CCC Annual Report

UIUC, August 20, 2014

Transient Two-phase Flow in a Slide-gate Nozzle and Mold with Double-ruler EMBr

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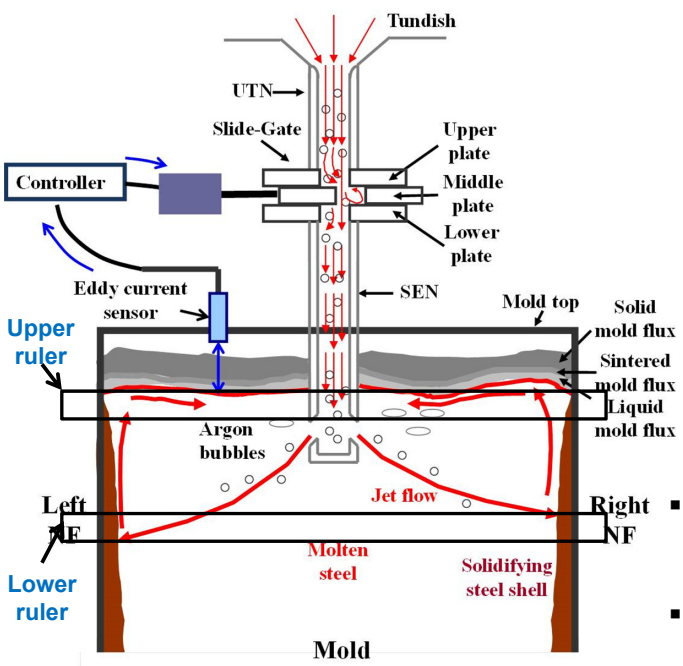
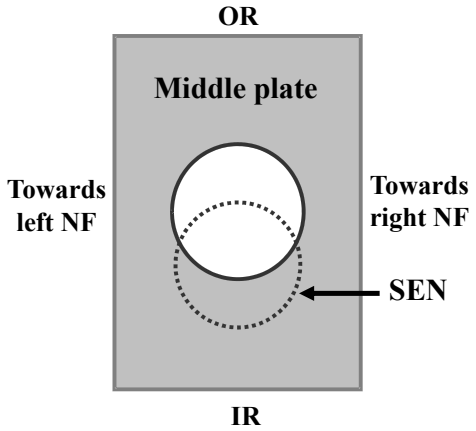
Slide-gate and Double-ruler EMBr in Continuous Slab Casting



<Schematic of continuous steel slab casting>



<Slide-gate middle plate on SEN>

- Slide-gate produces asymmetric open area for flowing molten steel
- Double-ruler EMBr locates magnet rulers at two regions: just above the port and below nozzle port

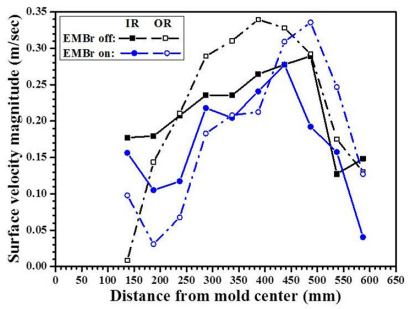
Research Scope

- **Previous works**
  - Quantified transient two-phase (molten steel-argon) flow in slide-gate nozzle and mold without EMBr, using LES coupled with DPM model and nail board tests
  - Investigated effects of double-ruler EMBr on single-phase (molten steel) flow in slide-gate nozzle and mold using standard $k-\varepsilon$ model and nail board tests
- **Objectives to**
  - Gain insight of effects of double-ruler EMBr on transient two-phase flow in slide-gate nozzle and mold
  - Develop and validate LES coupled with DPM and MHD to predict two-phase flow considering EMBr effect
  - Compare steady-state standard $k-\varepsilon$ model and LES to predict transient flow variations in the mold
- **Methodologies**
  - Plant Experiments: nail board tests, eddy-current sensor measurements
  - Computational Models: standard $k-\varepsilon$ model, LES coupled with DPM and MHD model

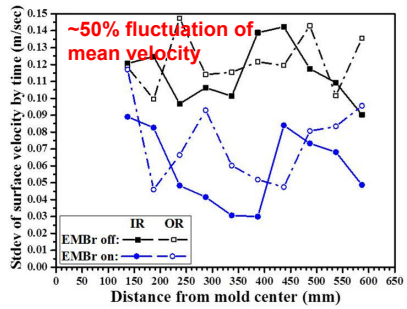
Process Conditions

Caster Dimensions		
Nozzle bore diameter (inner/outer)	90 mm (at UTN top) to 80 mm (at bottom well) / 160 mm (at UTN top) to 140 mm (at SEN bottom)	
Nozzle bottom well depth	19 mm	
Nozzle port area	80 mm (width) 85 mm (height)	
Nozzle port angle	*2008: 52 to 35 down degree step angle at the top, 45 down degree angle at the bottom *2010: 35 down degree angle at both top and bottom	
Mold thickness	250 mm	
Mold width	1300 mm	
Domain length	4648 mm (mold region: 3000 mm (below mold top))	
Process Conditions		
Steel flow rate	552.5 LPM (3.9 tonne/min)	
Casting speed	1.70 m/min (28.3 mm/sec)	
Argon gas flow rate & volume fraction	9.2 SLPM (1 atm, 273 K); 33.0 LPM (1.87 atm, 1827 K) & 5.6 % (hot)	
Submerged depth of nozzle	164 mm	
Meniscus level below mold top	103 mm	
EMBr current (both coils)	EMBr off: 0 A	EMBr on: 300 A

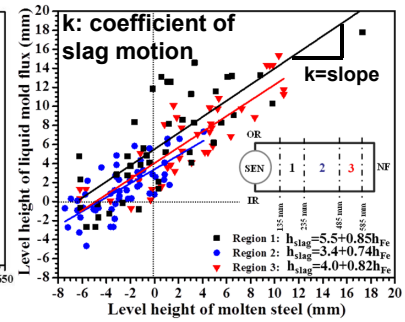
Plant Measurements: Nail Board Tests (2013 CCC Report)



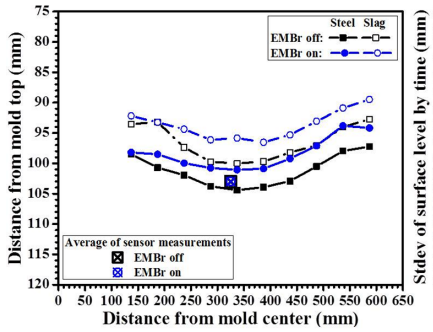
<Time-averaged surface velocity>



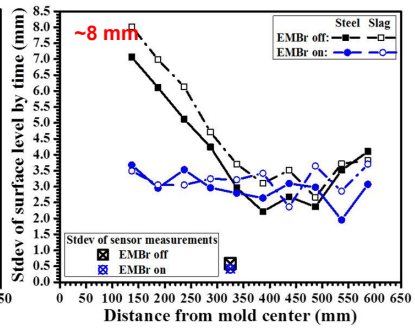
<Surface velocity fluctuation>



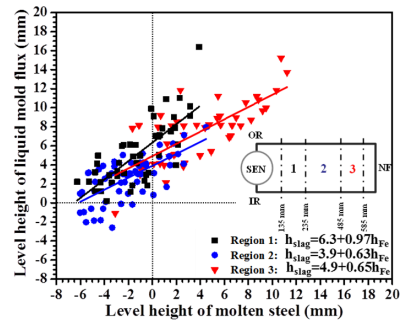
<Slag motion without EMBr>



<Time-averaged surface level>

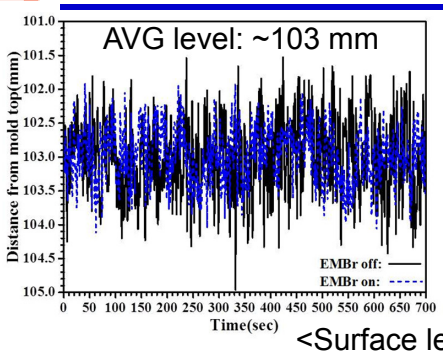


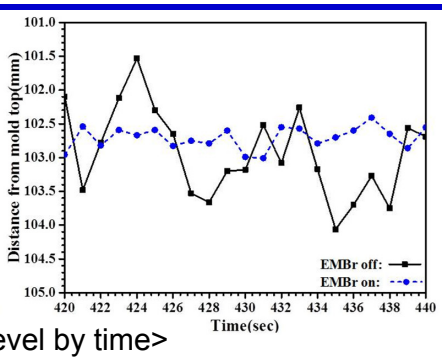
<Surface level fluctuation>



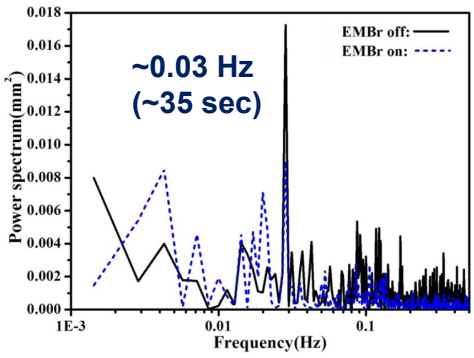
<Slag motion with EMBr>

Plant Measurements: Eddy Current Sensor Measurement (2013 CCC Report)





