COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

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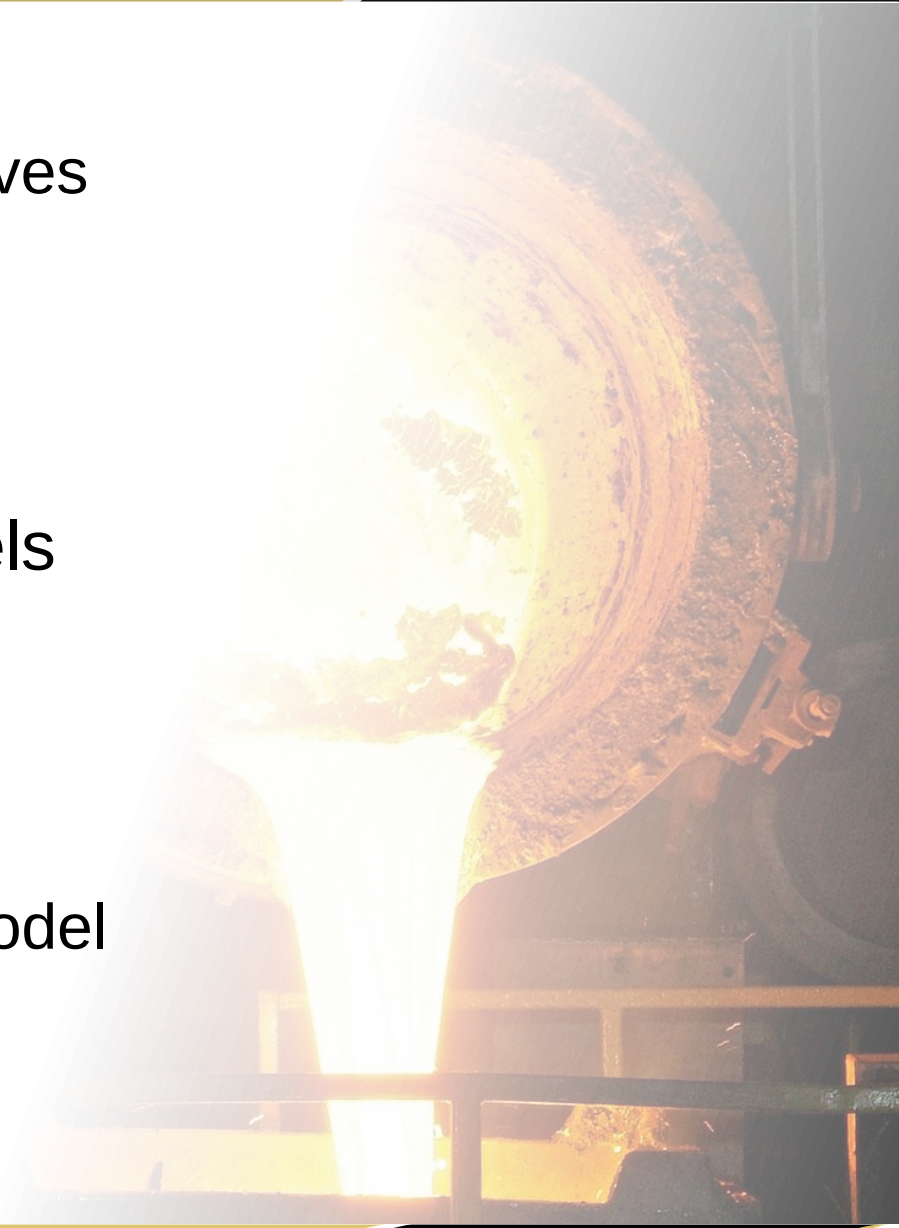
"Where Ideas Become Reality"

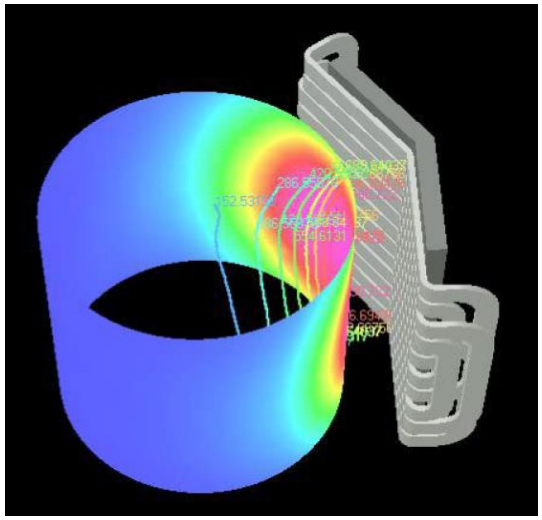
Presentation Outline

- Introduction
  - Project Motivation & Objectives
  - Ladle Subprojects
  - Research Outcomes
  - Project Timeline - 2019
- Methodology and CFD Models
- Results
  - Inclusion Removal Model
  - EMS Model
  - Ladle Chemical Reaction Model
- Summary
- Future work



Research Motivation

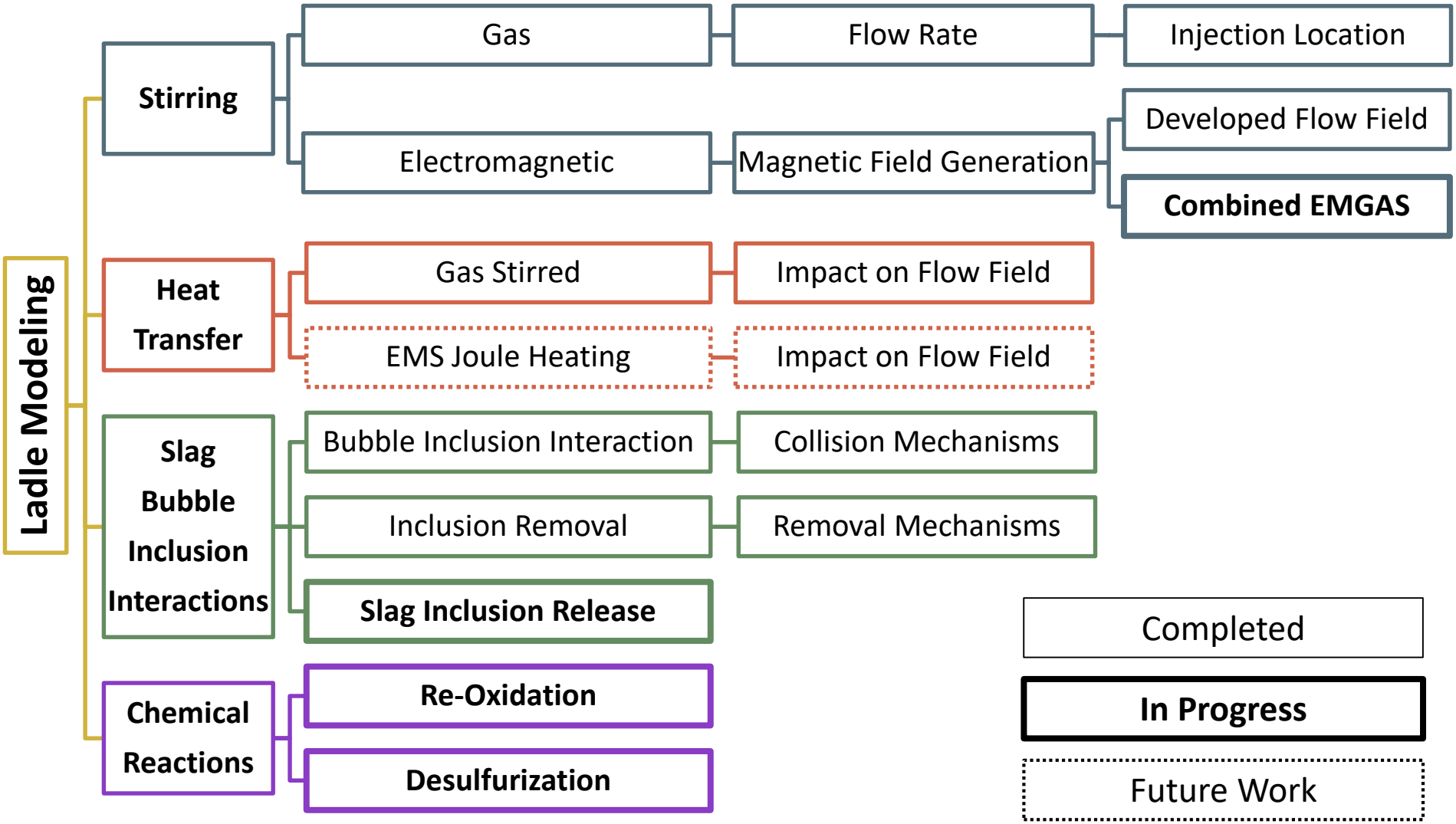
- **Current Issues**
  - Difficulty in understanding the dynamic evolution of multiphase flow and inclusions
    - Inclusions directly impact steel cleanliness
    - Ladle lifetime – wall shear stress
    - Different stirring methods (Gas & EMS)
  - Need cost-effective tool to guide ladle design and refining conditions
- **Potential Impacts**
  - Increased productivity through improved operating conditions
  - Steel cleanliness improvement and final defects reduction



Research Objectives

- **Long-term Objectives (5+ Years):**
  - Develop a validated comprehensive multiphase CFD model of a steel ladle using two stirring methods (Gas stirring & EMS)
  - Optimize ladle stirring conditions for steel cleanliness, productivity, and equipment lifetime
- **Current Objectives – 2019:**
  - **Investigation of Inclusion Removal in Gas-stirred & EMS Ladle**
    - Impacts of bubble-inclusion interaction and inclusion growth on overall inclusion removal
    - Impacts of electromagnetic stirring strength on flow field, slag eye formation, and wall shear stress
  - **Investigation of Chemical Reactions in Steel Ladle Refining**
    - *Development of kinetics for re-oxidation model*
    - *Development of kinetics for de-sulfurization model*
    - Optimize stirring conditions to minimize oxidation and heat losses while improving inclusion removal and desulfurization

Ladle Project Roadmap



Projects

	Projects	2016	2017	2018	2019	2020
1	Isothermal gas-stirring ladle model					
2	Heat transfer model					
3	Gas-stirred isothermal inclusion removal					
4	EMS isothermal inclusion removal					
5	Ladle chemical reaction					
6	Heat transfer effect on inclusion removal					

Outcomes & Deliverables

Projects (2016 – 2019): Completed: 3, Ongoing: 2

- **Project #1 (2016 – 2017):** Isothermal Gas-stirred Ladle Flow Simulation – Nucor Decatur Ladle
  - Validated CFD predictions of flow field and slag eye size against measurements (avg slag eye size error: **8.7%**)
  - Evaluated Nucor Ladle scenarios:
    - Increasing plug distance ratio by **10% of ladle diameter** (0.1D) **decreased** mixing time by **24 seconds (18% decrease)**
    - At 0.6D plug distance ratio, a **60º** plug separation angle yields **25% faster** mixing versus **180º** and **44% faster** than **120º**
- **Project #2 (2017):** Heat Transfer Effect in Gas-stirred Ladle – Nucor Decatur Ladle
  - CFD predictions of steel temperature align with literature[1]
  - Investigated effects of initial wall temperature on steel temperature stratification:
    - Temperature stratification decreases faster with higher wall initial temperature, **29% faster** (71 seconds versus 99 seconds)

[1]J. L. Xia and T. Ahokainen, "Thermal stratification in a steel ladle." Canadian metallurgical quarterly 40.4 (2001): 479-487.

