COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

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April 22, 2021

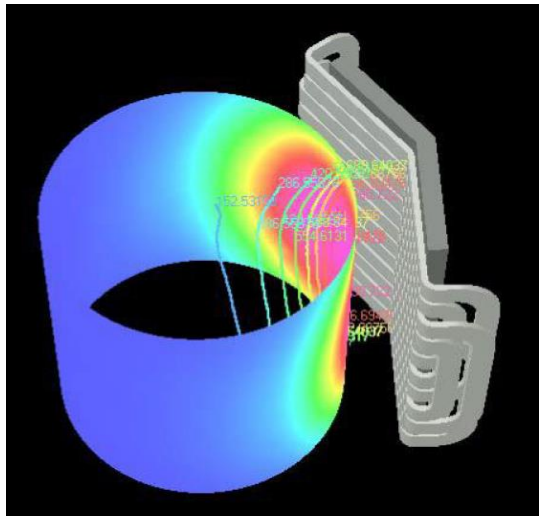
"Where Ideas Become Reality"

Presentation Outline

- Introduction
  - Objectives & Roadmap
  - Outcomes
  - Project Timeline
- Methodology and CFD Models
- 2021 Projects
  - Inclusion Growth & Removal
  - EMS Ladle
  - Chemical Model
  - Smart Ladle
- Summary & Future Work

Motivation

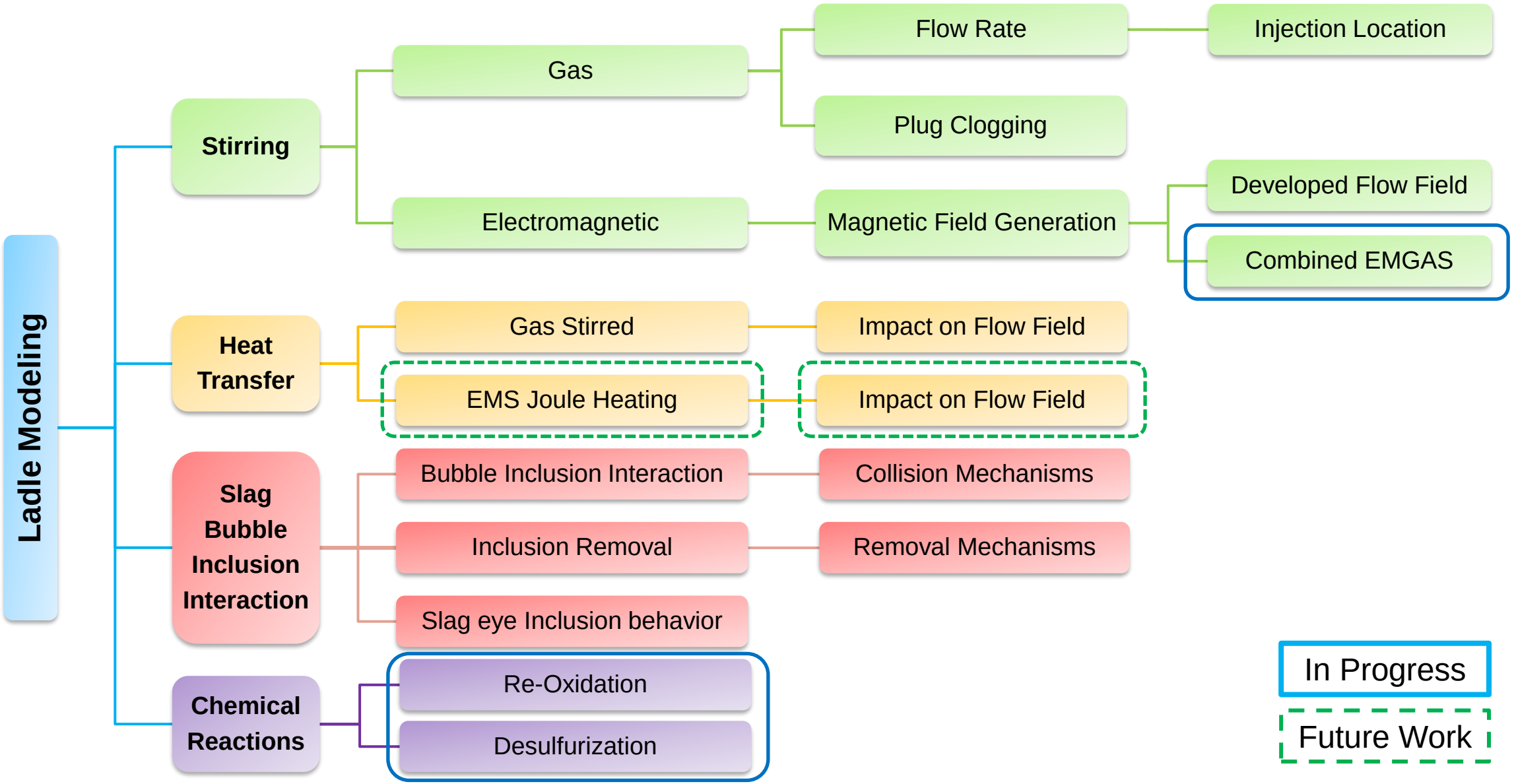
- Current Issues
  - Complex transport phenomena with multiple process variables
  - Difficulty in understanding the dynamic evolution of multiphase flow and inclusions
  - Correlations between LMF operation and ladle history with desired casting temperature
- Potential Impacts
  - Process design of optimized flow condition and physical properties
  - Steel cleanliness improvement and final defects reduction
  - Better operator control over steel temperatures and product quality