<Surface level by time>



<Power spectrum of level variation>

- With EMBr, surface level fluctuation at quarter point (located midway between SEN and NF) is reduced by ~33%: 0.6 mm (Without EMBr) and 0.4 mm (With EMBr)

Governing Equations

- **Molten steel flow field: Large Eddy Simulation (LES)**

Mass conservation: $\frac{\partial}{\partial x_i}(\rho u_i) = S_{shell,\ mass}$

Mass/momentum sink terms to account for solidification of the molten steel: $S_{shell,mass} = -\frac{\rho u_{casting} A}{V}$ $\quad S_{shell,mom,i} = -\frac{\rho u_{casting} A}{V}\bar{u}_i$

Momentum conservation: $\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p^*}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + S_{shell,mom,i} + S_{Ar,mom,i} + F_{L,i}$

- **Argon gas bubble motion: Discrete Phase Model (DPM)**

Bubble motion equation: $\frac{du_{Ar,i}}{dt} = F_{drag,i} + F_{buoyancy,i} + F_{virtual\_mass,i} + F_{pressure\_gradient,i}$

$$S_{mom,Ar,i} = -(F_{drag,i} + F_{buoyancy,i} + F_{virtual\_mass,i} + F_{pressure\_gradient,i})\dot{m}_{Ar}\Delta t$$

Force equations:

$$F_{drag,i} = \frac{3}{4}\frac{\mu C_D Re}{\rho_{Ar}(d_{Ar})^2}\cdot(u_i - u_{Ar,i})$$

$$F_{buoyancy,i} = \frac{\rho_{Ar} - \rho}{\rho_{Ar}} g_i \qquad F_{virtual\_mass,i} = \frac{1}{2}\frac{\rho}{\rho_{Ar}}\frac{d}{dt}(u_i - u_{Ar,i})$$

$$F_{pressure\_gradient,i} = \frac{\rho}{\rho_{Ar}} u_i \frac{\partial u_i}{\partial x_i}$$

Drag coefficient:

$$C_D = \frac{16}{Re} \quad (Re < 0.49)$$
$$= \frac{20.68}{Re^{0.643}} \quad (0.49 < Re < 100)$$
$$= \frac{6.3}{Re^{0.385}} \quad (100 < Re)$$
$$= \frac{We}{3} \quad \left(\frac{2065.1}{We^{2.6}} < Re\right)$$
$$= \frac{8}{3} \quad (8 < We)$$

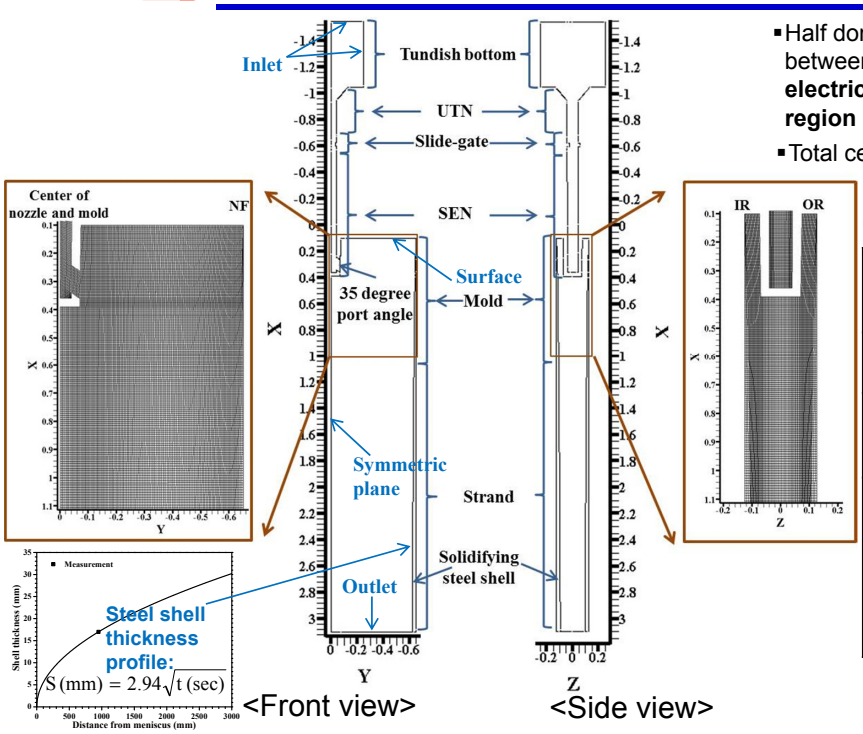
$$We = \frac{\rho d_{Ar}|u_{Ar} - u|^2}{\sigma_{steel-argon}} \qquad Re = \frac{\rho d_{Ar}|u_{Ar} - u|}{\mu}$$

- **Electromagnetic force induced by EMBr: Magneto-Hydro-Dynamics (MHD) model**

Lorentz force: $\vec{F}_L = \vec{j} \times (\vec{B}_0 + \vec{b})$

Induced current density: $\vec{j} = \frac{1}{\mu}\nabla \times (\vec{B}_0 + \vec{b})$ $\quad$ Induced magnetic field: $\frac{\partial \vec{b}}{\partial t} + (\vec{u}\cdot\nabla)\vec{b} = \frac{1}{\mu\sigma}\nabla^2\vec{b} + ((\vec{B}_0 + \vec{b})\cdot\nabla)\vec{u} - (\vec{u}\cdot\nabla)\vec{B}_0$

Domain, Mesh, and Boundary Conditions

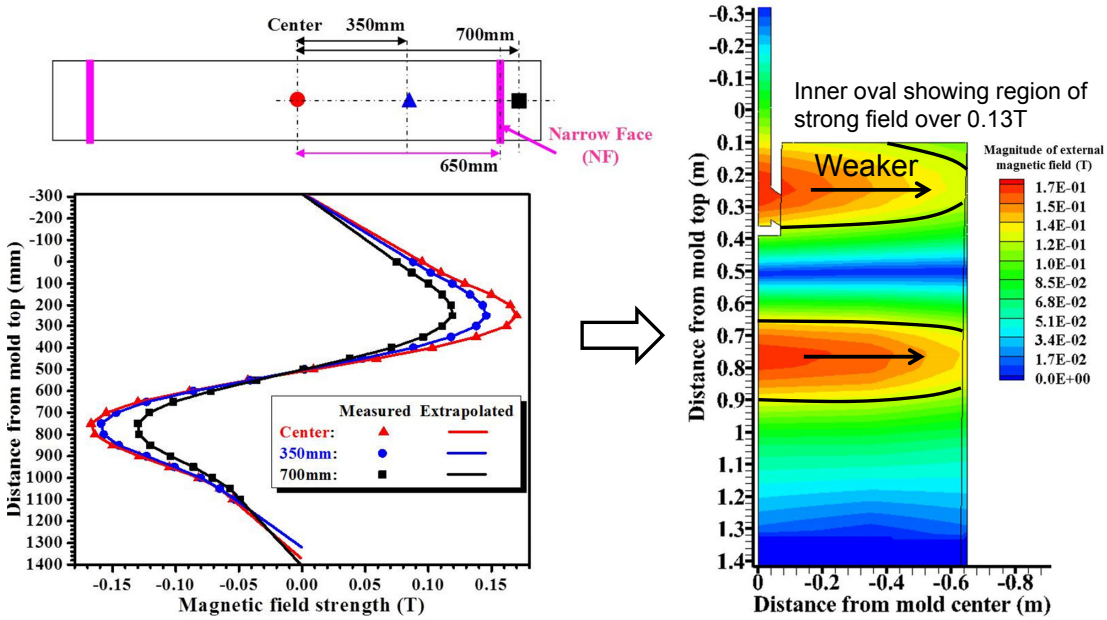


<Front view> <Side view>

- Half domain (assuming symmetry between NFs, **containing the electrically-conducting steel shell region as a solid zone**)
- Total cells in the domain: ~1.8 million
- Boundary conditions

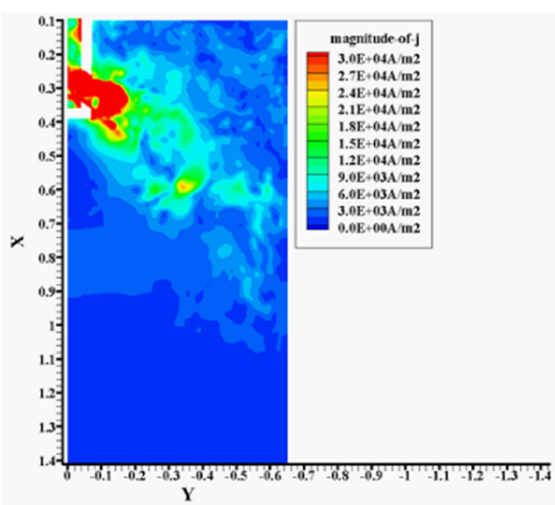
Inlet	0.00938 m/sec, **5.6 % volume fraction of Argon**
Outlet	0 Pa (gauge pressure), particle escape
Surface	Stationary wall with a no slip shear condition, particle escape
Interface between the molten steel /the steel shell	Stationary wall with a no slip shear condition, molten steel mass/momentum sink, particle reflect