Outcomes & Deliverables

Projects (2016 – 2019): Completed: 3, Ongoing: 2

- **Project #3 (2018 – 2019):** Gas-Stirred Isothermal Inclusion Growth and Removal – Generic Ladle
  - Developed inclusion growth and removal model to predict inclusion removal efficiency based on design and conditions
  - Investigated effects of plug separation angle:
    - Increasing plug separation angle from **90° to 180°** improved inclusion removal efficiency by **5%**
- **Project #4 (2019):** EMS Isothermal Flow, Inclusion Growth and Removal
  - Developed EMS transient multiphase flow model
  - Investigated impacts of taper angle on bulk velocity and slag-eye size
    - 5° taper angle **decreases bulk vel. and slag eye size by 13%** relative to 0°
  - Investigated wall shear stress in EMS ladle

Timeline for 2019

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Project 3 Improvement of Inclusion Removal Model	Improve Current Bubble Model												
	Add Buoyancy Collision Efficiency												
	Validate Improved Inclusion Removal Model												
	Modified Bubble Model Applied in Generic Model												
Project 4 Isothermal EMS Inclusion Removal	EMS Multiphase Model												
	Add of Inclusions to EMS Multiphase Model												
	Combined Gas-Stirring and EMS												
Project 5 Develop Chemical Reaction Model	Literature Research												
	Basic Model Development and validate												
	Chemical Reaction Model Applied in Generic Model												

Results Since Semi-Annual Meeting

in April 2019

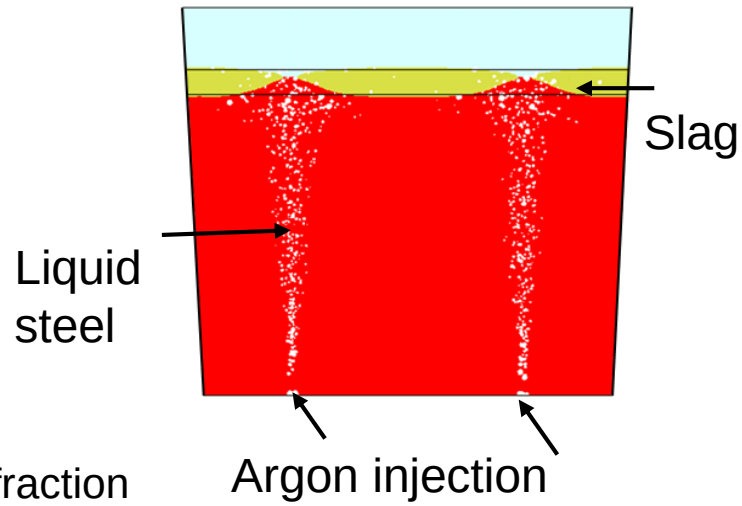
Project 3:
GAS-STIRRED LADLE MODEL WITH INCLUSION

- Validation with Lou et al.'s ladle inclusion removal
- Generic ladle inclusion removal

Methodology & CFD Models

Gas-stirring ladle model

- Fluid zones (slag, melt, inclusion and air)
  - Eulerian-Lagrange multiphase flow
  - Realizable k-epsilon turbulent model
- Argon injection
  - Discrete phase model (DPM)



1) Import quasi-steady velocity ($u_{x,y,z}$), volume fraction (α_{phase}), turbulence k & ε (for slag, steel and air)
2) Apply steel $u_{x,y,z}$, k & ε into inclusion phase

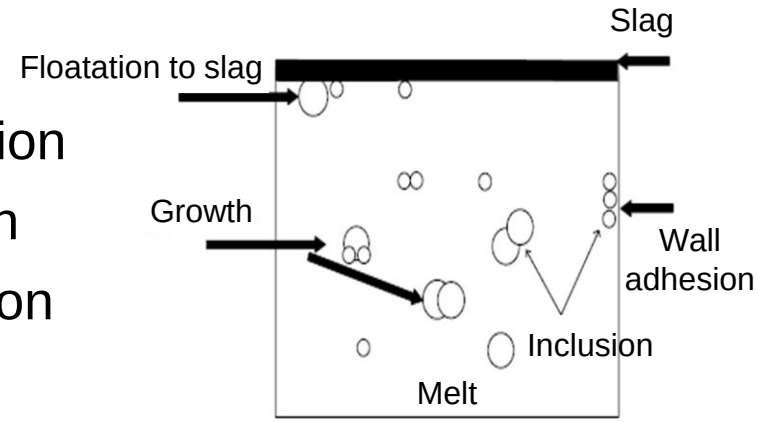
Inclusion removal and growth model

- **Inclusion removal and growth**
  - Population balance model (PBM) – continuum method
  - **Transport by bubble, removal by slag and wall**

Inclusion Growth and Removal Model

Inclusion removal behavior

Inclusion growth
- Turbulent random collision
- Turbulent shear collision
- Stokes buoyancy collision



Inclusion removal
- Slag
  - Inclusions flow motion and flotation.
- Wall
  - Inclusion attachment to refractory
- Bubble
  - Buoyancy collision
  - Turbulent random collision
  - Turbulent shear collision
  - Bubble wake capture

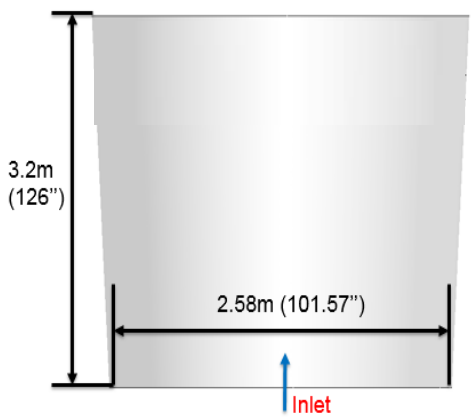
  } Inclusion transport to slag

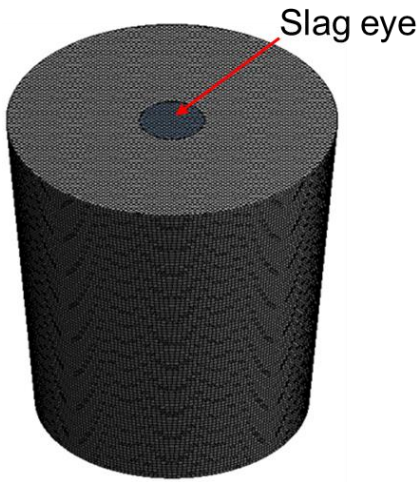
- Lou, Wentao, and M. Zhu. "Numerical Simulations of Inclusion Behavior in Gas-Stirred Ladles." Metallurgical & Materials Transactions B Process Metallurgy & Materials Processing Science 44.3(2013):762-782.
- Cao, Qing, and L. Nastac. "Numerical modelling of the transport and removal of inclusions in an industrial gas-stirred ladle.".

Inclusion Model Validation

- Work by Lou et al. (2013)
  - 150-ton ladle
  - Flow rate: 200NL/min (7.45 SCFM)
  - Bubble size: 4mm (constant)
  - CFD-PBM coupled method, Eulerian-Eulerian multiphase model
  - Isothermal condition and top flat free surface (no slag)
  - Slag eye size: 0.316 m^2

Lou et al. (2013)





Parameters	Lou et al. (2013)
Diameter of ladle	2.58 m
Height of ladle	3.2 m
Number of plugs	1
Inclusion size	4~200 μm
Group of inclusion	18

- Lou, et al. "Numerical Simulations of Inclusion Behavior in Gas-Stirred Ladles." *Metallurgical & Materials Transactions B* 44.3(2013):762-782.

Inclusion Removal Validation

	Slag	Wall	Bubble	Total Inclusions Removed	Approximate rate with inclusion release	Inclusion Release Results Lou et al.
SMSVC Ladle	1.87%	0.001%	96.72%	98.61%	69.53%	68.16%

Rupture at slag	Rupture at slag eye
70.24%	29.76%

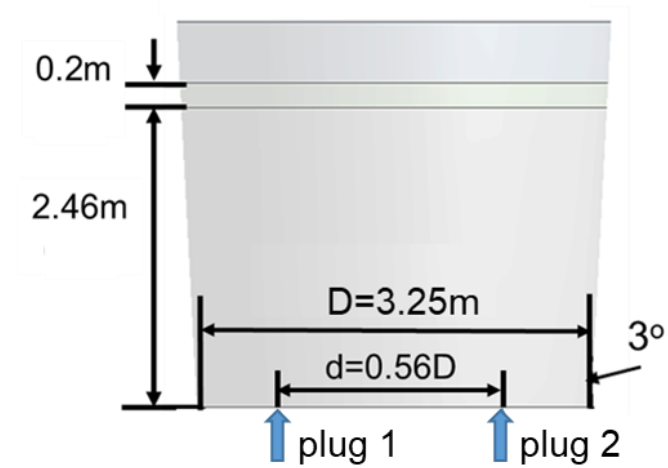
- Note: Based on Bubble mass

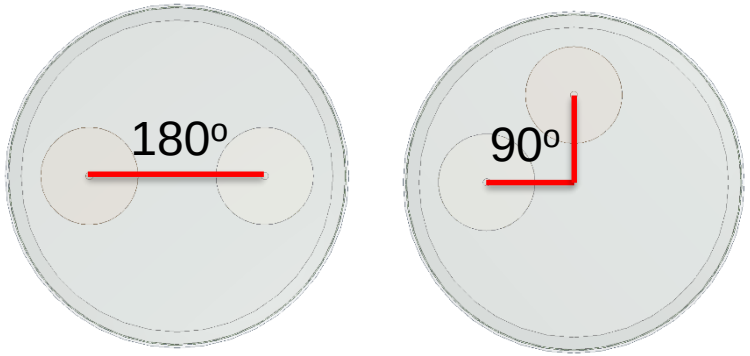
- Bubble attachment mechanism is shown to be the most dominant removal mechanism
- Inclusions carried by bubbles which reach and rupture at slag eye will be released back to steel.
  - Current model does not factor inclusion release at slag eye, resulting in overprediction of inclusion removal rate.
- Assumption: when a bubble ruptures at slag eye, 100% of bubble-captured inclusions will release into steel
  - 29.76% of bubbles breakup at the slag eye area, therefore all inclusions captured by these bubbles are assumed to be released back into the steel
  - Overall removal rate will drop from 98.61% to 69.53%

Generic Ladle Geometry

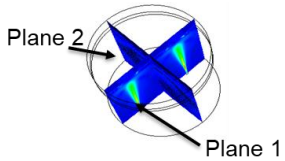
- Generic model based on Nucor Decatur ladle
- Effect of plug separation angle and gas flow rate on inclusion removal will be studied

Case	Plug separation angle	Gas flow rate	Slag eye diameter
Case 1 (Base)	180°	5/5 SCFM	0 m
Case 2	90°	5/5 SCFM	0 m
Case 3	90°	5/20 SCFM	0.64 m (x1)
Case 4	90°	20/20 SCFM	0.62 m (x2)

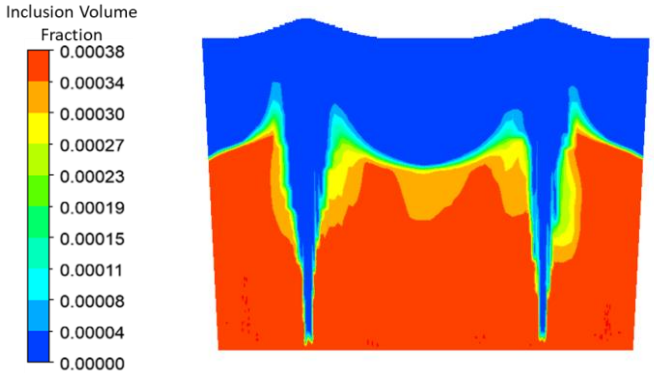




Inclusion Volume Fraction (Base Case)



Plug cross sectional plane (Plane 1)



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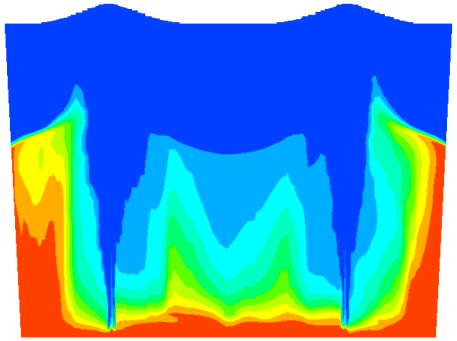

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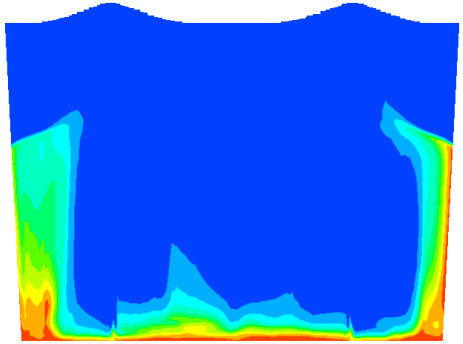

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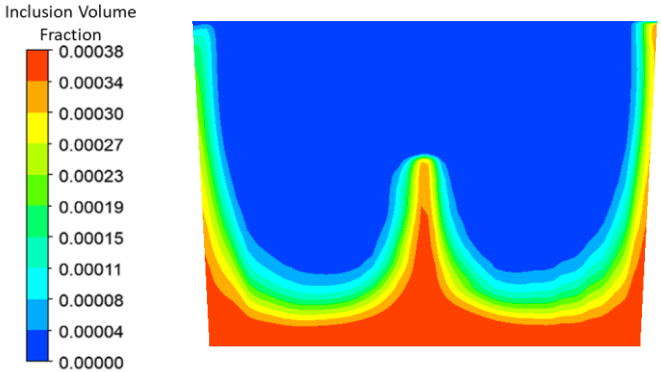
Center plane (Plane 2)