Objectives

- Long-term Objectives
  - Develop a validated comprehensive multiphase CFD model of a steel ladle using three stirring methods
    - Gas stirring
    - EMS stirring
    - Combined EM-Gas stirring
  - Optimize ladle stirring conditions for
    - Steel cleanliness
    - Productivity
    - Equipment lifetime
    - Unexpected industrial problems

Model Development Roadmap



Major Outcomes – Models & Applications

Projects (2016 – 2021): Completed: 4, Ongoing: 5

- **Project #1:** Isothermal Gas-stirred Ladle Flow Simulation - Nucor Decatur
  - Validated against measurements (avg. 8.7% slag eye size difference)
  - 18% time decrease for homogenization by increasing plug distance ratio by 0.1D
  - 25% time decrease for homogenization by changing separation angle from 180° to 60° with fixed plug distance
- **Project #2:** Heat Transfer Effect in Gas-stirred Ladle - Nucor Decatur
  - 29% faster temperature loss on cold ladle wall (1200K) compared to preheated ladle walls (1525K)
- **Project #3:** Gas-Stirred Isothermal Inclusion Growth and Removal – Nucor Generic Ladle
  - Developed inclusion growth and removal model based on Eulerian-Lagrangian multiphase approach
  - 5% increase in inclusion removal efficiency by changing 90° to 180° plug separation angle
- **Project #4:** EMS Isothermal Ladle – AM Generic Ladle
  - Identified effect of EMS flow on wall shear stress, bulk velocity & slag-eye size

Major Outcomes – Models & Applications

Projects (2016 – 2021): Completed: 4, Ongoing: 5

- **Project #5:** Inclusion Removal Enhancement & Validation – Nucor Generic Ladle
  - Developed slag eye inclusion release model
  - Validated against measurement data (avg 12.1% number density difference)
- **Project #6:** Plug Clogging Study - Nucor Generic Ladle
  - 37% decrease in mixing time by doubling flow rate to offset lost plug, but with increased wall shear stresses (98% increase in peak stress)
- **Project #7:** Combined Gas-EMS Ladle Model Study – AM Generic Ladle
  - Preliminary results show 98% slower mixing time and 30% higher wall shear stress for EMS+Gas compared to EMS because of higher flow turbulence near wall
- **Project #8:** Desulfurization and Re-oxidation in Refining Ladle
  - Developed preliminary CFD-SRM coupled desulfurization in gas-stirred ladle
- **Project #9:** Smart Ladle
  - Developed deep learning algorithm using SDI data
  - Prediction of tundish midpoint temperature and slope
  - The Mean Average Error for the current model is 2.62°F with a standard deviation of 3.49 °F
  - Implemented data-filtering based on sanity checks for physical values