Double-ruler EMBr Field: External Magnetic Field

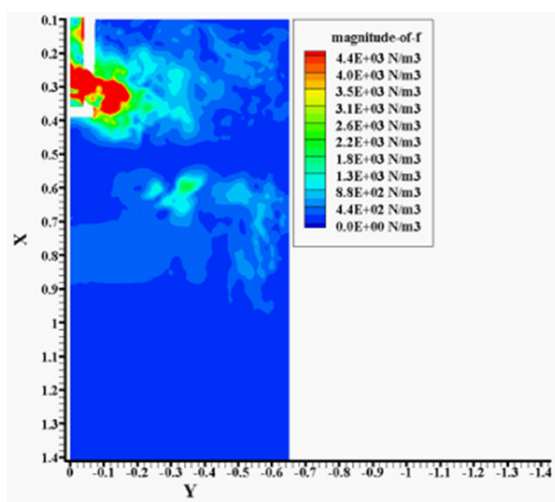


- Magnetic field applied by the double-ruler EMBr has high peaks in two regions: **one centered just above the port and the other below the nozzle port**

Double-ruler EMBr Field: Current Density & Electromagnetic Force



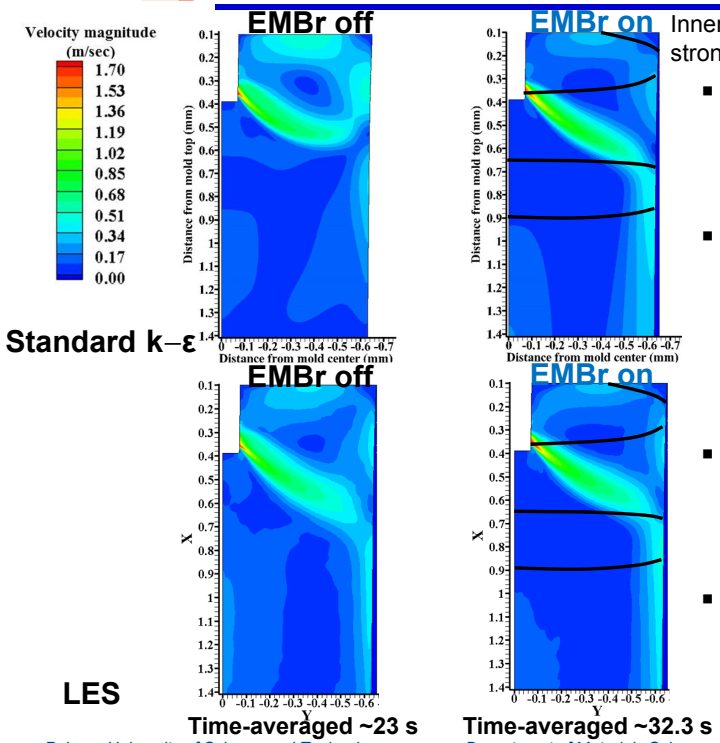
<Induced current density>



<Electromagnetic force>

- High current density and electromagnetic force are generated in two regions: **near the nozzle port and near the NF 600mm below the mold top**

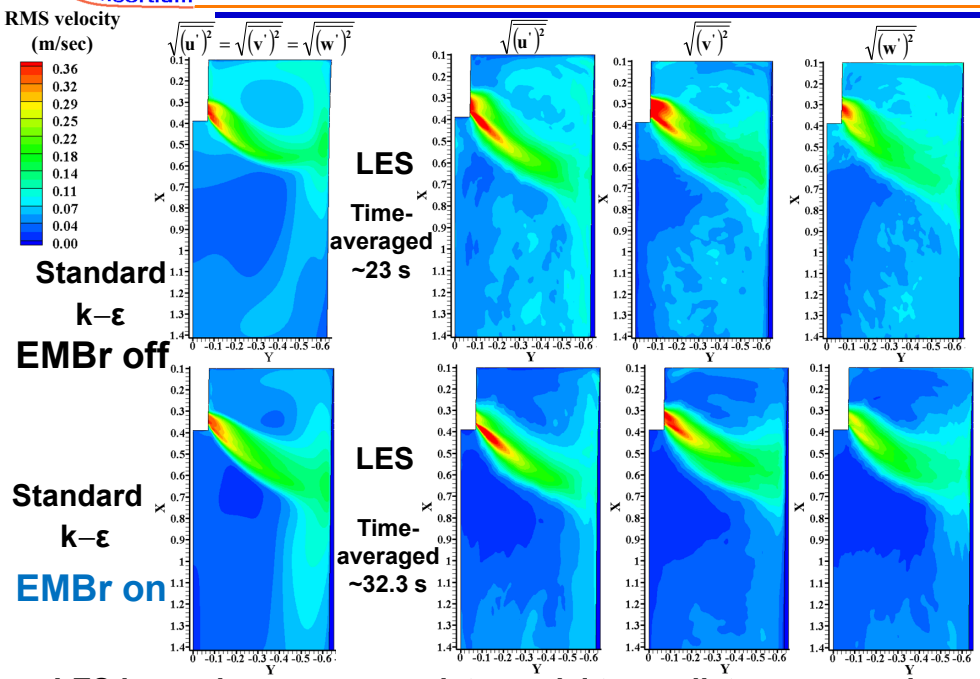
Comparison of Time-averaged Mold Flow Pattern between Standard $k-\varepsilon$ Model and LES (Single Flow)



Inner oval showing region of strong field over 0.13T

- Standard $k-\varepsilon$ model and LES both predict double-role flow pattern and high surface velocity in the mold without EMBr
- Both two models show EMBr produces less flow up the NF (600 mm below mold top), resulting in slower surface velocity and stronger downward flow along the NF
- In EMBr on case, steady-state standard $k-\varepsilon$ model shows better agreement with LES than EMBr off case
- The limited accuracy of this steady-state model is perhaps due to complex transient flow variation (anisotropic variations)

Comparison of Mold Flow Fluctuations between Standard $k-\varepsilon$ Model and LES (Single Flow)

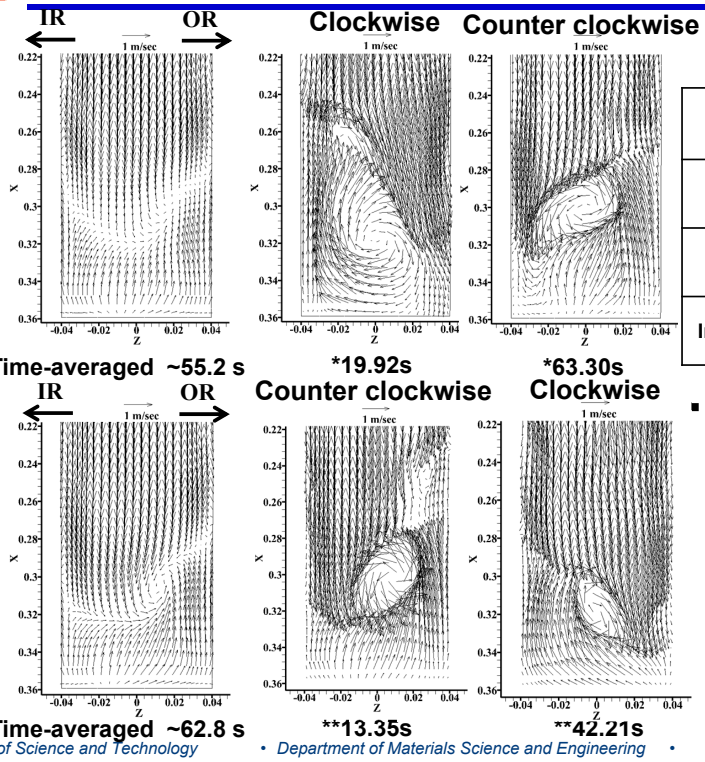


- Two models both predict EMBr induces smaller flow variation towards the top surface
- LES predicts EMBr is more effective to reduce the variations along mold thickness; same trend with R. Singh et al. result[*]
- Steady-standard $k-\varepsilon$ model well-predicts isotropic variations however, shows limited accuracy for anisotropic variations

- **LES is much more appropriate model to predict more complex flow variations induced by two-phase flow**

*R. Singh, B. G. Thomas, and S. P. Vanka, Metall. Mater. Trans. B., 2014, vol. 45B, pp. 1098-1115

Transient Swirl Flow in Slide-gate Nozzle (Two-phase Flow)



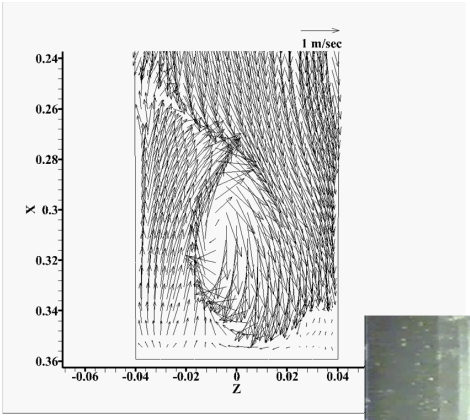
Period of flow directions

	EMBr off	EMBr on
Clockwise	23.4 s (43%)	14.4 s (23%)
Counter clockwise	29.4 s (54%)	46.2 s (74%)
Intermediate	1.2 s (3%)	1.8 s (3%)

- With EMBr, period of the counter-clockwise swirl flow becomes longer: EMBr makes the flow (from asymmetric open area in the middle plate to nozzle bottom) go down by longer path with imposing electromagnetic force

