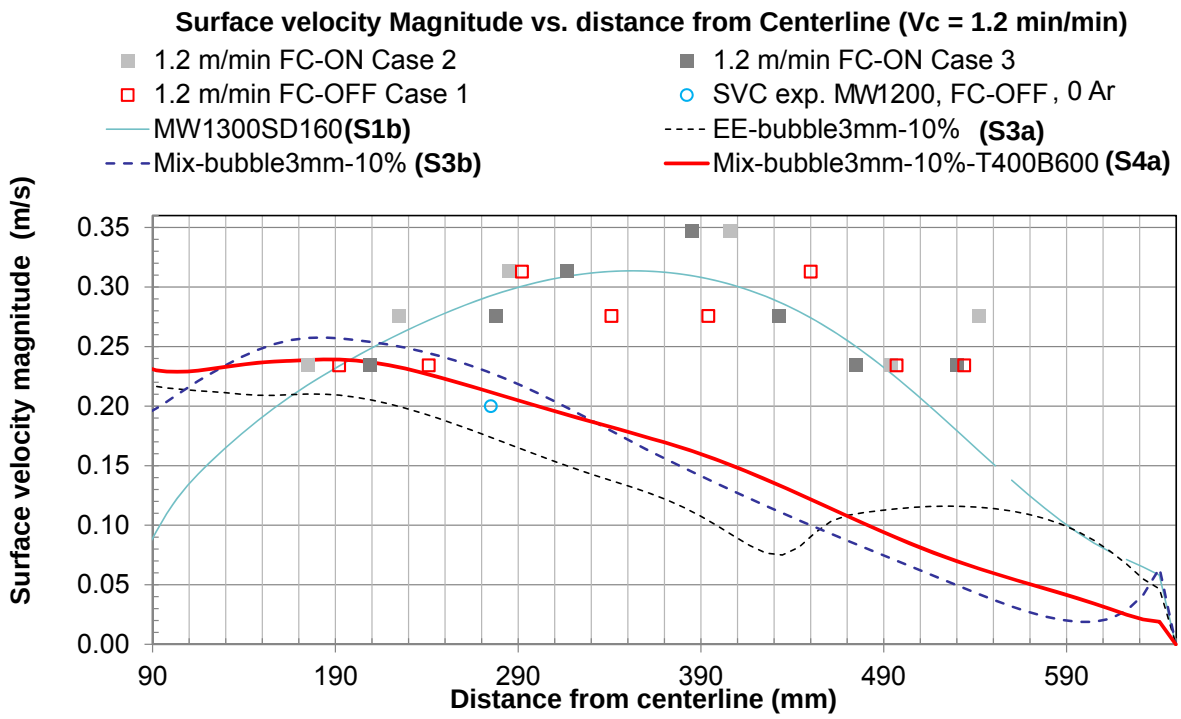
S4a Results - Effect of EMBr on Multiphase Flow Ar Distribution



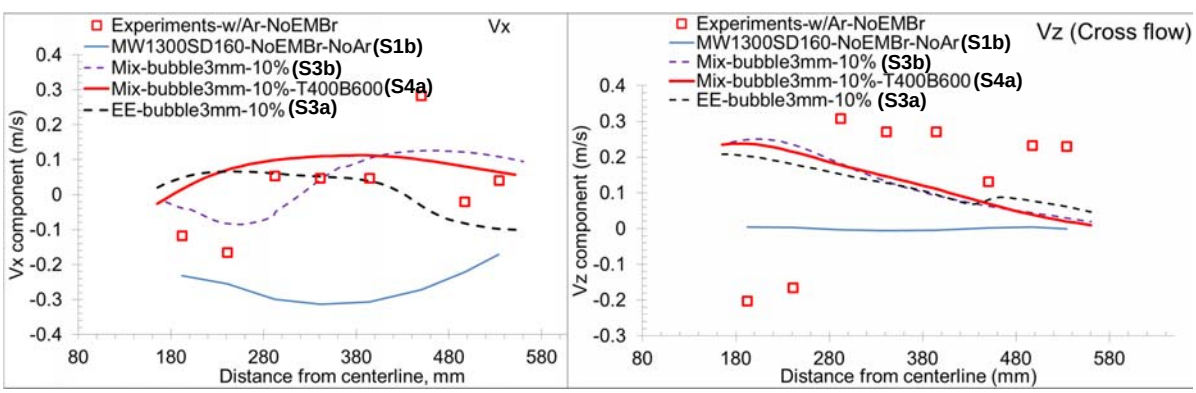
S4a Results - Effect of EMBr on Multiphase Flow Steel Velocity