Major Accomplishments since November 2020

- Inclusion Removal Enhancement & Validation
  - Trend from optimized inclusion model is validated well with industrial measurements
- Cleveland Cliffs Mansfield Ladle Study
  - Examined interface velocity distribution in different stirring scenarios
- Smart ladle
  - The accuracy of the predictions increased, the Mean Average Error for the current model is 2.62°F with a standard deviation of 3.49 °F
  - Standalone interface has been implemented and is being tested

Ladle Application Roadmap

Project 10: Cleveland-Cliffs Mansfield Stirring Ladle

Associated Models:
- *Gas Stirring Models*

Companies interested:
- ***Cleveland-Cliffs (Site company)***

Project 11: Shipping Temperature and Superheat Control

Associated Models:
- *Smart Ladle*

Companies interested:
- ***Steel Dynamics, Inc. (Site company)***
- *AK Steel Corp (avg: 100)*
- *ArcelorMittal Global R&D (avg: 100)*
- *Charter Steel (avg: 100)*
- *Evraz (avg: 20)*
- *SSAB Americas (avg: 80)*

Project 13: Stirring Time Optimization for Homogenization and Inclusion Floatation

Associated Models :
- *Gas and EMS Stirring Models*
- *Inclusion Removal Models*

Companies interested:
- ***Nucor Steel (Site company)***
- *AK Steel Corp (avg: 70)*
- *ArcelorMittal Global R&D (avg: 100)*
- *Charter Steel (avg: 100)*
- *Evraz (avg: 63)*
- *SSAB Americas (avg: 80)*

01/2022 – 04/2022

01/2021 – 05/2021

01/2021 – 07/2021

06/2021 – 12/2021

01/2022 – 05/2022

06/2022 – 12/2022

Gerdau Stirring Side Project

Associated Models:
- *Gas Stirring Models*
- *Inclusion Removal Models*

Companies interested:
- ***Gerdau (Site company)***

Project 12: Minimization of Ladle Erosion and Wear

Associated Models:
- *Gas and EMS Stirring Models*

Companies interested:
- ***Charter Steel (Site company)***
- *ArcelorMittal Global R&D (avg: 100)*

Project 14: Steel Quality Improvement through Desulfurization and Re-oxidation

Associated Models:
- *Chemical Reaction Model*

Companies interested:
- ***Evraz (Site company)***
- *ArcelorMittal Global R&D (avg: 100)*

2021 Objectives

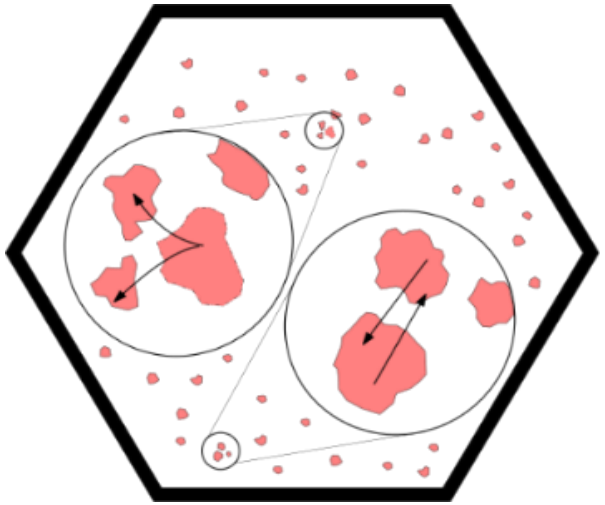
- Investigate Inclusion Removal in Gas-stirred & EMS Ladle
  - Validate inclusion removal results with industrial measurement data
  - Apply inclusion model to EMS & EM-gas ladle
- Investigate Chemical Reactions in Steel Ladle Refining
  - Develop chemical reaction model including desulfurization and re-oxidation
- Smart Ladle
  - Implement interface at industry site and adjust with operator's feedback and suggestions