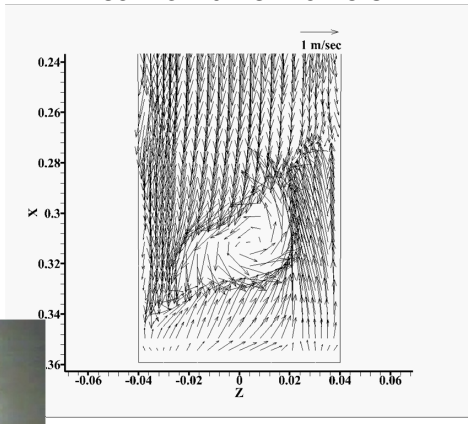
Swirl Flow Videos

Real flow time ~55.2 s

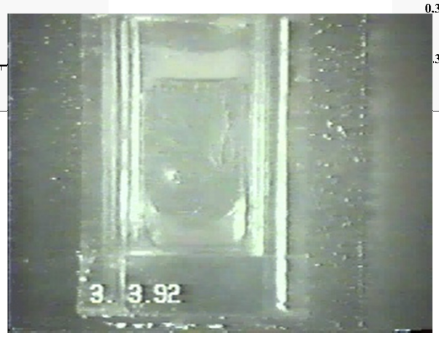


EMBr off

Real flow time ~62.8 s



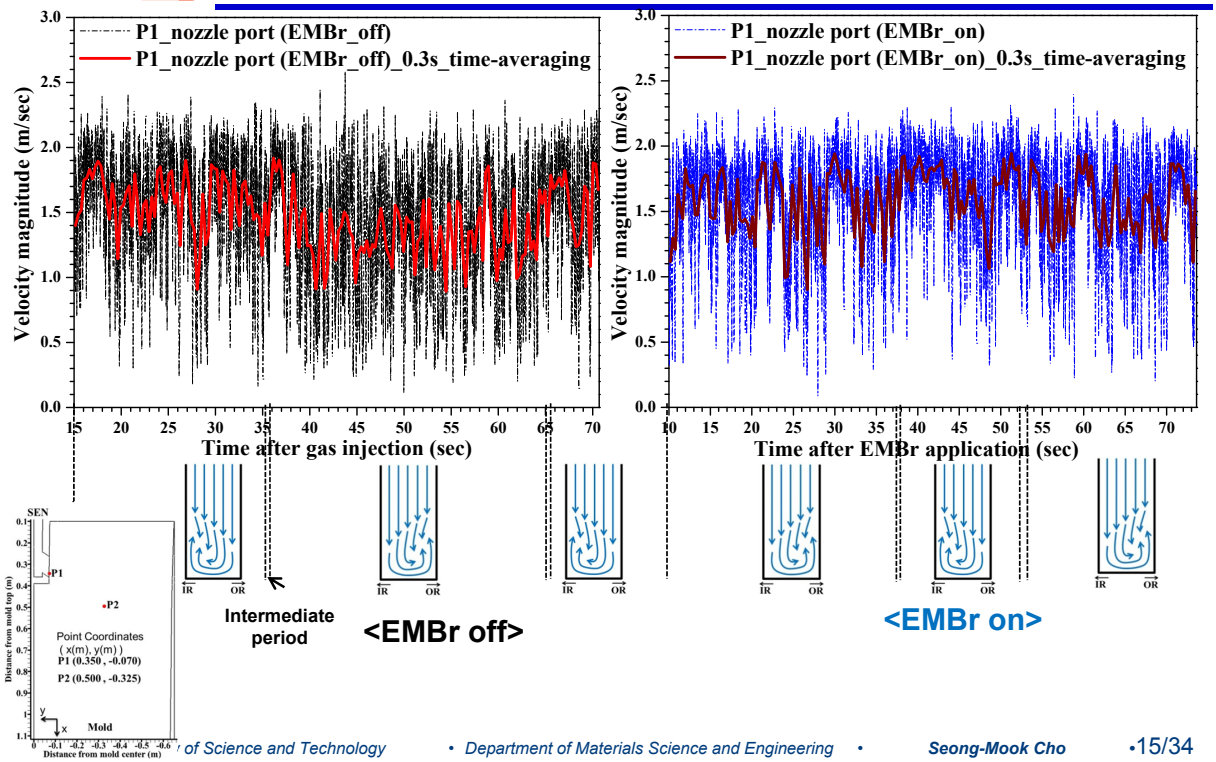
EMBr on



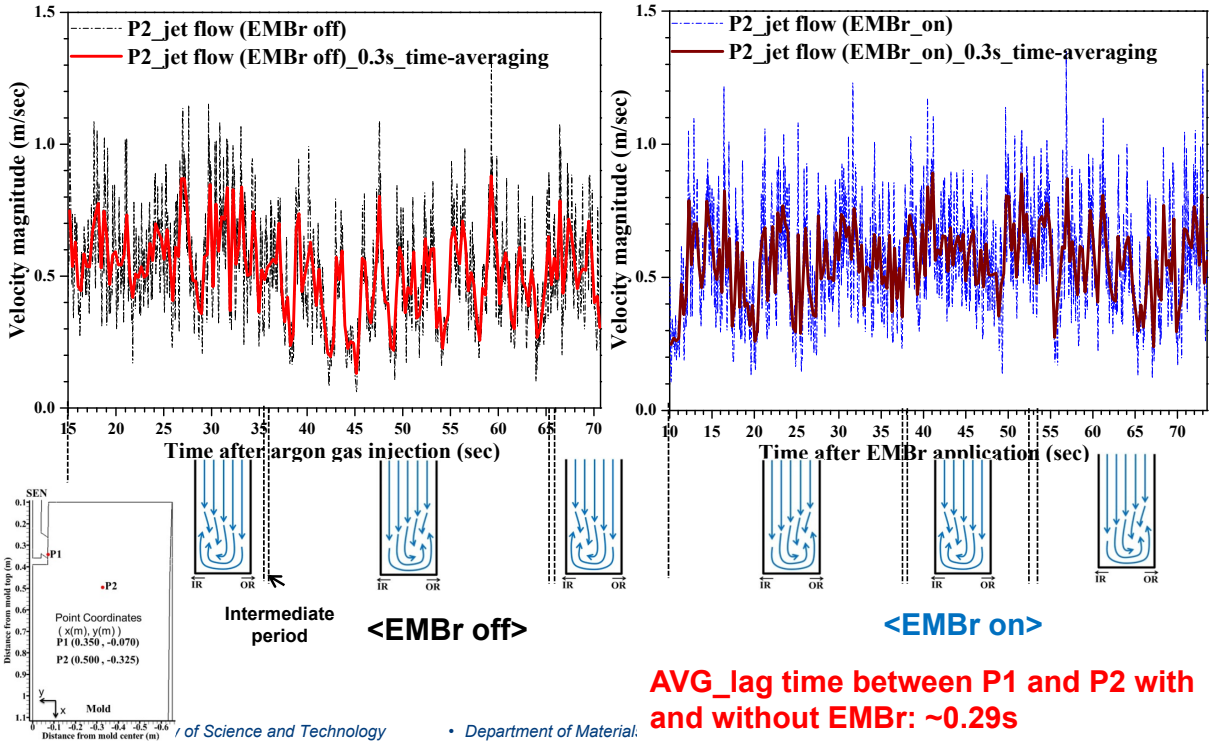
Swirl in nozzle[*] (Water model experiment)

*Hershey, D. E., B. G. Thomas, and F. M. Najjar, "Turbulent Flow through Bifurcated Nozzles," *International Journal for Numerical Methods in Fluids*, 17:1, 23-47, 1993.

Nozzle Port Velocity Histories (Two-phase Flow at P1-Nozzle Port)

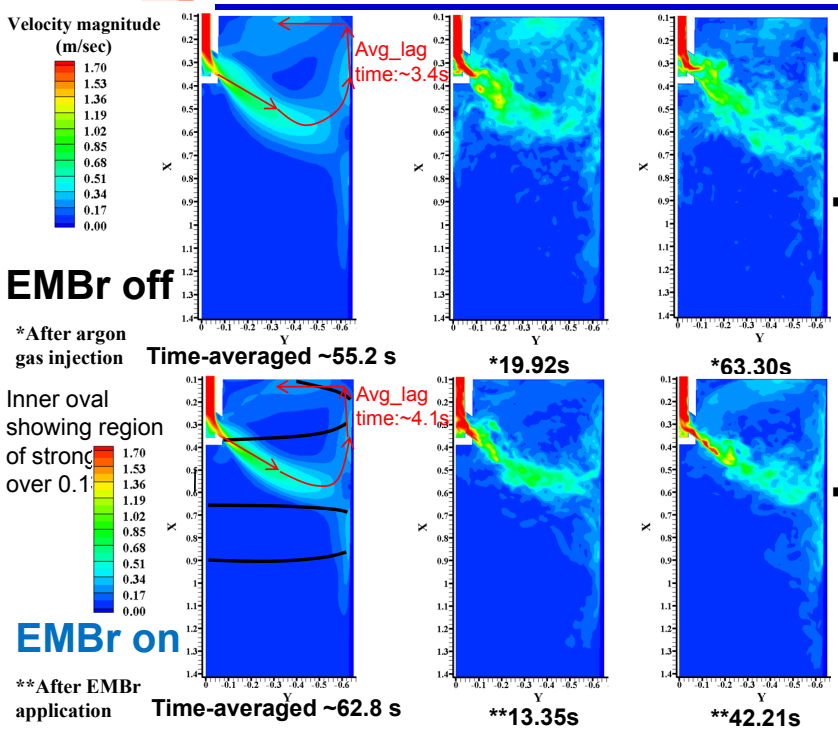


Jet Velocity Histories (Two-phase Flow at P2-Jet Flow)