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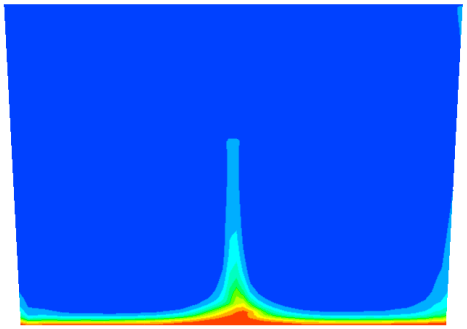

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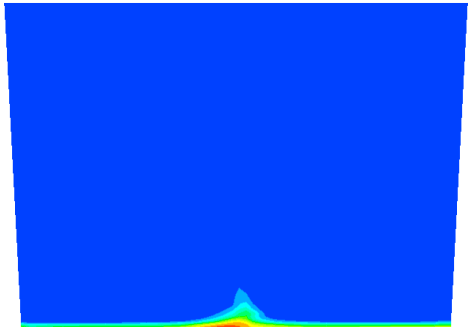


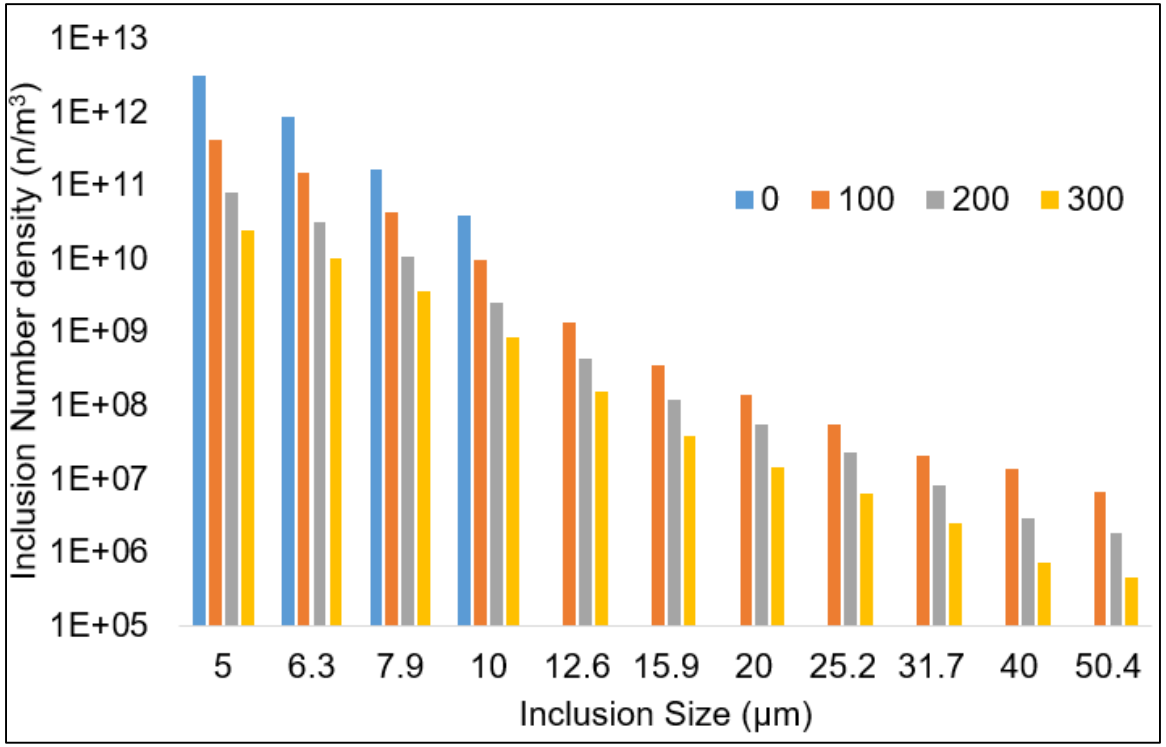
300 s

Inclusion Size Distribution (Base Case)

- Initial distribution can be calculated: (Lou et al., 2013)

$$n(d_i)_{\ t=0} = 2 \times 10^{14} e^{-d_i \times 10^6}$$

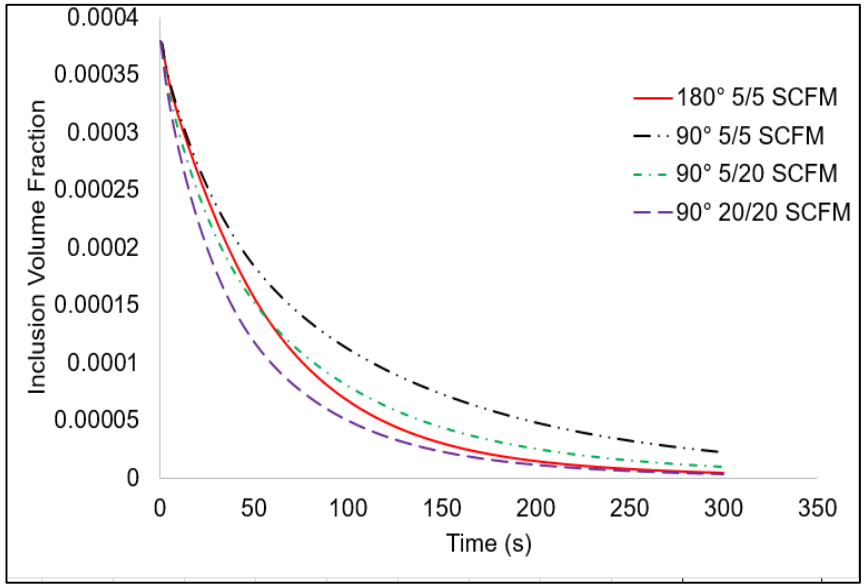
- All size inclusion being removed over time
- From 0s to 300s, smaller sizes remain dominant population



- Lou et al. "Numerical Simulations of Inclusion Behavior in Gas-Stirred Ladles." *Metallurgical & Materials Transactions B* 44.3(2013):762-782.

Effects of Plug Position and Flow Rate

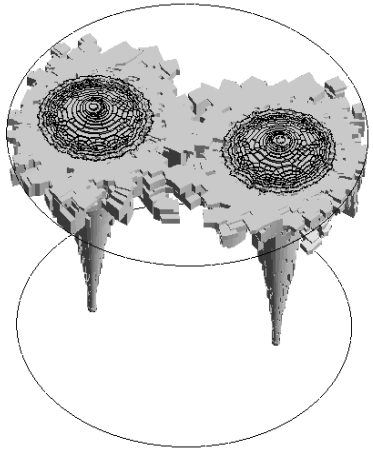
- Removal rates for 90° 5/20 and 20/20 cases were adjusted based on bubble rupture at slag eye assumption
- For the same gas flow rate, separation angle of 180º shows better overall inclusion removal
- For the same plug separation angle, increased flow rate will decrease inclusion removal rate as slag eye appears
- Turbulence dissipation rate (ε) corresponds to improved inclusion removal (without slag eye)



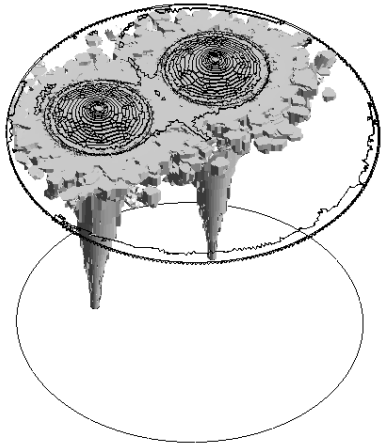
Case	180º 5/5	90º 5/5	90º 5/20	90º 20/20
% bubble rupture at slag eye	0%	0%	11.12%	9.55%
Removal Rate	98.8%	94.1%	86.8%*	89.7%*
ε (m^2/s^3)	0.0075	0.0072	0.0213	0.0353

* After slag eye inclusion re-release adjustment

Effects of Plug Position and Flow Rate

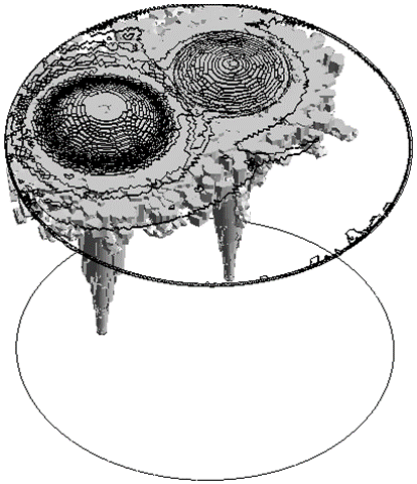


- 180° 5/5

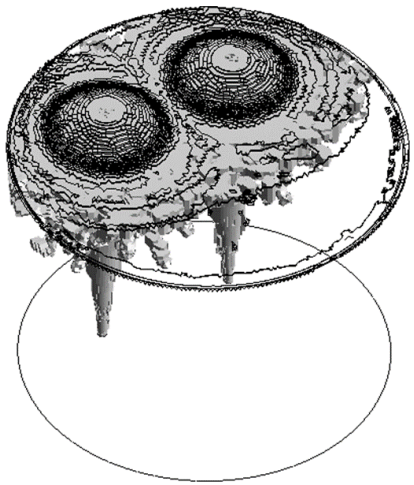


- 90° 5/5

Case	180° 5/5	90° 5/5	90° 5/20	90° 20/20
Removed by bubble	95.2%	86.4%	83.1%	87.5%
Removal Rate	98.8%	94.1%	86.8%*	89.7%*
Plume Vol. (m^3)	2.05	2.03	2.56	3.03



- 90° 5/20



- 90° 20/20

- Larger bubble plume leads to higher removal rate
  - Inclusions are more likely to interact and be attached to bubbles

Project 4:
EMS LADLE MODEL

Numerical Models

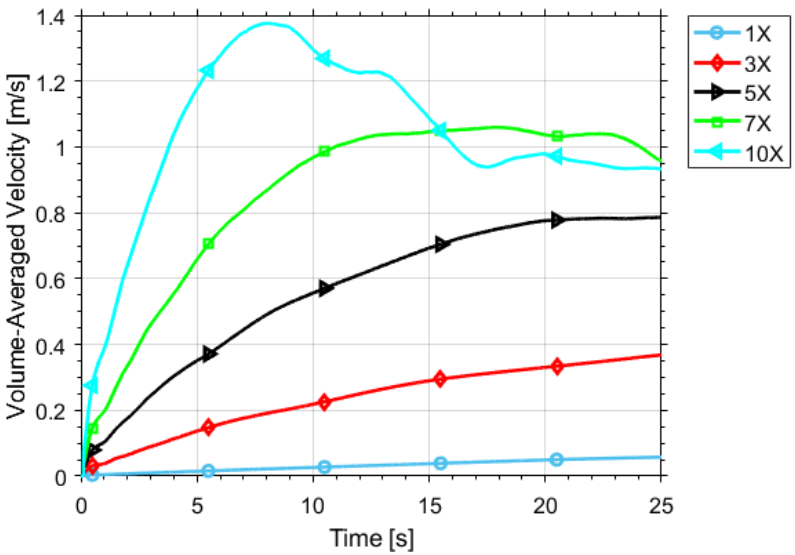
- **Magnetic Field Model** (ANSYS Maxwell FEM)
  - Fluid domain: Single phase (vacuum or steel)
  - Alternating current: $I = I_o \cos(2\pi f t + \phi_s)$
  - Traveling magnetic field: $\phi_s = \frac{180°}{\text{Number of Coils}}$
    - Magnetic field magnitude: deciTesla range
      - Amperage: 800-1500 [A]
- **Fluid Flow Model** (ANSYS Fluent CFD)
  - Three-dimensional
  - Transient ($\Delta t = 0.01$s)
  - Isothermal
  - Multiphase VOF (Steel, Slag, Air)
  - k-ϵ turbulence model
  - MHD Solver: ANSYS Fluent MHD module

[17] V. Fireteanu Etienne Rousset. Simultaneous induction heating and electromagnetic stirring of a molten glass bath. 10 2015.