2021 Timeline

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Project 5 Inclusion Removal Enhancement & Validation	Inclusion model refinements												
	Validation and Industry Applications												
	EMS Inclusion Removal												
Project 6 Plug Clogging and Erosion	Literature Search												
	Ladle erosion and wear model												
Project 7 Combined Gas-Stirring and EMS	EM-Gas Flow Field												
Project 8 Desulfurization and Reoxidation in Ladle	Literature Search												
	Desulfurization												
	Reoxidation												
Project 9 Smart Ladle	Smart Ladle Development												
	Integration and Generalization												

2021 Timeline (cont.)

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Project 10 Application of Cleveland Cliffs Gas Stirring Ladle	Geometry development												
	Simulation of flow field												
Project 11 Shipping Temperature and Superheat Control	Data collection												
	Model development and implement												
Project 12 Minimization of Ladle Erosion and Wear	Literature Search												
	Ladle erosion and wear applications												



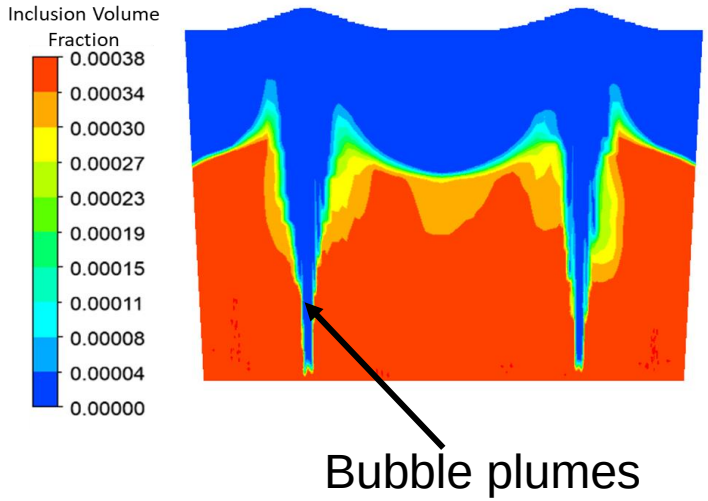
Project 5:
Isothermal Inclusion Removal Enhancement and Validation

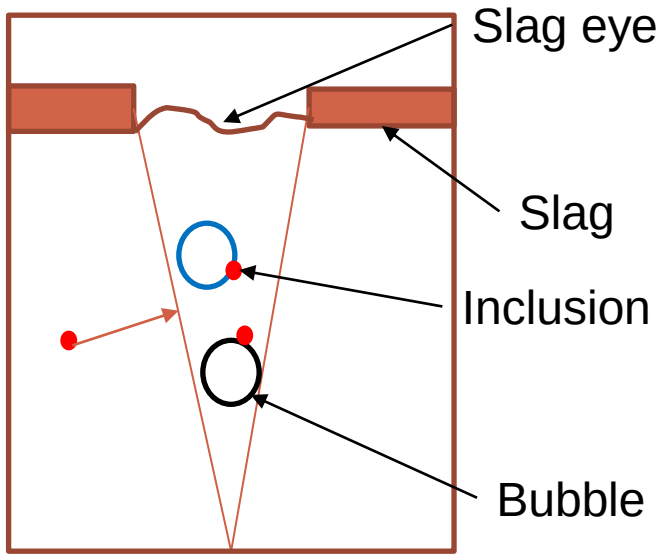
Site: Nucor Decatur

Start: November 2019

Inclusion Removal Modeling

- **Motivation**
  - Non-metallic inclusions directly affect steel products' fatigue strength, impact toughness, corrosion resistance, and machinability factors
  - 65-75% inclusion removed by ladle operation
- **Objective**
  - To develop a inclusion removal model for refining ladle system
  - To validate the model with industrial measurements
  - To apply the model to practical plant ladle and predict inclusion removal rate
- **Potential Impact**
  - Improved product quality and castability