AVG_lag time between P1 and P2 with and without EMBr: ~0.29s

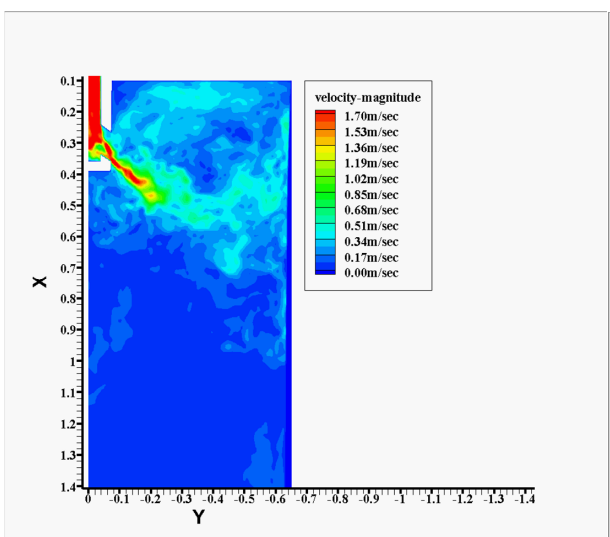
Transient Flow Pattern in the Mold (Two-phase Flow)



- With and without EMBr, double-role pattern is induced in two-phase flow in the mold
- Without EMBr, up-and-down wobbling of the jet flow induces variations of velocity magnitude and direction at the surface, and changes the jet flow impingement point on the NF
- EMBr makes the slightly thinner jet flow and reduces the wobbling, resulting in more stable surface flow

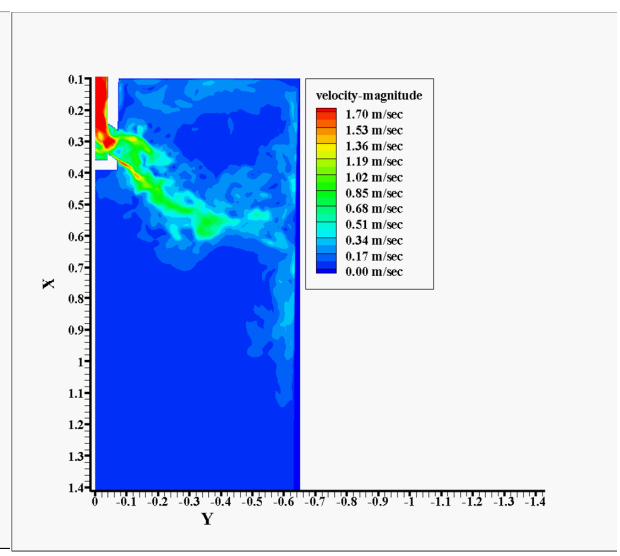
Mold Flow Videos

Real flow time ~55.2 s



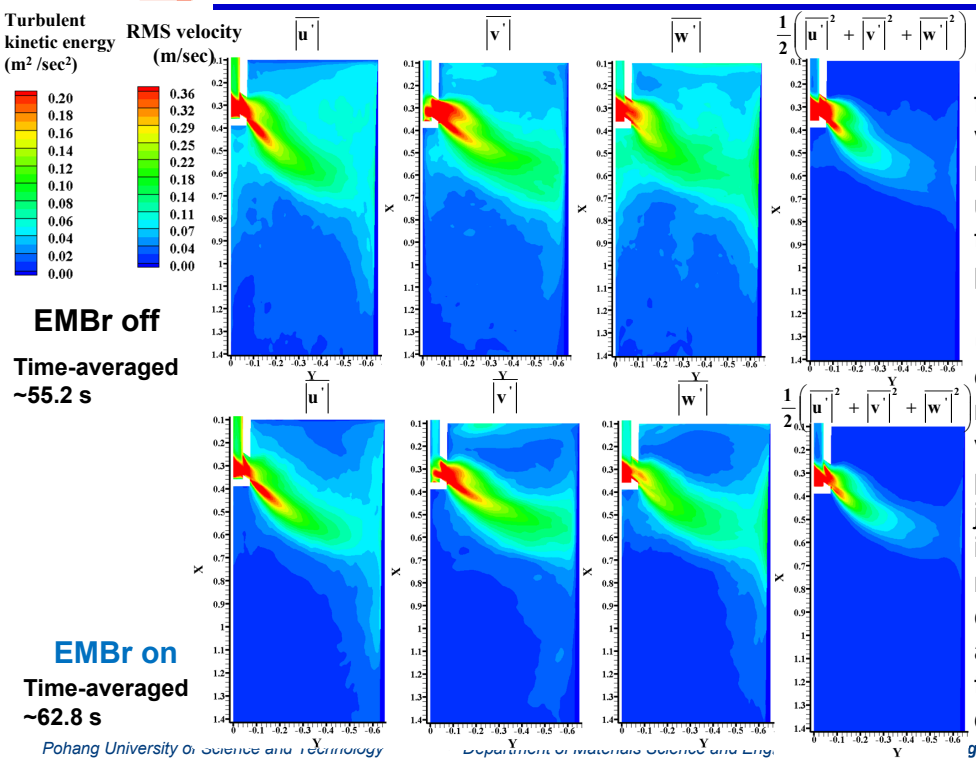
EMBr off

Real flow time ~62.8 s



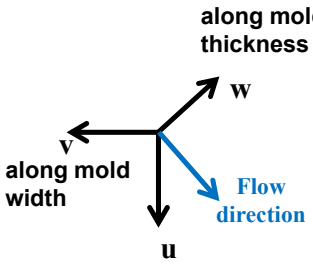
EMBr on

Velocity Fluctuations & Turbulent Kinetic Energy in the Mold (Two-phase Flow)



- Two-phase flow shows more variations in nozzle port and upper-role region than single-phase flow does
- EMBr is more effective to reduce the variations produced by the jet flow wobbling in upper-role region; especially, casting direction and mold thickness direction

Calculation of Jet Flow Angle



Instantaneous vertical angle: $\alpha_i = -\tan^{-1}(u_i / v_i)$

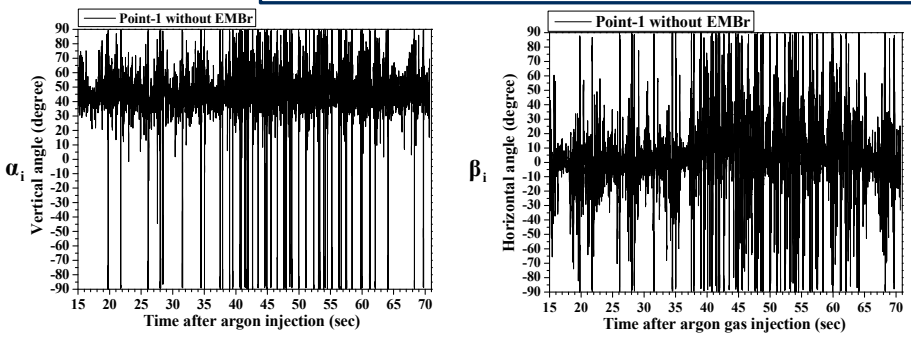
Instantaneous horizontal angle: $\beta_i = -\tan^{-1}(w_i / v_i)$

Averaged vertical angle: $\alpha_{avg} = \frac{1}{n}\sum_{i=1}^{n}\alpha_i$

Averaged horizontal angle: $\beta_{avg} = \frac{1}{n}\sum_{i=1}^{n}\beta_i$

Vertical angle fluctuation (standard deviation): $\sigma_\alpha = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\alpha_i - \alpha_{avg})}$

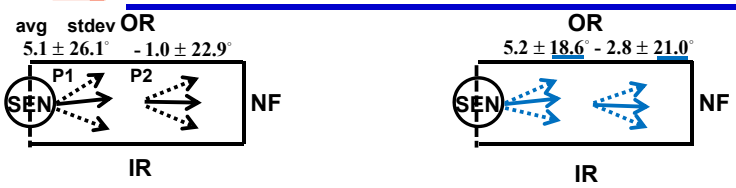
Horizontal angle fluctuation (standard deviation): $\sigma_\beta = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\beta_i - \beta_{avg})}$



α_{avg}	45.4°
σ_α	21.1°
β_{avg}	5.1°
σ_β	26.1°

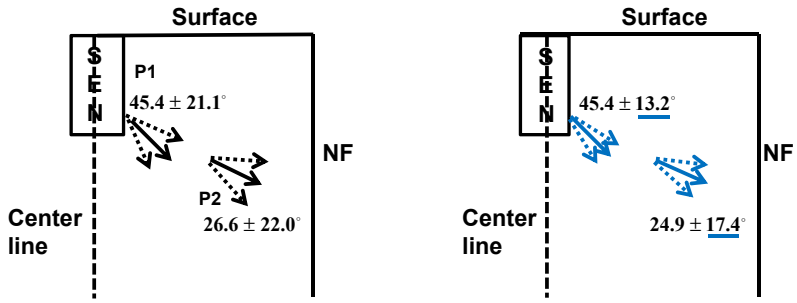
<Instantaneous angle histories of two-phase flow without EMBr (at P1)>