MHD Module Scaling Factor

- Scaling factor:
  - Gradually increases the MHD effect to its actual magnitude through a series of restarts by scaling the external magnetic field
  - Used to **calibrate** the magnetic field generated to properly implement the MHD effects within the known flow time
  - Highly dependent on the strength of the magnetic field

- Viscous resistance limits liquid metal bulk velocity due to MHD to around 1 [m/s]



B_o Magnitude	Scaling	CFD	Literature
DeciTelsa	5	0.72 m/s	0.72 m/s
MilliTelsa	30	4.5 cm/s	4.3 cm/s

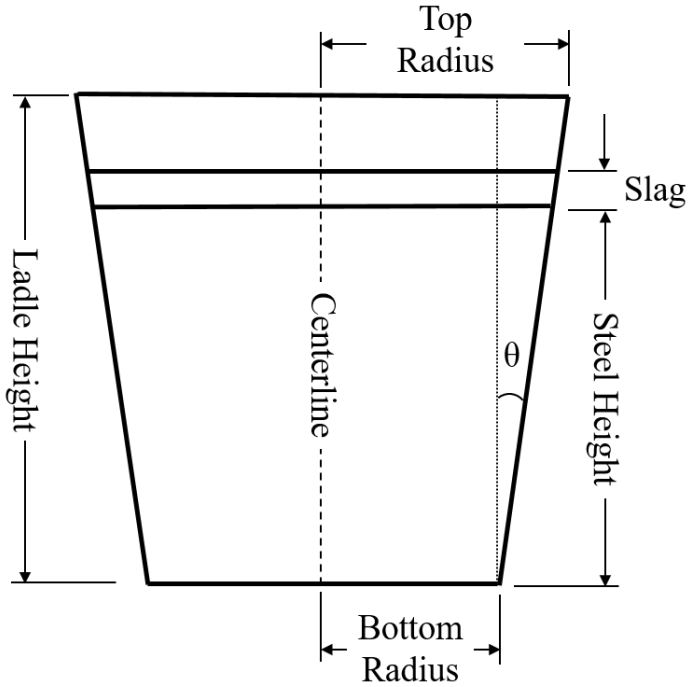
[18] U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, "Numerical and Experimental Study on Fluid Dynamic Features of Combined Gas and Electromagnetic Stirring in Ladle Furnace." 2009

Ladle Geometry & LF-EMS Unit

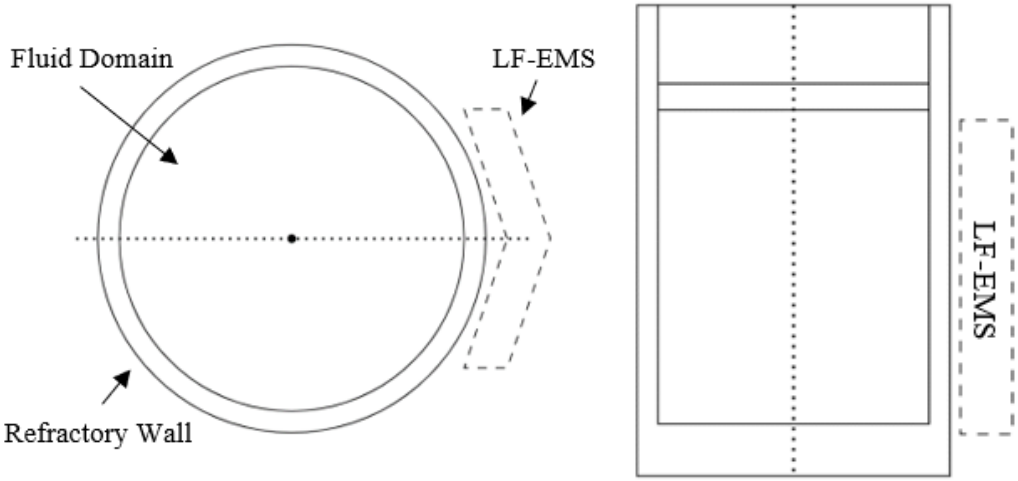
- Two simplified ladle geometries:
  - Case I: Cylindrical ladle (Sand et al., 2019)
  - Case II: Nucor Decatur ladle

Ladle Parameters	Case I	Case II
Top Radius [m]	1.425	1.79
Bottom Radius [m]	1.425	1.62
Steel Height [m]	2.80	2.46
Slag Thickness [m]	0.1	0.15
Taper Angle [deg]	0	3
Steel Tonnage [Tonne]	128.6	157.1

Generic Ladle



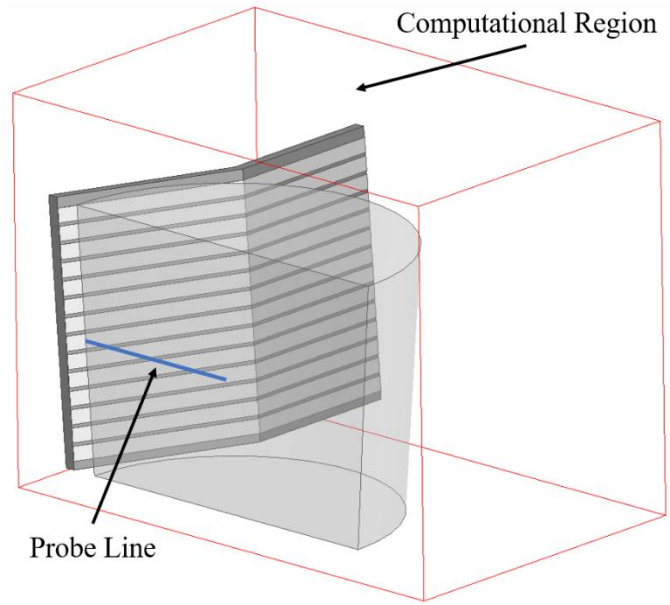
LF-EMS Unit Position

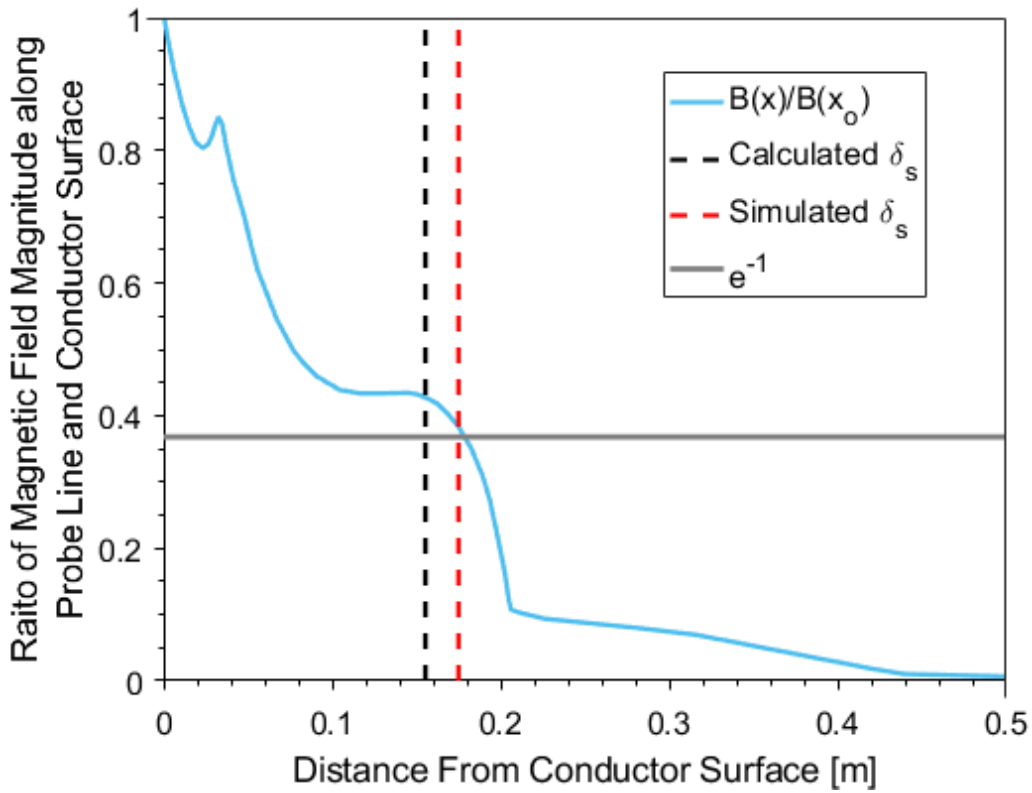


[19] U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, "Numerical and Experimental Study on Fluid Dynamic Features of Combined Gas and Electromagnetic Stirring in Ladle Furnace." 2009

Effective Stirring Region

- ***Skin depth*** measures how well a electromagnetic field can penetrate a conductive medium given by $\delta_S = 1/\sqrt{\pi f \sigma \mu}$





- Calculated δ_S: 0.155 [m]
- Simulated δ_S: 0.174 [m]
- Percent difference: 12%
- Absolute difference: **0.019 [m]**

[20] F.T. Ulaby. Electromagnetics for Engineers.

Mesh Sensitivity Study

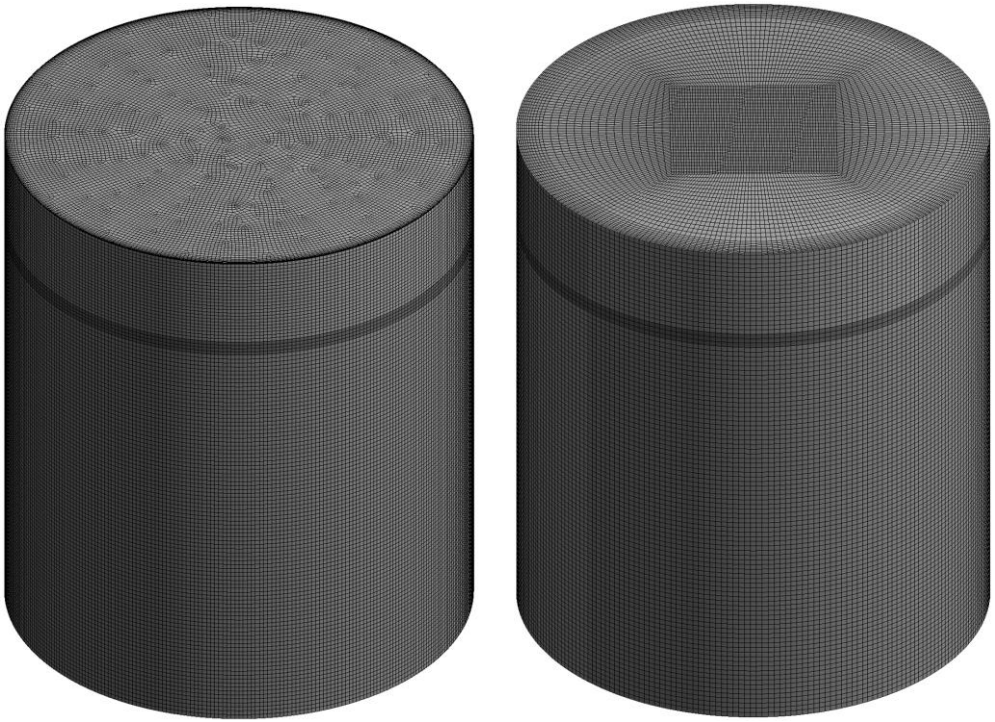
- Three fluid domain grids were compared with an amperage of 1500 [A]
- M3 is with *skin depth* refinement

Mesh	M1	M2	M3
Element Count	1.6E6	9.57E5	1.1E6
Min. Quality	0.128	0.553	0.479

Bulk Velocity for Each Mesh

Mesh	15s	20s	25s	% Diff. M3
M1	0.69	0.74	0.77	2.4%
M2	0.71	0.80	0.82	4.3%
M3	0.69	0.78	0.79	-

- M3 was selected for its balance of cell quality and density along with the refinement criterion