S4a Results – Compare Velocity Magnitude



S4a Results – Compare Velocity Components



- In two-phase flow, adding EMBr may increase top surface velocity V_x components, and the direction is toward NF;
- EMBr has little affect on decreasing cross flow;

Multi-phase Simulation Conclusions

- Eulerian-mixture and Eulerian- Eulerian multiphase models are compared with nailboard experiments, and the 2 different models have some differences but generally have the same trends. More nailboard measurements are needed to confirm the real behavior;
- Ar gas injection has HUGE effect and can greatly change the flow pattern in mold region, also generate cross flow on top surface;
- Huge asymmetry problem is more important than EMBr effect; EMBr cannot help with solving asymmetric flow problem;
- EMBr may increase the velocity magnitude near the meniscus when there is Ar injection;
- Minimize Ar gas injection prior to optimizing flow with EMBr.

Optimization of EMBr in Single Phase Flow

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Department of Mechanical Science and Engineering
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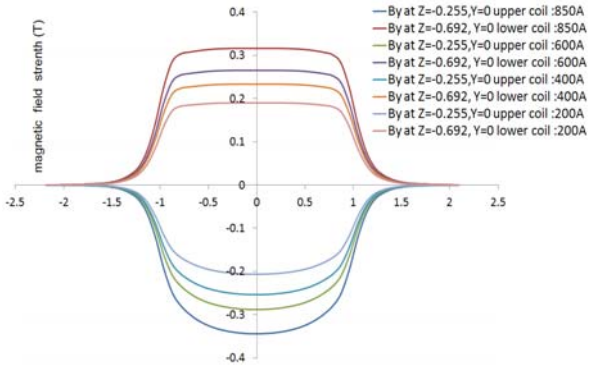
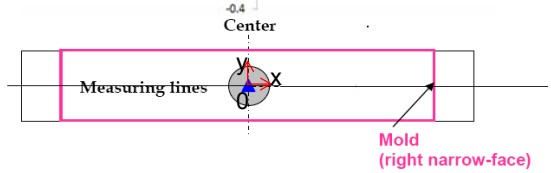
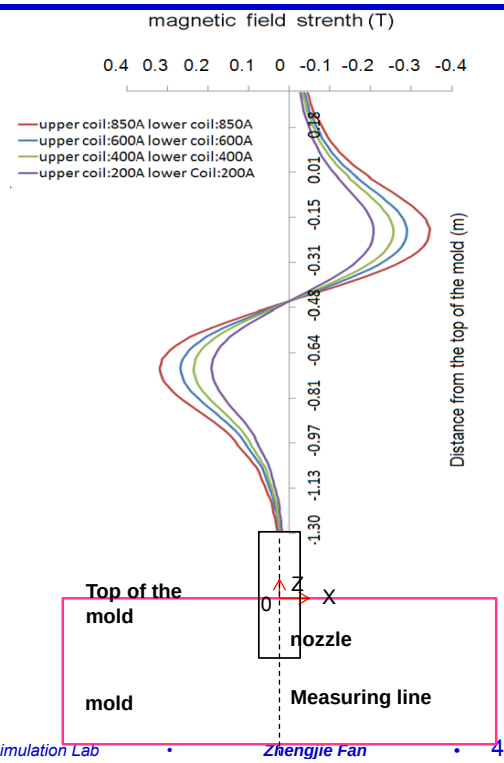
EMBr Magnetic Field Strength