Jet Flow Angle in the Mold (Effect of EMBr on mean and variation)



<Top view: horizontal jet angle> <Top view: horizontal jet angle>

- Horizontal angle fluctuation is slightly larger than vertical angle fluctuation



	Reduction in angle variation by EMBr	
	P1-nozzle	P2-jet
Vertical angle fluctuation	37.4 %	20.9 %
Horizontal angle fluctuation	28.7 %	8.3 %

<Front view: vertical jet angle> <Front view: vertical jet angle>

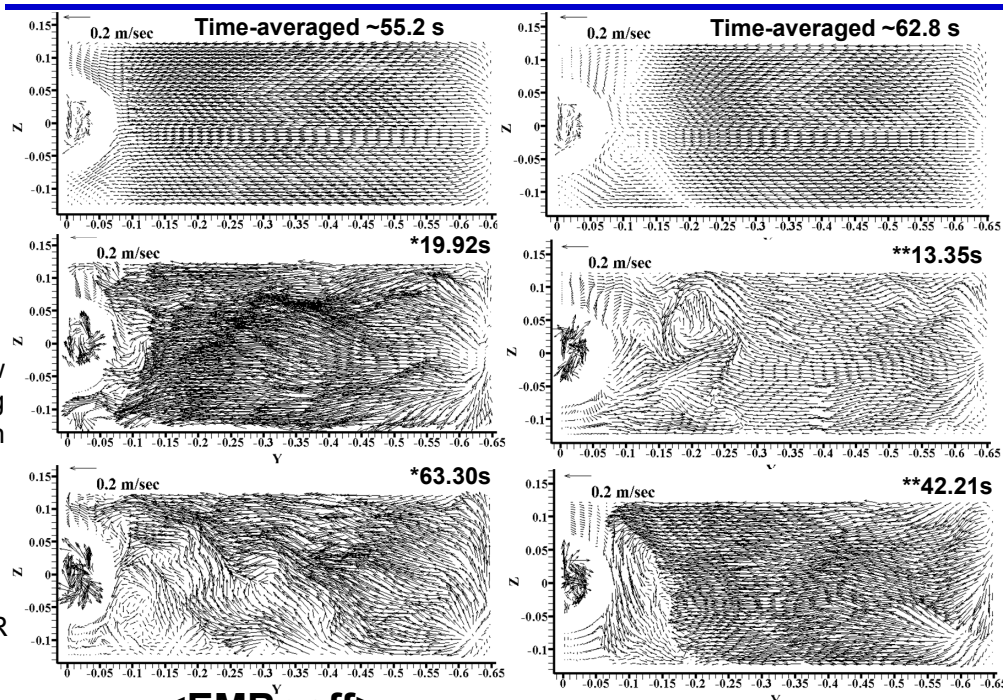
"EMBr off" **"EMBr on"**

- EMBr reduces jet wobbling along both casting direction (vertical angle) and mold thickness direction (horizontal angle)

Transient Surface Flow Pattern (Two-phase Flow)

*After argon gas injection

**After EMBr application

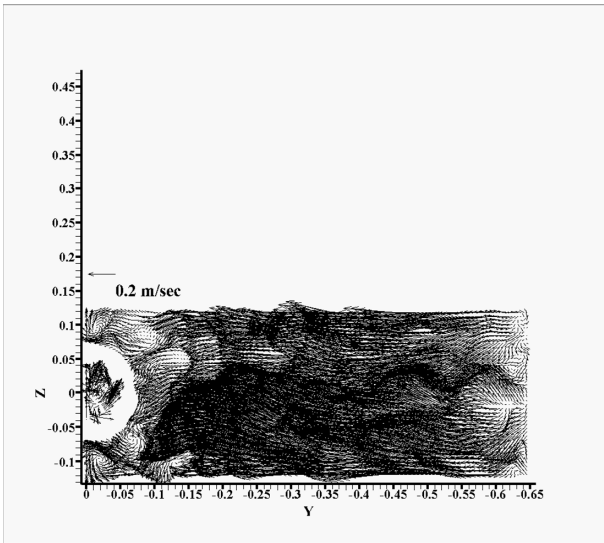


- Decreased jet wobbling by EMBr reduces the surface flow variations along both mold width and thickness; the horizontal velocity fluctuation and the asymmetric flow between IR and OR are suppressed

<EMBr off> **<EMBr on>**

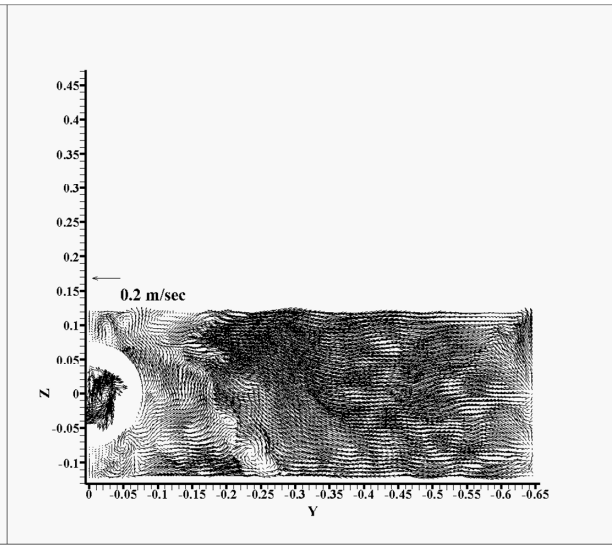
Surface Flow Videos

Real flow time ~55.2 s



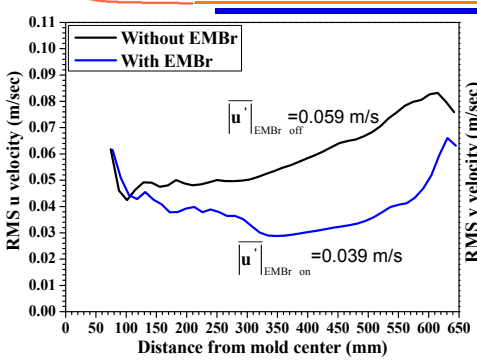
EMBr off

Real flow time ~62.8 s

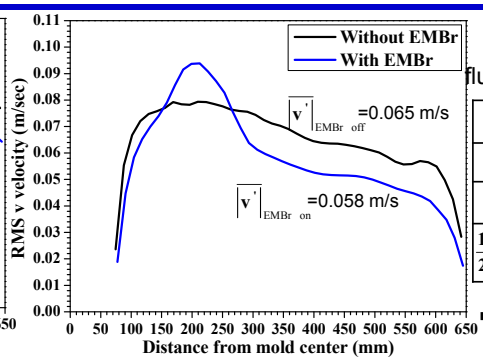


EMBr on

Velocity Fluctuations & Turbulent Kinetic Energy at the Surface (Two-phase Flow)



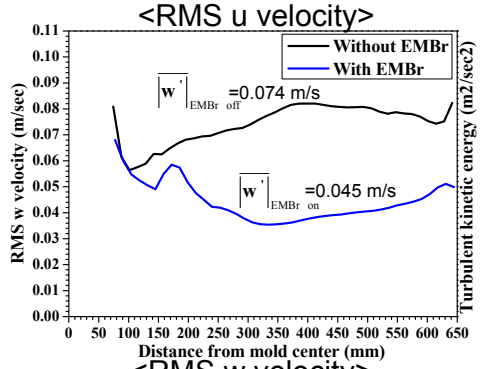
<RMS u velocity>



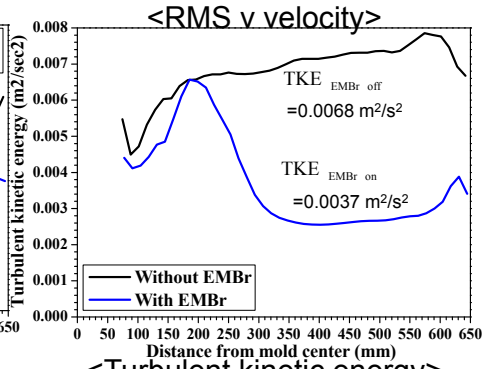
<RMS v velocity>

Reduction in Velocity fluctuations & TKE by EMBr

$\overline{\lvert u' \rvert}$	33.7 %
$\overline{\lvert v' \rvert}$	10.8 %
$\overline{\lvert w' \rvert}$	39.9 %
$\frac{1}{2}\left(\overline{\lvert u' \rvert}^2 + \overline{\lvert v' \rvert}^2 + \overline{\lvert w' \rvert}^2\right)$	45.6 %