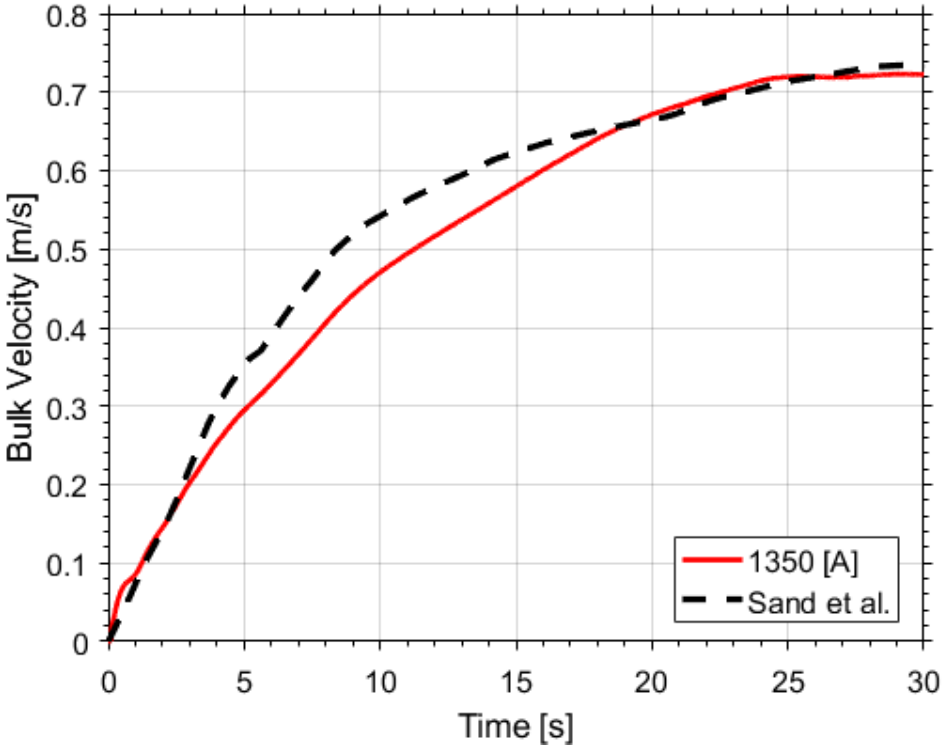
M1 **M3 (skin depth refinement)**

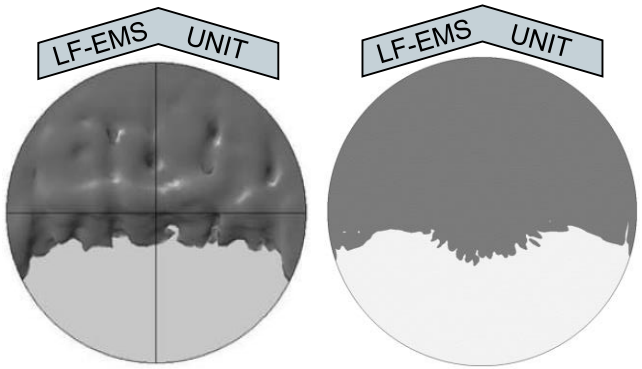
[21] M. Javurek, M. Barna, P. Gittler, K. Rockenschaub, and M. Lechner, "Casting and solidification flow modelling in continuous casting of round bloom strands with electromagnetic stirring," Steel Research International, vol. 79, 08 2008.

Validation

- Sand et al. (2009) used a Lorentz force distribution paired with:
  - Semi-empirical force: $F_z = F_{o,z}\left(1 - \frac{w}{2v\tau}\right)$

Study	10s	15s	20s	25s	Abs. Diff.	% Diff.
Sand et al.	0.54	0.62	0.66	0.714	-	-
SMSVC	0.48	0.60	0.67	0.719	0.006	0.83%



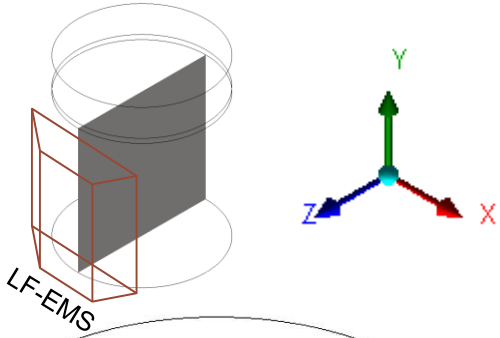


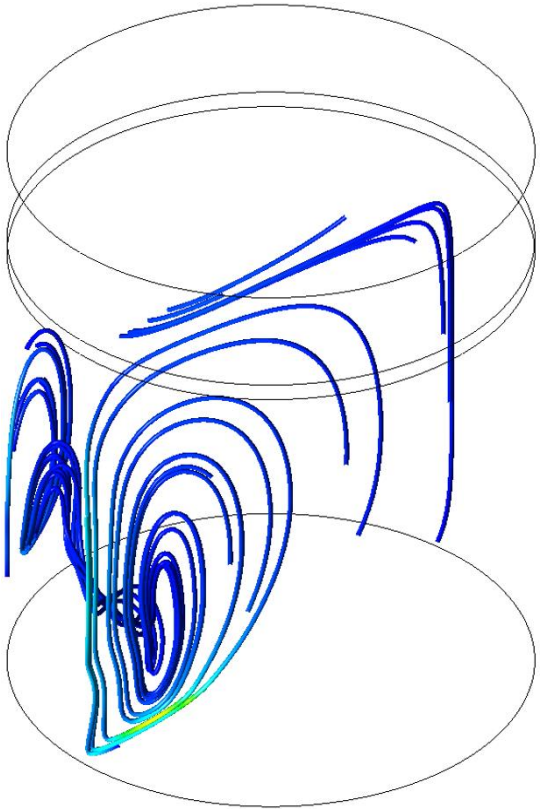
Sand et al. **SMSVC**

25s	Eye [m²]	Abs. Diff.	% Diff.
Sand et al.	1.55	0.39	25%
SMSVC	1.94		

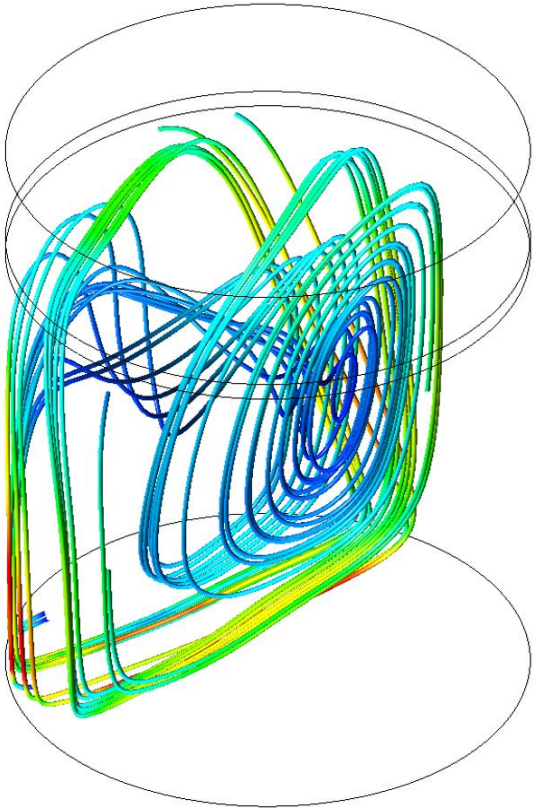
Case I – Vortex Development

- Vortex begins at wall closet to LF-EMS unit
- Vortex arms spread out toward to side walls
- Vortex is symmetric about zy-plane