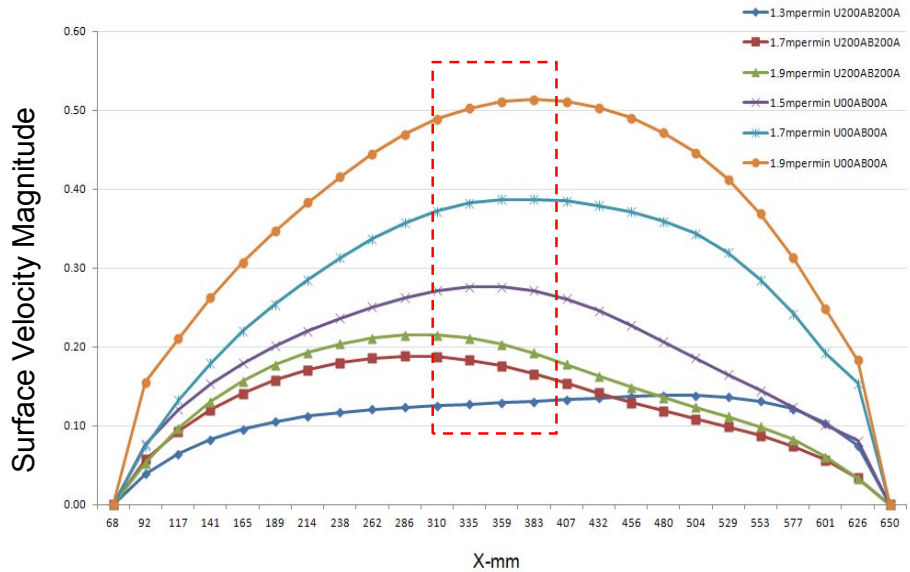


Surface Velocity at ¼ the mold (m/s) for Different Casting Speed and EMBr settings

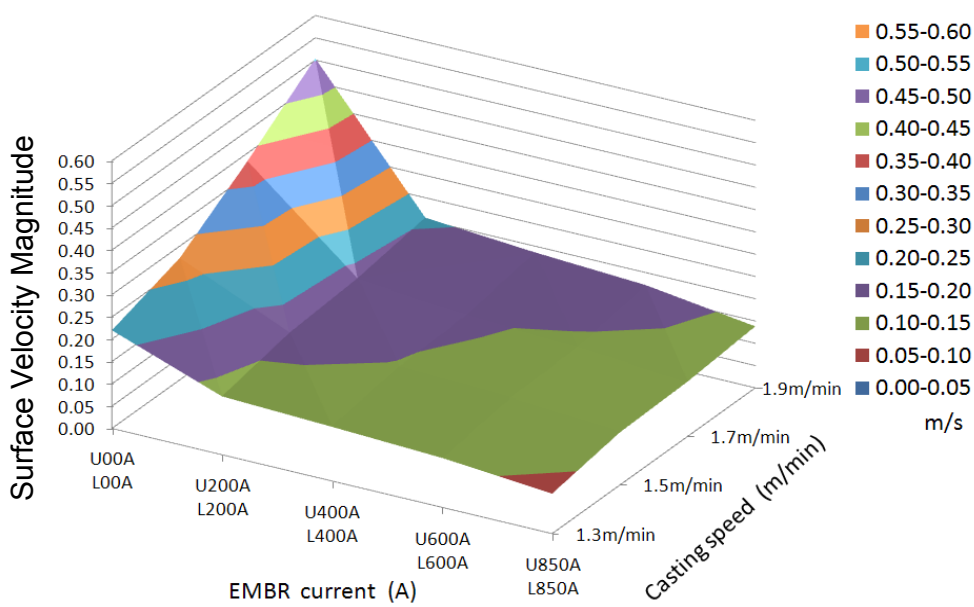
Velocity magnitude at 10 mm deep (m/s)

CC condition	1.3 m/min	1.5 m/min	1.7 m/min	1.9 m/min
EMBR OFF	0.220	0.273	0.382	0.504
U200A B200A	0.131	0.165	0.178	0.205
U400A B400A	0.115	0.148	0.155	0.176
U600A B600A	0.107	0.137	0.143	0.165
U850A B850A	0.097	0.118	0.123	0.143