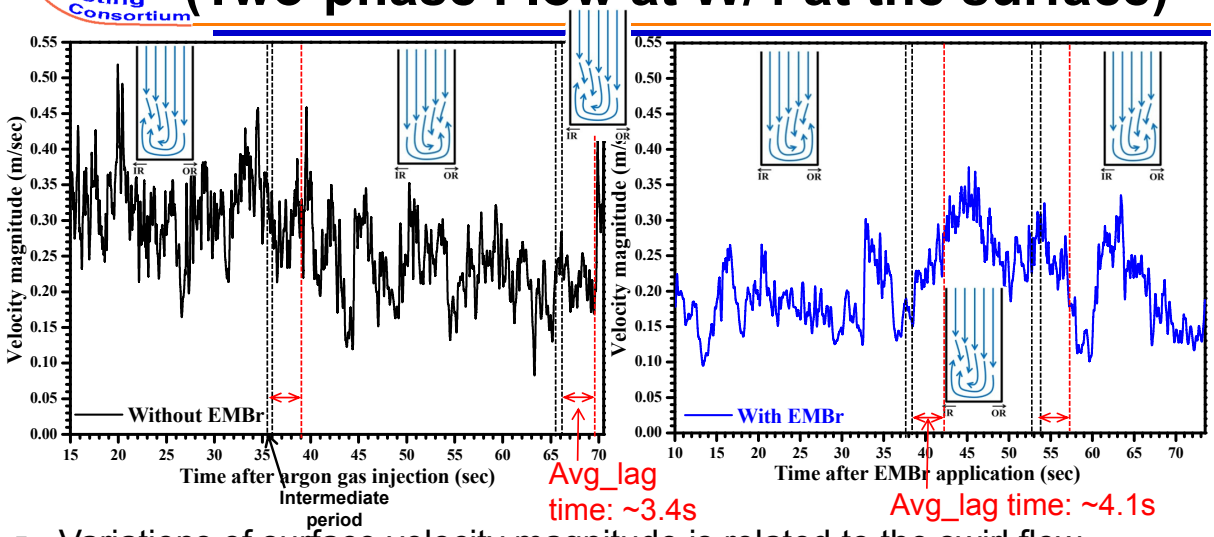
<RMS w velocity>



<Turbulent kinetic energy>

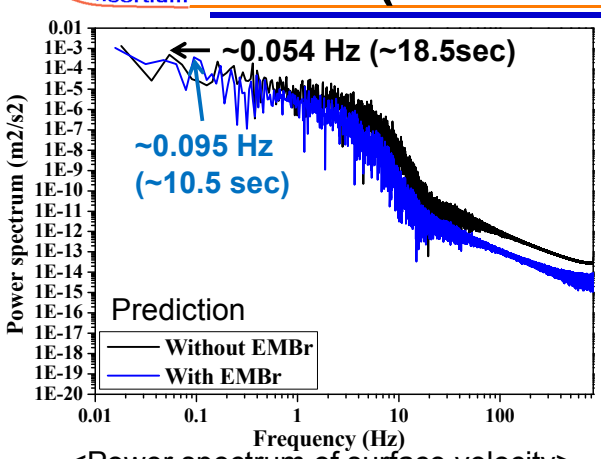
- EMBr mainly reduces surface velocity fluctuations along mold thickness (between IR and OR) and casting direction; the swirl flow variations produced by slide-gate can be controlled by the EMBr

Surface Velocity Histories (Two-phase Flow at W/4 at the surface)

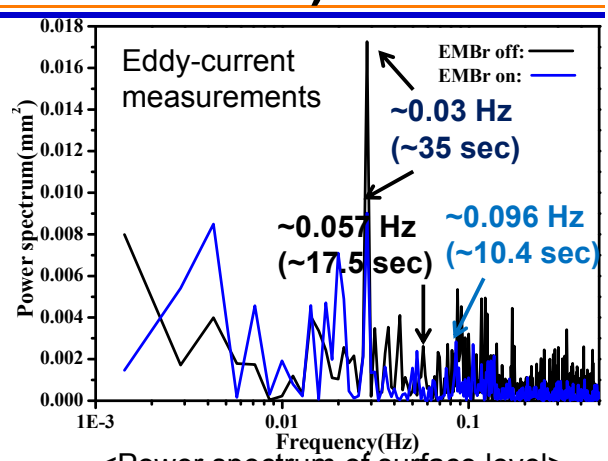


- Variations of surface velocity magnitude is related to the swirl flow direction in the nozzle bottom with slide-gate
- Clockwise swirl induces high momentum jet flow, resulting in high surface velocity after lag time (without EMBr: ~3.4s(avg), with EMBr: ~4.1s(avg)). On the other hand, counter clockwise swirl produces lower surface velocity

Frequency Analysis at the Surface (W/4 at the surface)



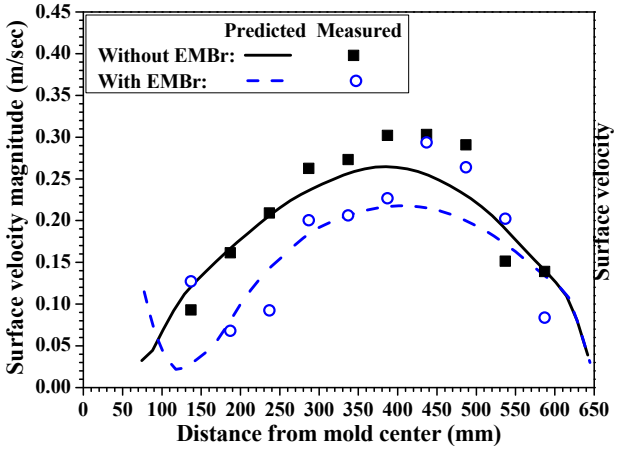
<Power spectrum of surface velocity>



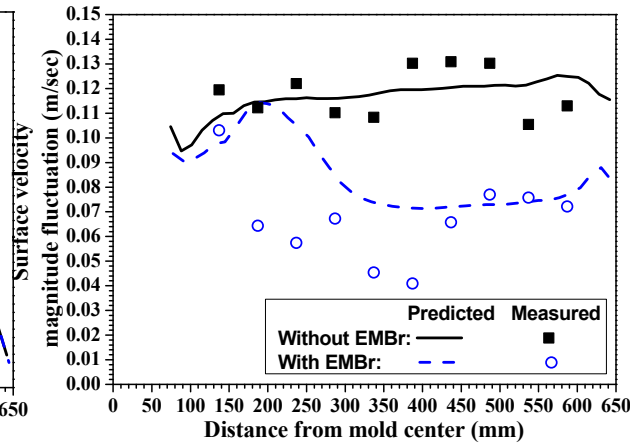
<Power spectrum of surface level>

- The characteristic frequencies (EMBr off: ~0.054 Hz, EMBr on: ~0.095 Hz) of surface velocity seem to produce similar peaks as the measured surface level fluctuations
- The strong maximum peak (~0.03 Hz) at the surface, both with and without EMBr, might be produced by low frequency sloshing between right and left narrow face; the half model of LES fails to capture low peak (≤0.03 Hz) OR this peak would be shown by longer flow time (over 70 s)

Model Validation with Nail Board Tests: Surface Velocity



<Surface velocity magnitude>



<Surface velocity fluctuation>

- The predicted surface velocity magnitude and its fluctuation profiles show remarkable agreement with measurements for both EMBr off and on case
- With EMBr, surface flow is slightly slower (by ~17 %) with **smaller fluctuations (by ~43 %)**
- This finding suggests that use of the double-ruler EMBr may help to reduce defects caused by **surface flow instability**.

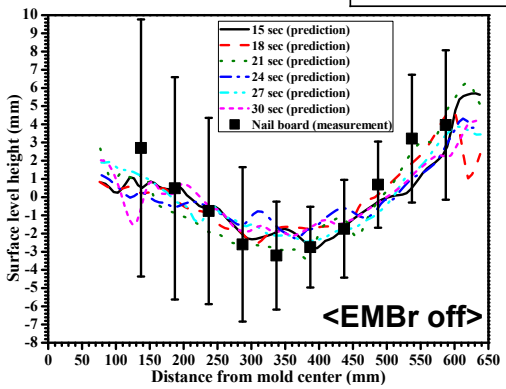
Model Validation with Nail Board Tests: Surface Level

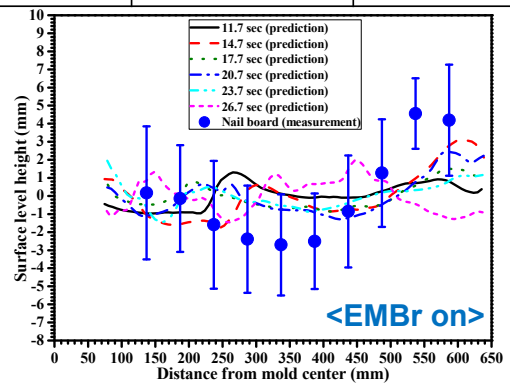
New Semi-empirical equation to relate pressure to surface level:

$$H_i = \frac{P_i - P_{avg}}{(\rho_{steel} - (1-k)\rho_{slag})g}$$

<Coefficient (k) of slag motion at the surface regions with and without EMBr>

	Region 1 (near SEN: 0~235mm)	Region 2 (midway: 235~485mm)	Region 3 (near NF: 485~650 mm)
Without EMBr	0.85	0.74	0.82
With EMBr	0.97	0.63	0.65