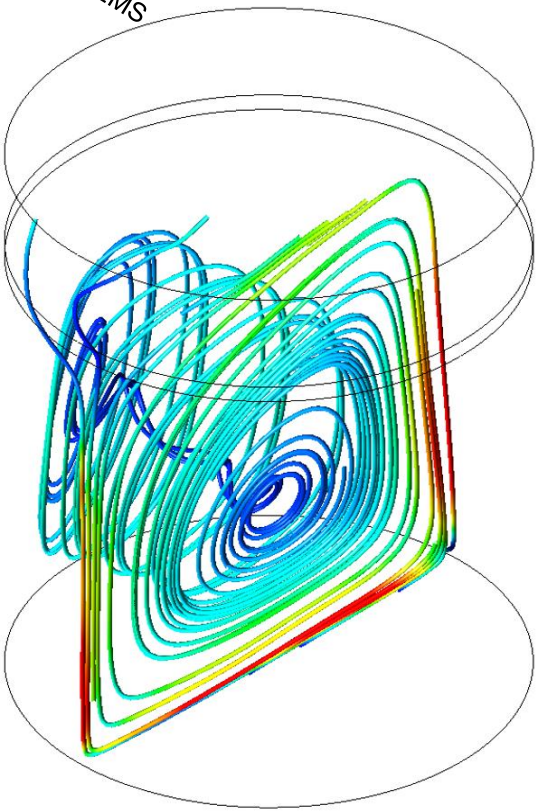




1s



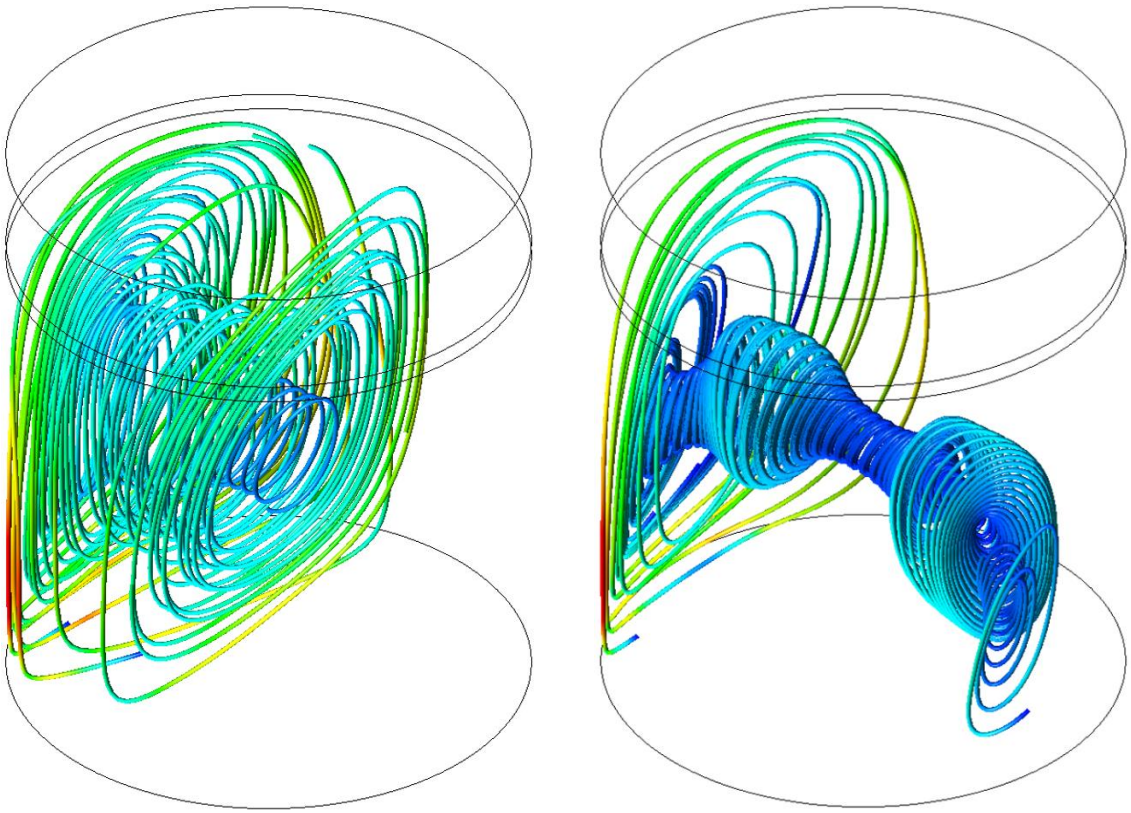
10s



15s

Case I – Vortex Development

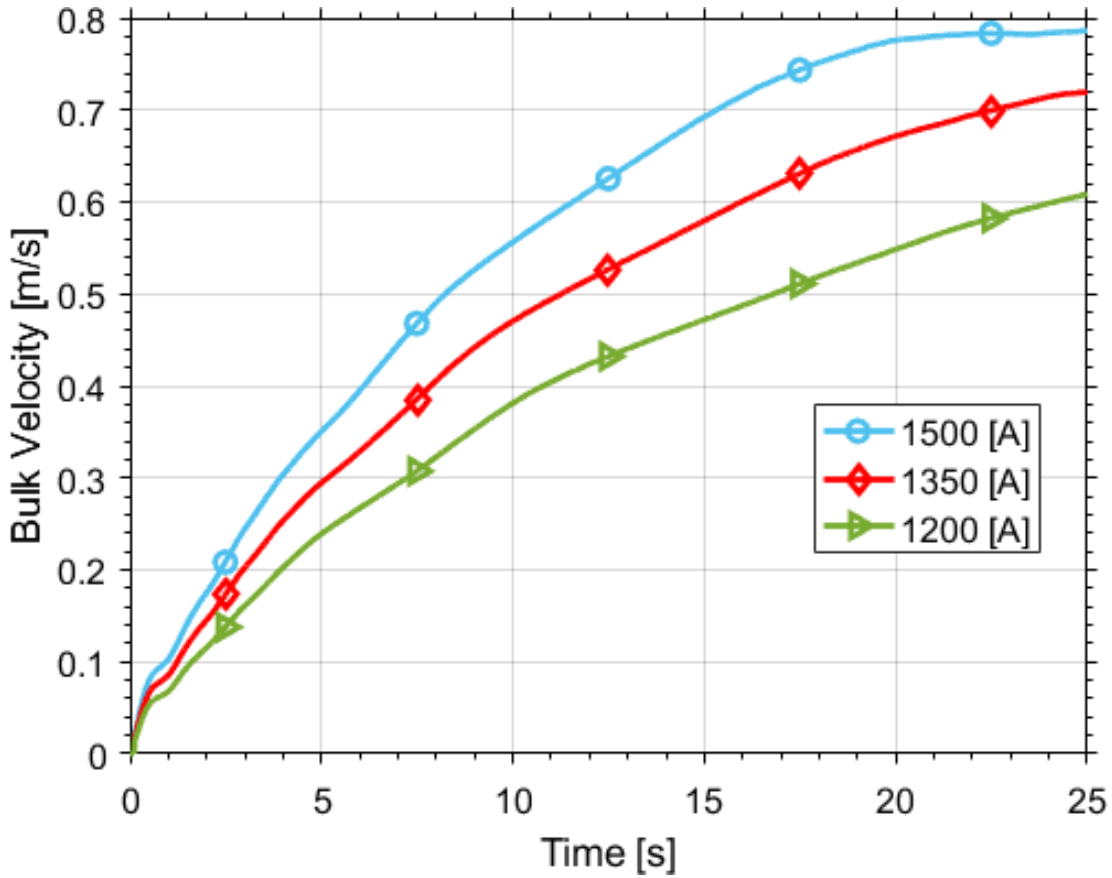
- Fully-developed vortex encompasses the entire steel domain
- Two symmetric recirculation plumes at core
- Effect of these plumes on slag eye formation is evident with harsh stirring conditions



25s | 25s | Core

Effects of Current Amplitude

- This study aimed to find a correlation between bulk velocity and current amplitude
- Decreasing the amperage by 300 [A] reduces the velocity by 0.2 [m/s]
- Constant MHD scaling factor of 5 results in similar velocity development profiles



Case I – Effects of Taper Angle

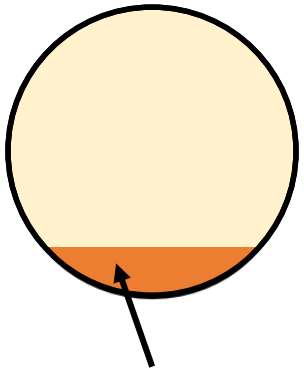
- Constant bottom radius:
  - 0°: 128 [Metric Ton]
  - 5°: 147 [Metric Ton]

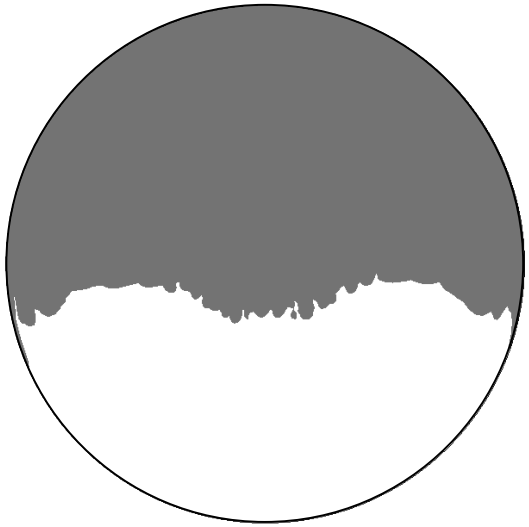
- Taper angle elongates the core
- Increased taper angle results in decreased bulk velocity and slag-eye

$$\text{Area Ratio} = \frac{\text{Eye Area}}{\text{Total Area}}$$

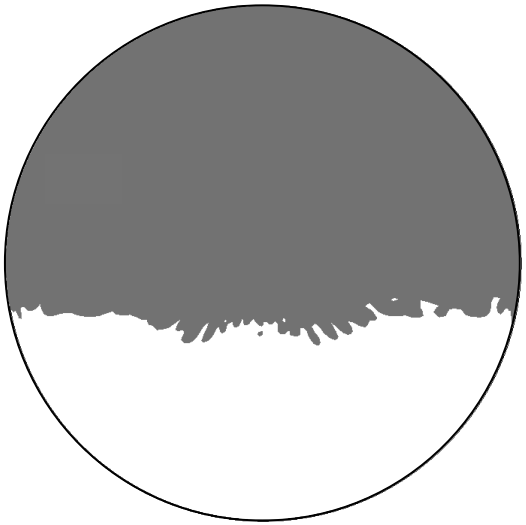
Current Amplitude: 1500 [A]

Taper Angle	0°	3°	5°
Bulk Velocity [m/s]	0.79	0.73	0.69
Area Ratio	0.41	0.38	0.34





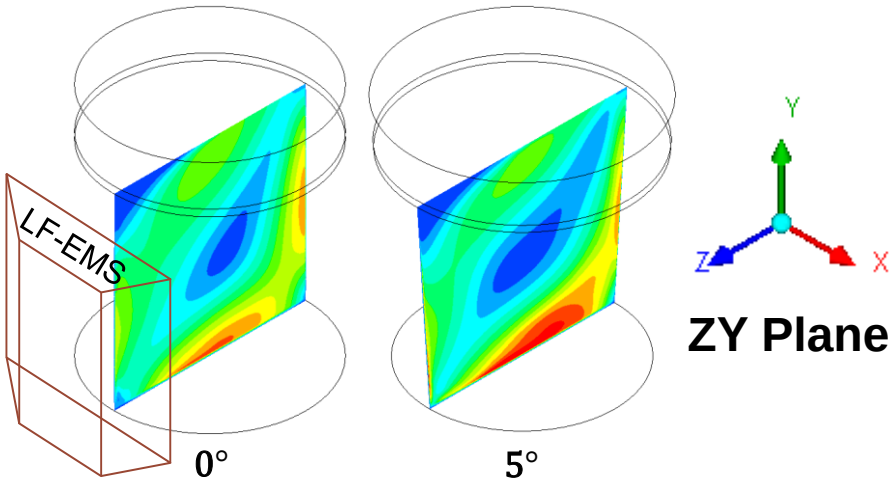
Taper Angle: 0°

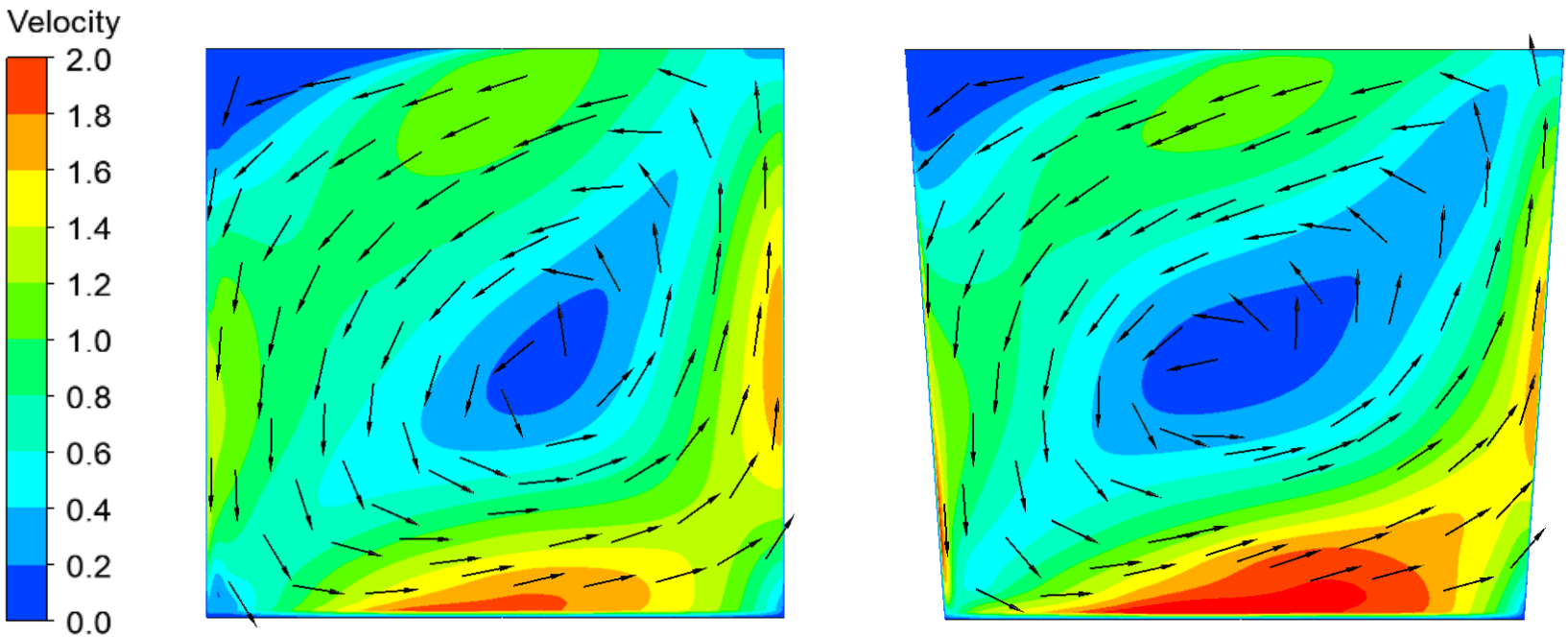


Taper Angle: 5°

Case I – Effects of Taper Angle

- Increased taper angle:
  - Larger inertia
  - Reduced momentum transfer
  - Elongated vortex core