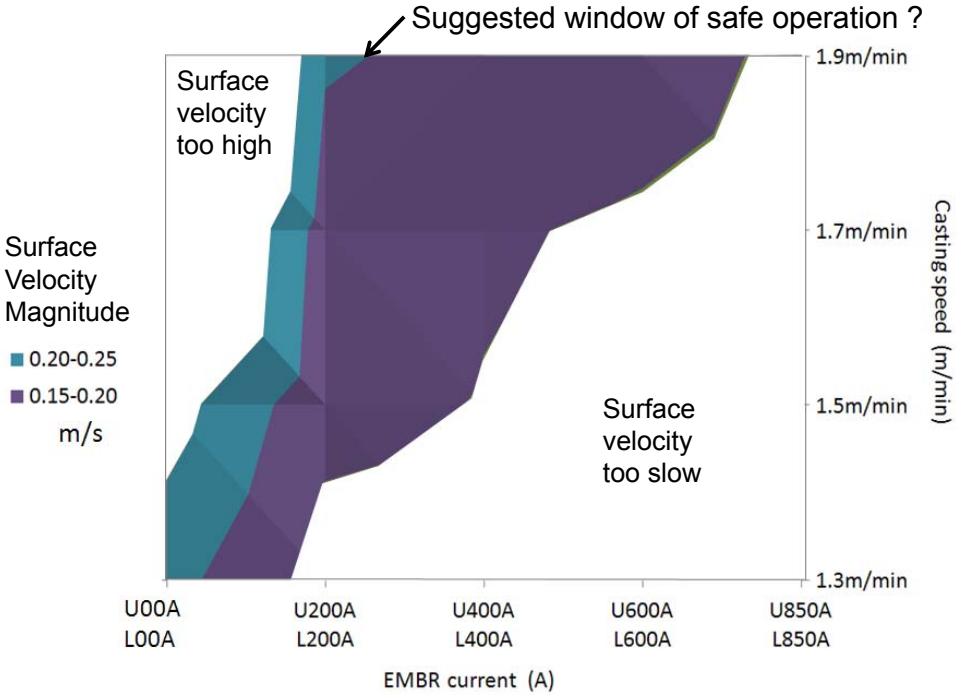
Surface Velocity for Different Casting Speed and EMBr Settings



3D-Contour of Surface Velocity for Different Casting Speeds and EMBr Settings



Contour of Surface Velocity for Different Casting Speeds and EMBr Settings



Conclusions

- Single-phase, Eulerian-mixture, and Eulerian- Eulerian multiphase models are compared with nailboard experiments;
- In single-phase flow, slide gate can cause asymmetric flow through port but cannot generate large asymmetric flow in top surface;
- EMBr has little effect on asymmetry in single phase flow;
- In single-phase flow, adding EMBr can decrease surface velocity, but it's not true in multiphase flow; surface velocity may be increased by adding EMBr;
- The 2 different multiphase models have some differences but generally same trends. More nailboard measurements are needed to confirm the real behavior;
- Huge asymmetry problem is more important than EMBr effect; Ar gas injection is the major cause of asymmetric flow in near top surface;
- Minimize Ar gas injection prior to optimizing flow with EMBr.

References

[1] Ansys, Inc, FLUENT Manual.

[2] Rui Liu, GroupMeeting Sep.26, 2011, R. Liu *Shell and Particle*.

[3] Yu Haiqi, Wang Baofeng, Li Huiqin, Li Jianchao, *Influence of electromagnetic brake on flow field of liquid steel in the slab continuous casting mold*, Journal of Materials Processing Technology, Volume 202, Issues 1–3

[4] S. D. Pawar, P. Murugavel, D. M. Lal, *Effect of relative humidity and sea level pressure on electrical conductivity of air over Indian Ocean*, Journal of Geophysical Research, vol. 114, D02205, 8 PP., 2009

THANK YOU