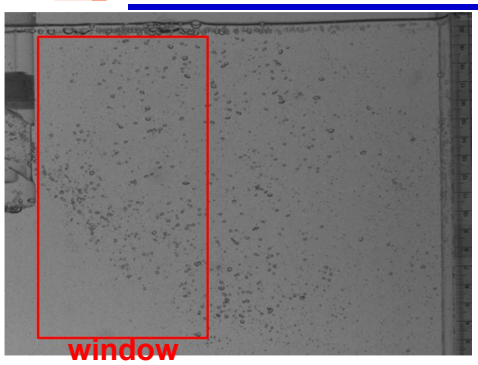




- The improved pressure-based surface level prediction agrees with measured surface level profiles with and without EMBr
- Predictions are less accurate near SEN without EMBr; perhaps due to low frequency and high amplitude wave motion near SEN
- The model might benefit from true free-surface analysis, instead of simple surface-pressure method

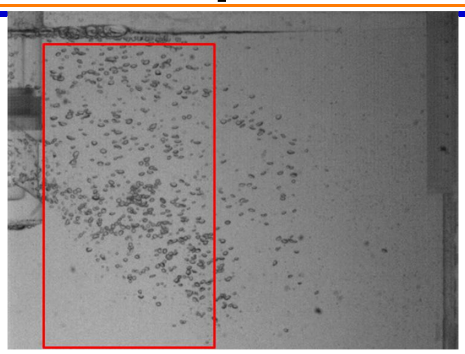
Bubbles Distribution in the Mold (1/3 Scale Water Model Experiment)

Volume fraction: **0.6 %**



<35.0 LPM (Water)_**0.2** SLPM (Air)>

Volume fraction: **2.4 %**



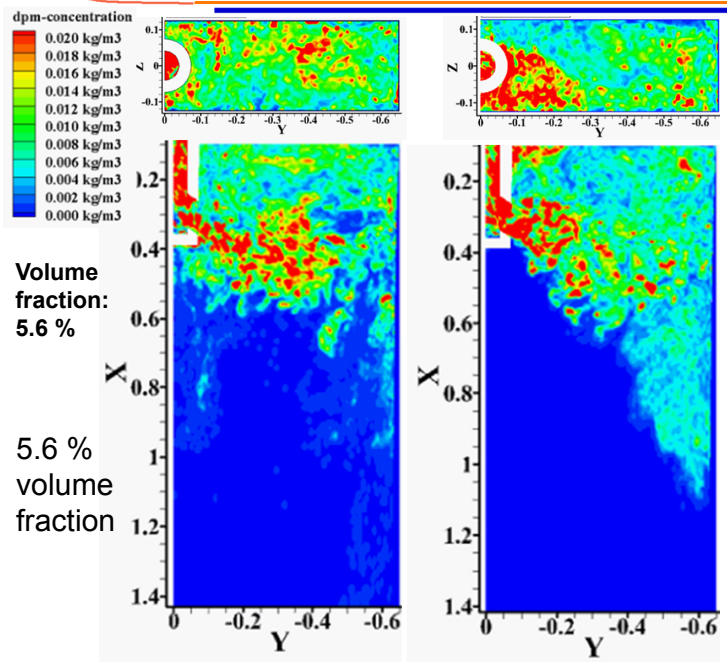
<35.0 LPM (Water)_**0.8** SLPM (Argon)>

Volume fraction: **4.6 %**

<35.0 LPM (Water)_**1.6** SLPM (Argon)>

- With higher gas flow rate, bubbles in the mold are larger
- With small gas flow rate, bubbles are carried throughout larger mold region; (because they are small), causing more chance to touch the NF
- With high gas flow rate, most bubbles float to the surface near the SEN (because the flow cannot carry bigger bubbles as easily), so less are found near the NF

Effect of EMBr on Argon Bubble Distribution in the Mold



Volume fraction: 5.6 %

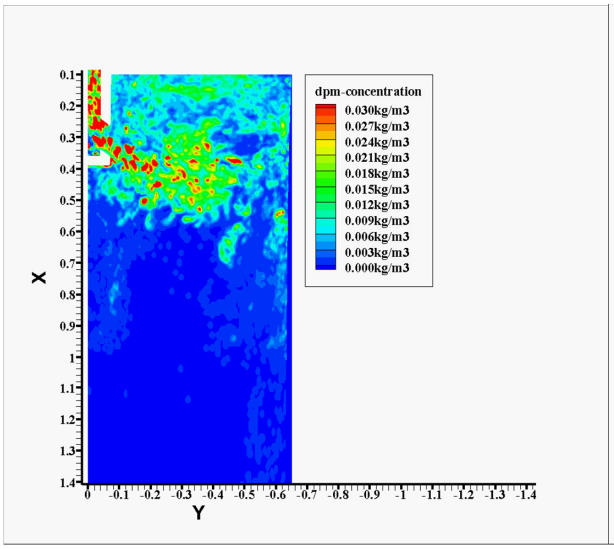
5.6 % volume fraction

<EMBr off> **<EMBr on>**

- Transient gas distribution changes (agrees with measured) are induced by jet flow wobbling.
- Most bubbles found in upper recirculation region; this trend agrees with the water model measurement
- Predicted bubble spreading across top region (differing from measurement) might be due to incorrect assumption of constant bubble size (1mm) vs. (1-5mm with 2.5mm mean)
- With EMBr, more argon bubbles float up to the surface near the SEN wall. In the region 600~1200 mm from the mold top, many bubbles have longer residence time near NF.

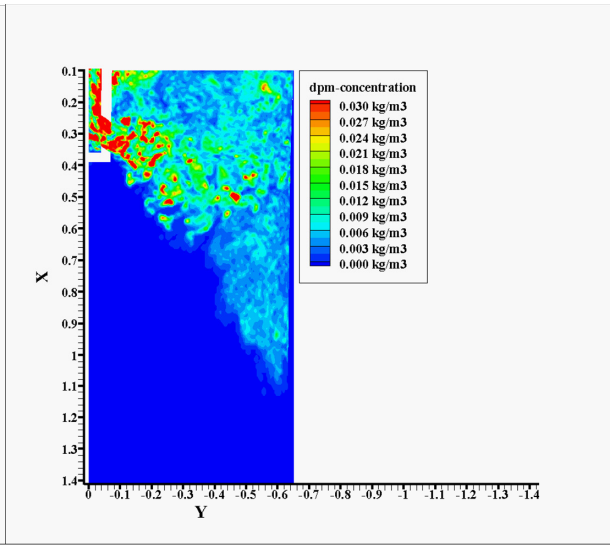
Argon Gas Distribution Videos

Real flow time ~55.2 s



EMBr off

Real flow time ~62.8 s



EMBr on

Summary: Modeling

- LES coupled with DPM and MHD model is used to predict transient molten steel-argon flow in slide-gate nozzle and mold with and without EMBr, and the model is validated with nail board tests and eddy-current sensor measurements showing remarkable agreements.
- Steady-standard $k-\varepsilon$ model well-predicts isotropic variations, however, shows limited accuracy for anisotropic variations, especially produced by swirl flow near nozzle port
- Predicted surface velocity magnitude and its fluctuation profiles show remarkable agreement with the measurements for both EMBr off and on case
- The improved pressure-based surface level prediction (new semi-empirical equation to relate pressure to surface level) agrees with measured surface level profiles with and without EMBr
- Half model of LES predicts the characteristic frequencies of surface velocity fluctuations, which seem to produce similar peaks as the measured surface level fluctuations. The measured strong peak (~0.03 Hz) by an eddy-current sensor at the surface, both with and without EMBr, might be produced by low frequency sloshing between right and left narrow face; the model fails to capture the low peak (0.03 Hz) OR this peak would be shown by longer flow time (over 70 s)
- LES coupled with DPM shows reasonable match with water model measurements of argon bubble distribution
- For better prediction of bubble distribution in the mold, bubble size distribution is needed to be implemented to transient two-phase flow model

Summary: Swirl Flow and Its Effect

- Slide-gate induces swirl flow in nozzle bottom region with clockwise, counter-clockwise, and intermediate directions. EMBr makes the flow (from asymmetric open area in middle plate to nozzle bottom) go down by longer path with imposing electromagnetic force, resulting in longer period of the counter-clockwise flow
- Swirl flow induces jet wobbling showing high jet flow angle fluctuations (vertical and horizontal angle) in the mold. Both angle fluctuations with EMBr are decreased.
- EMBr decreases jet wobbling, reducing flow variations produced by slide-gate, including variations in thickness direction in both jet & top surface, and along NF (in casting direction)
- **Clockwise swirl** induces high momentum jet flow, resulting in **high surface velocity** after lag time for the jet flow to move toward to surface. On the other hand, counter clockwise swirl produces lower surface velocity
- Transient gas distribution changes are induced by jet flow wobbling.
- With higher gas flow rate, bubbles in the mold are larger and most bubbles float to the surface near the SEN (because the flow cannot carry bigger bubbles as easily), so less are found near the NF
- With small gas flow rate, bubbles are carried throughout larger mold region; (because they are small), causing more chance to touch the NF
- Most bubbles found in upper recirculation region with and without EMBr
- With EMBr, more argon bubbles float up to the surface near the SEN wall. In the region 600~1200 mm from the mold top, many bubbles have longer residence time near NF. This phenomena may induces more chances for small bubbles to be entrapped by solidifying steel shell (13.5~19.1 mm below slab surface).

Acknowledgments

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