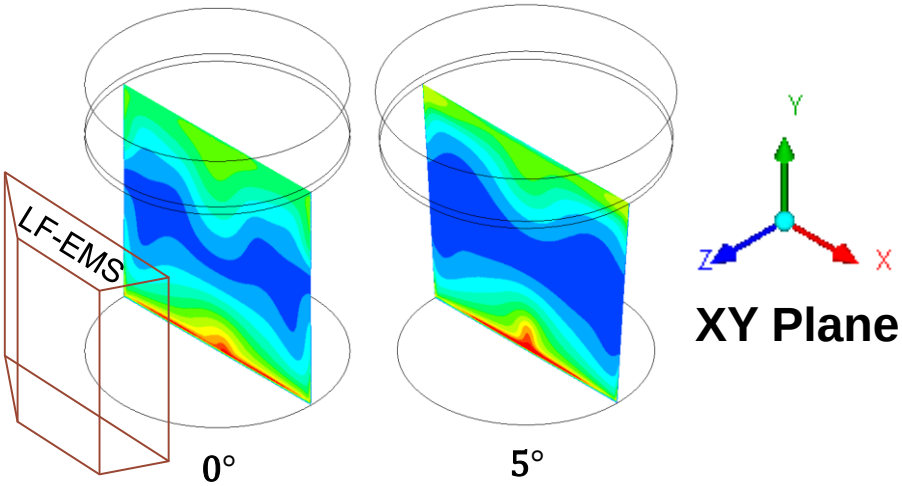


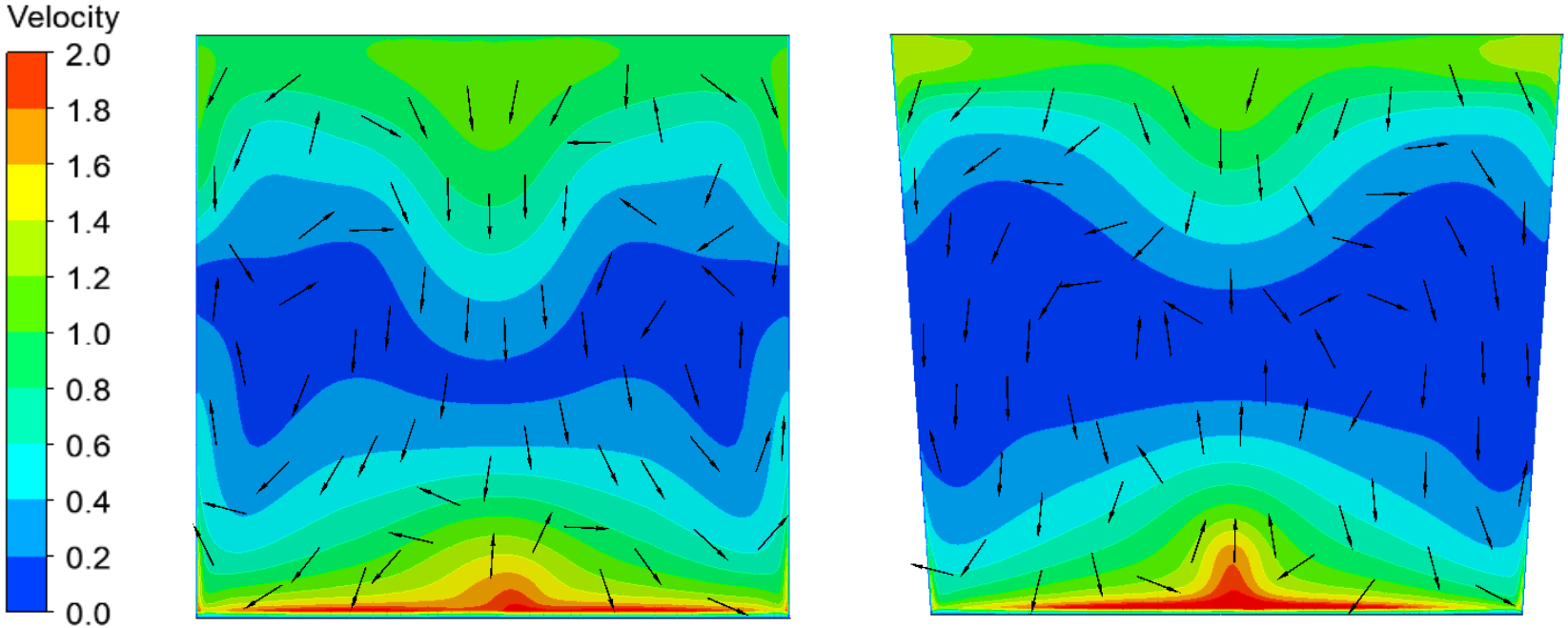
Taper Angle: 0°

Taper Angle: 5°

Case I – Effects of Taper Angle

- Increased taper angle:
  - Vortex plumes spread out
  - Larger low velocity zones



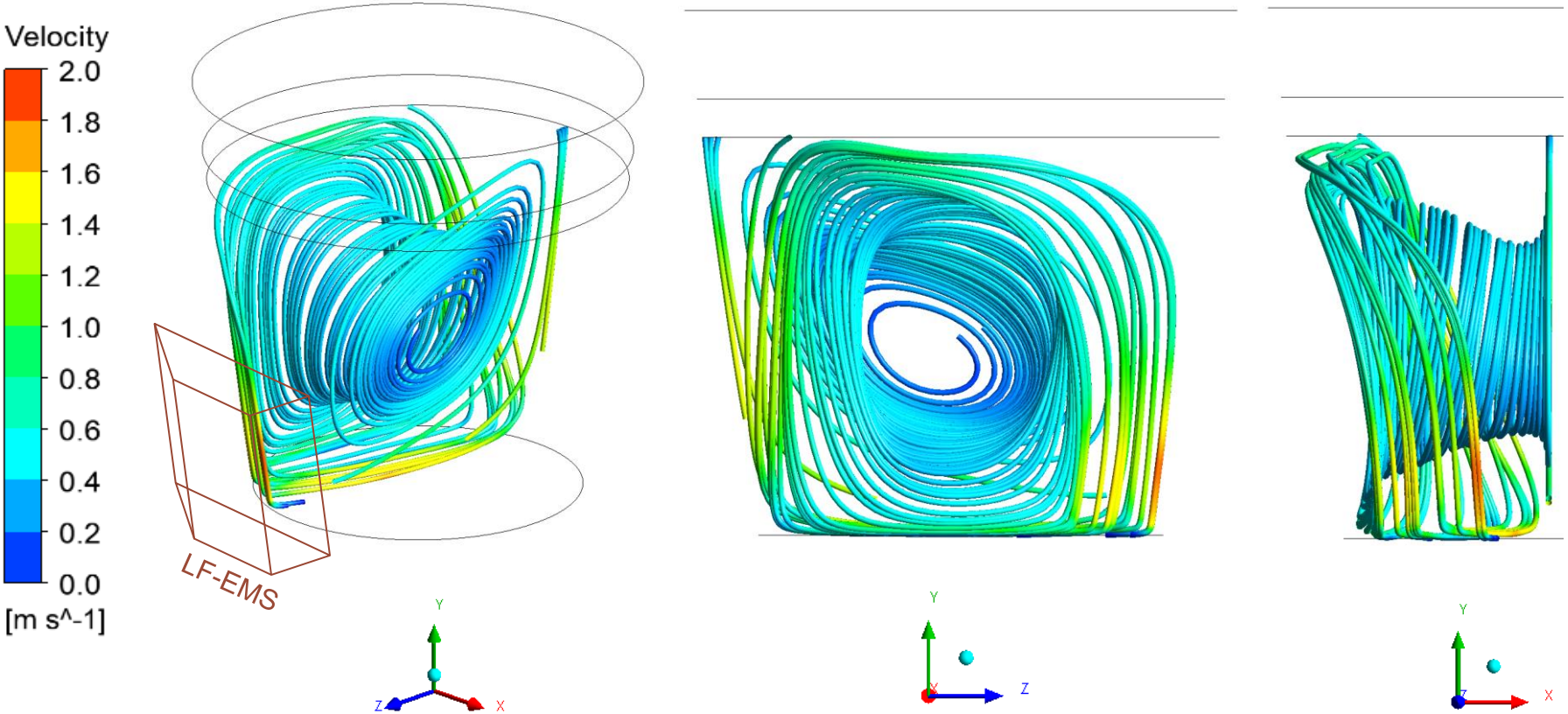


Taper Angle: 0°

Taper Angle: 5°

Case II – Vortex Development

- Simplified Nucor Decatur ladle geometry
- Taper angle and larger ladle diameter elongate the core along the positive zy-plane

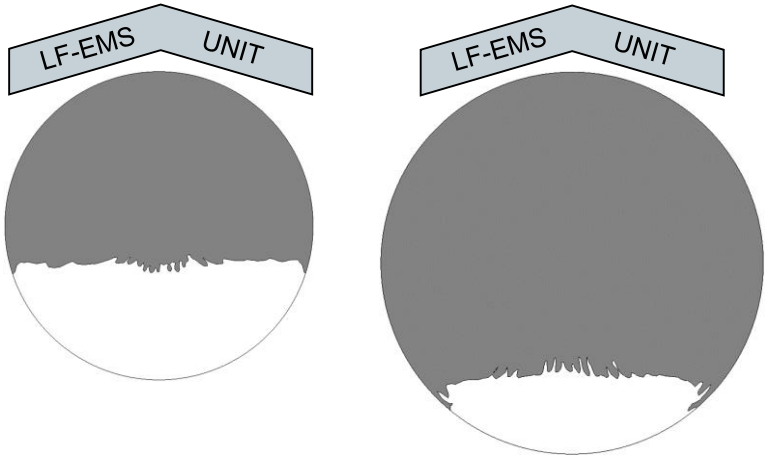


Effects of Ladle Geometry

- Taper angle influences slag eye size
  - Potential for less oxidation
- Both cases are impacted by the dual vortex plumes

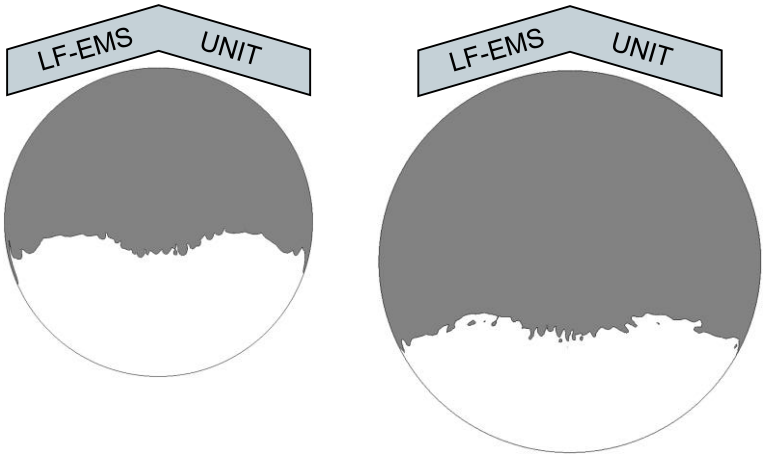
Case	Eye Area [m²]	Area Ratio	Velocity [m/s]
I	2.2	0.35	0.61
II	1.4	0.14	0.50

Case	Eye Area [m²]	Area Ratio	Velocity [m/s]
I	2.9	0.41	0.78
II	2.75	0.28	0.66



Case I Case II

1200 [A]

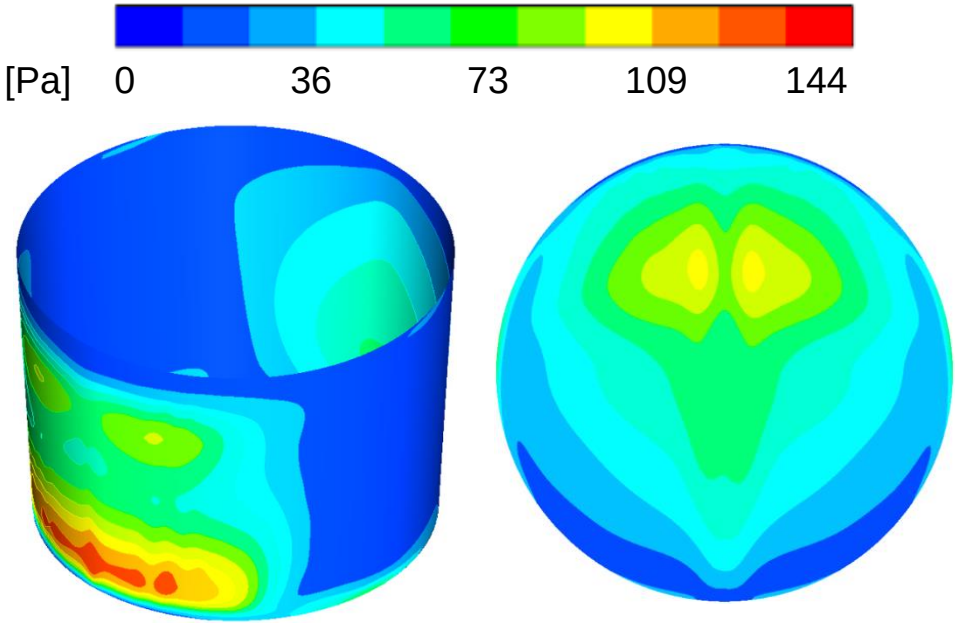


Case I Case II

1500 [A]

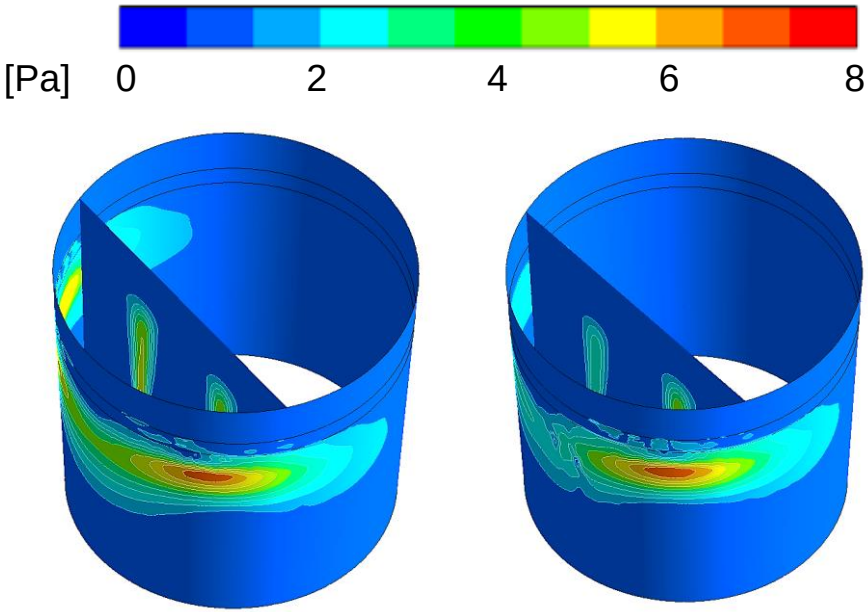
Wall Shear Stress per Stirring Method

- **Simplified Nucor EMS (1200 [A]):**
  - Two high stress regions
  - Two recirculation zones cause high shear stress on the side and bottom surfaces closest to LF-EMS
- **Simplified Nucor Gas (90°):**
  - Two orientations:
    - 90° and 180° plug separation
  - Stress resides near steel/slag interface



Isometric View

Bottom View

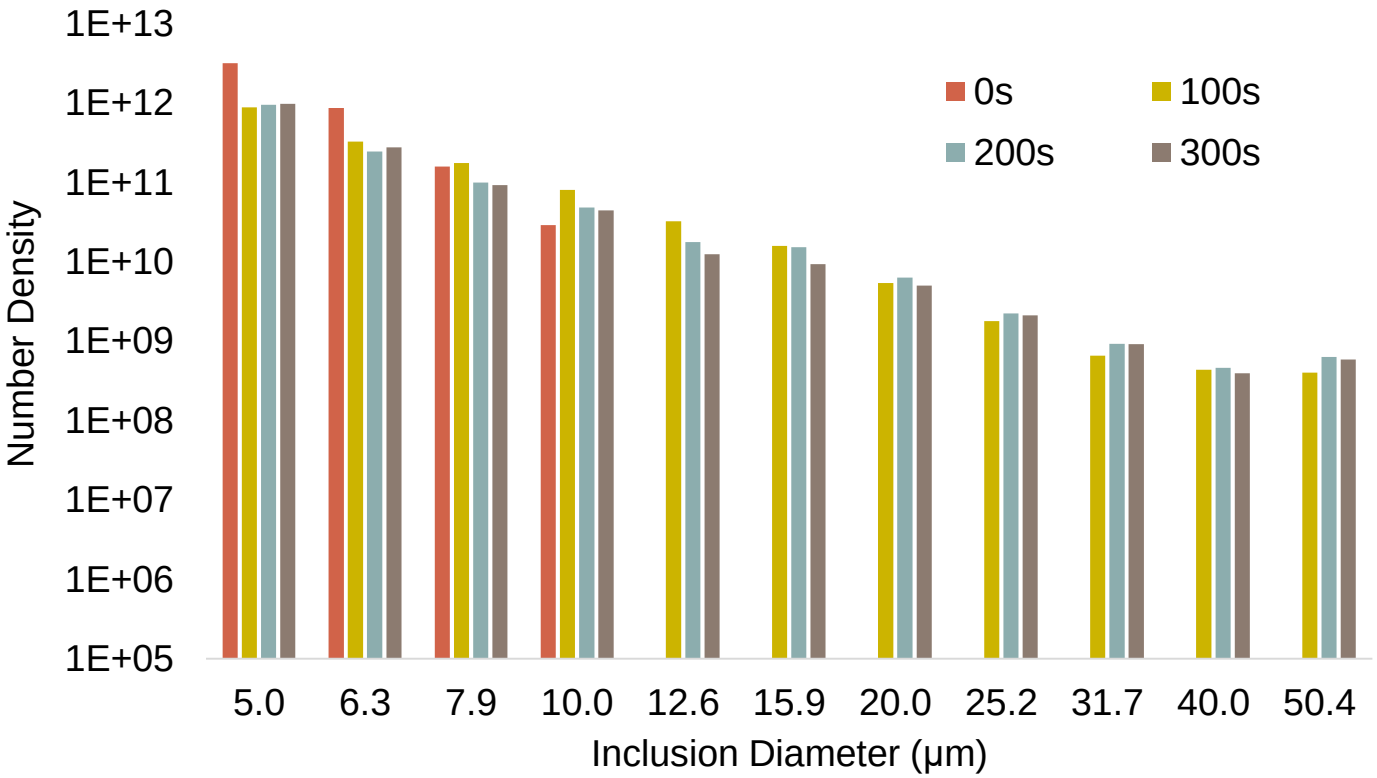


(5/20 SCFM)

(20/20 SCFM)

Inclusion Removal

- Relies only on wall and slag removal (no bubble removal)
  - Removal runtime of 300 seconds results in:
    - EMS: **24%** removal at 1500 [A]
    - Gas: **89%** removal at 90° separation with 20 SCFM flow rate
- Literature [22] states EMS inclusion removal is typically between 30-50%

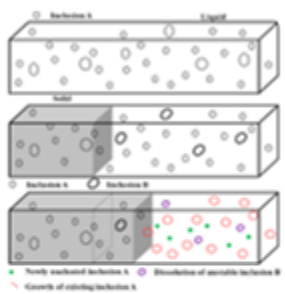


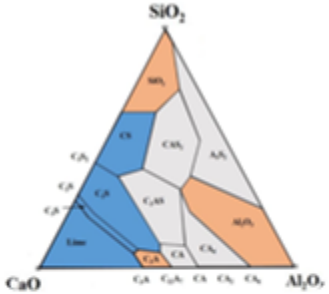
[22] T. Lidong, "Effect of ems on inclusion removal in ladle furnace for specialty steel production," 2017.

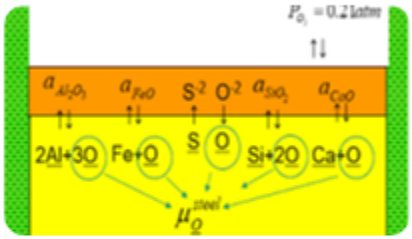
Project 5:
CHEMICAL REACTION MODEL

Chemical Reaction Modeling

- Purpose: Investigate effects of chemical reactions on the model
  - Optimal temperature for desulfurization
  - Reoxidation effects







Inclusion Model

- Nucleation
- Growth
- Removal

Kinetic Model

- Chemical Reactions
- Chemical Composition
- Slag-Metal Equilibrium

Thermodynamics

- Thermodynamic Effects
- Reaction Rates

Numerical Models

- **Chemical Model**
  - Formation and reaction of inclusion species
    - Potential for liquid and solid inclusions
  - Reaction rates and coefficients
- **Fluid Flow Model**
  - Three-dimensional
  - Transient
  - Multiphase VOF (Steel, Slag, Argon)
  - k-ϵ turbulence model
  - MHD Solver: ANSYS Fluent MHD module

Potential Implementation

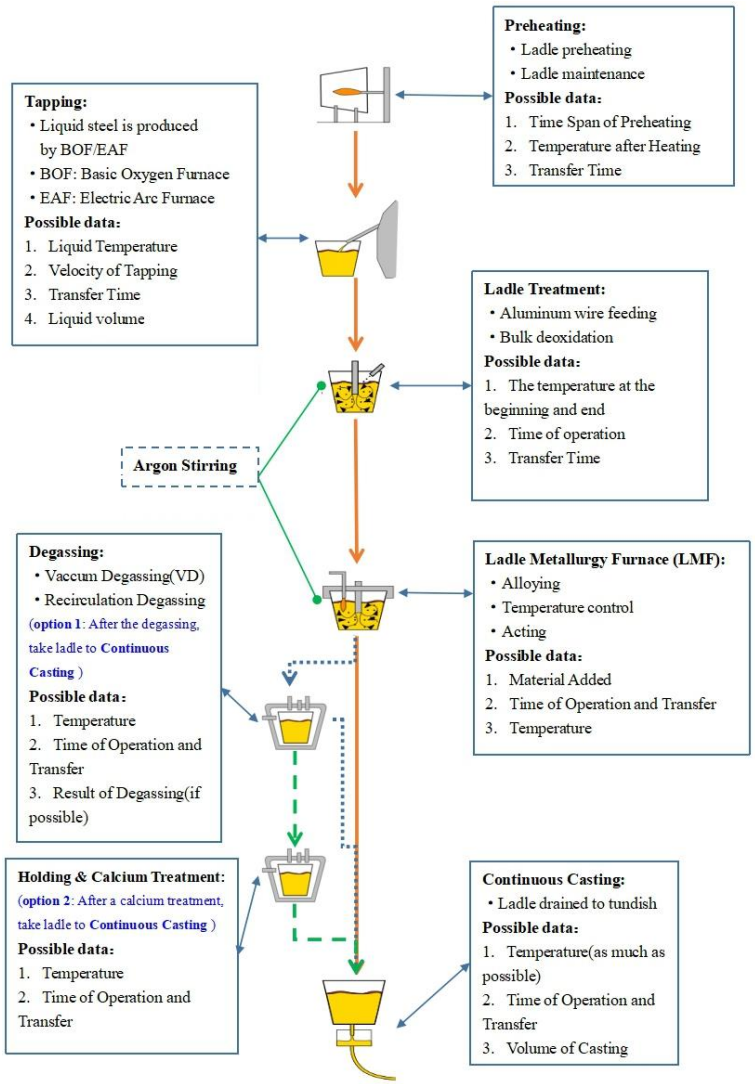
- **Optimized ladle stirring conditions**
  - Minimize slag eye formation by altering gas injection rate and plug placement
  - Maximize inclusion removal for improved steel quality and higher productivity
    - Balance flow velocity and slag-eye size
  - Minimize wall shear stress for longer ladle lifetime
    - Prediction of maintenance cycles
- **EMGAS Ladle**
  - Wall shear stress reduction due to plug placement
  - Inclusion removal efficiently and productivity

Future Work

- Gas-stirred Ladle
  - Inclusion removal upon slag-eye impact
  - Validation inclusion removal model with industry measurement
- EMS Ladle
  - Validate with force distribution data from industry
  - Combined EMGAS simulation
    - Wall shear stress
    - Plug placement
- Chemical Modeling
  - Build the chemical kinetic CFD models

AIST Digital Transformation 2019: Smart Ladle

- **Issues:**
  - Current ladle procedures rely on operator expertise
    - Experience and "gut feeling"
  - Operators may not have all information (e.g. cold ladle)
- **Objectives:**
  - Use deep learning methods to predict steel tundish/casting temperatures using process data
  - Improved quality and consistency in steel casting process

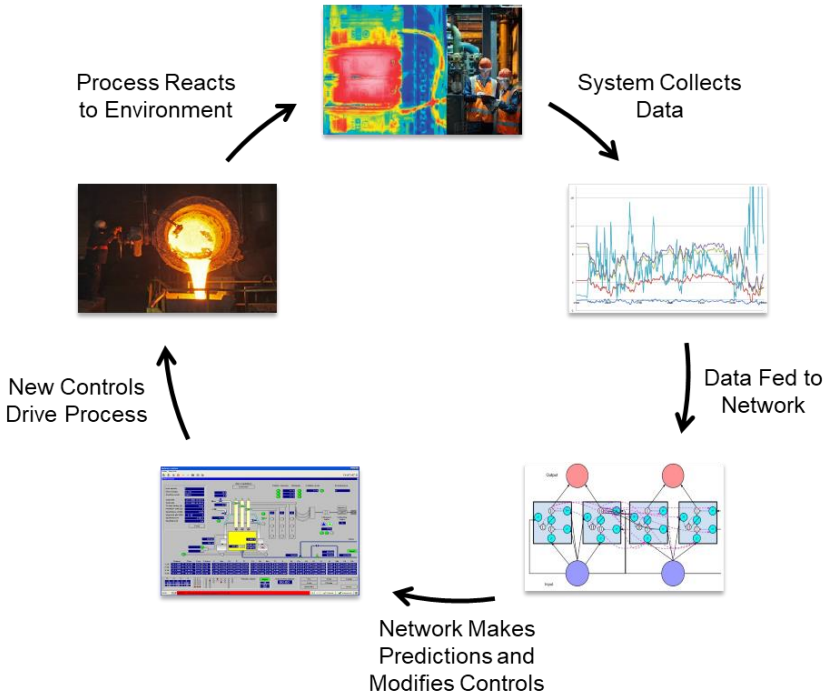


Refining ladle process and variables

Smart Ladle:
AIST Digital Transformation 2019

- **Process:**
  - Data provided to deep learning network, which finds *quantitative* correlations
  - Network learns from data to **predict** future trends from real-time data feed
  - **Real-time** predictions can be used to control process
- **Expected Outcomes:**
  - Process-integrated deep learning network predicting tundish temperature
  - Student engagement in digital technologies and deep learning
  - Student awareness of steel industry careers
  - Procedures for further deep learning in smart manufacturing

Deep learning network process cycle



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- PNW faculty collaborators
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  - Mingyi Liang
  - Huinan Shao
  - Justina Lee
  - Dan Yan
  - Wenjie Liu

Comments from Industry Collaborator

Thank You

Questions and Comments

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