Revised Methodology

1. Flow field simulation (Generate slag eye shape)

- Fluid zones: steel, slag and argon
- Eulerian-Lagrange multiphase flow

Mesh with shape of slag eye

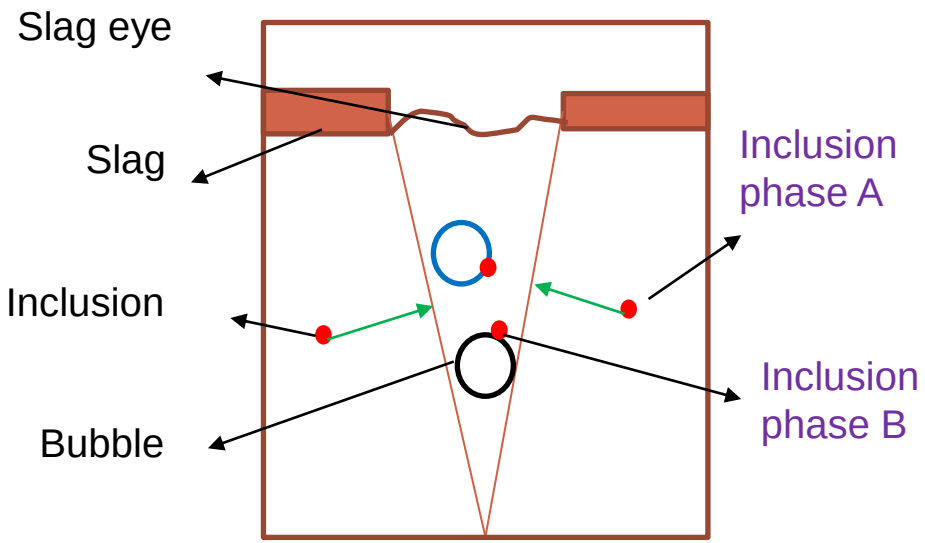
2. Flow field simulation (Find velocity of gas phase)

- Fluid zones: steel and argon
- Eulerian-Lagrange multiphase flow

Velocity, turbulence, pressure, etc.

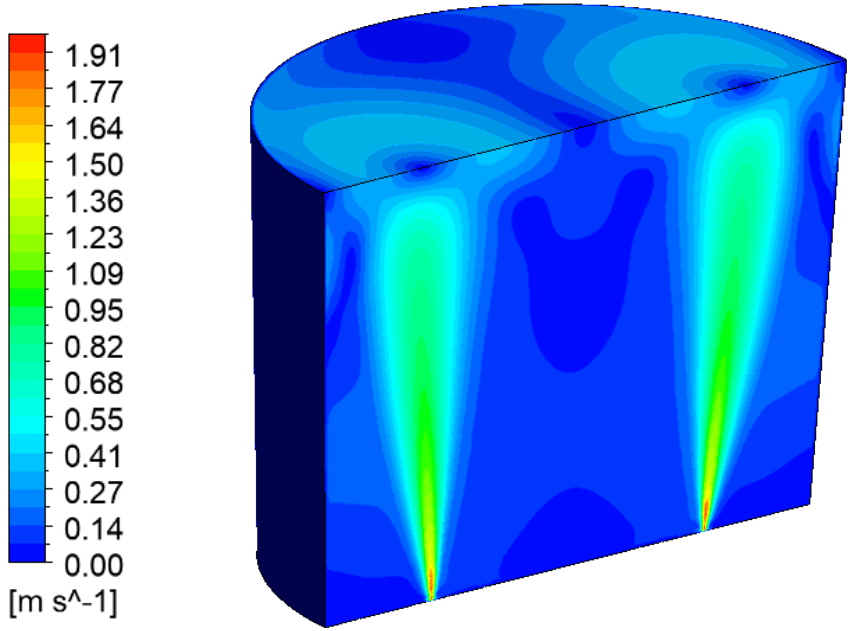
3. Inclusion removal and aggregation model

- Fluid zones (steel, argon and inclusion)
- Inclusion removal and aggregation
  - Population balance model (PBM)
  - Inclusion-Bubble attachment model
    - Inclusions attaches to bubble -> transfer from phase A to phase B
    - Inclusion aggregation only applied to phase A
    - At wall or slag area
      - Inclusion phase A removed by associated mechanism
      - Captured inclusion phase B fully removed

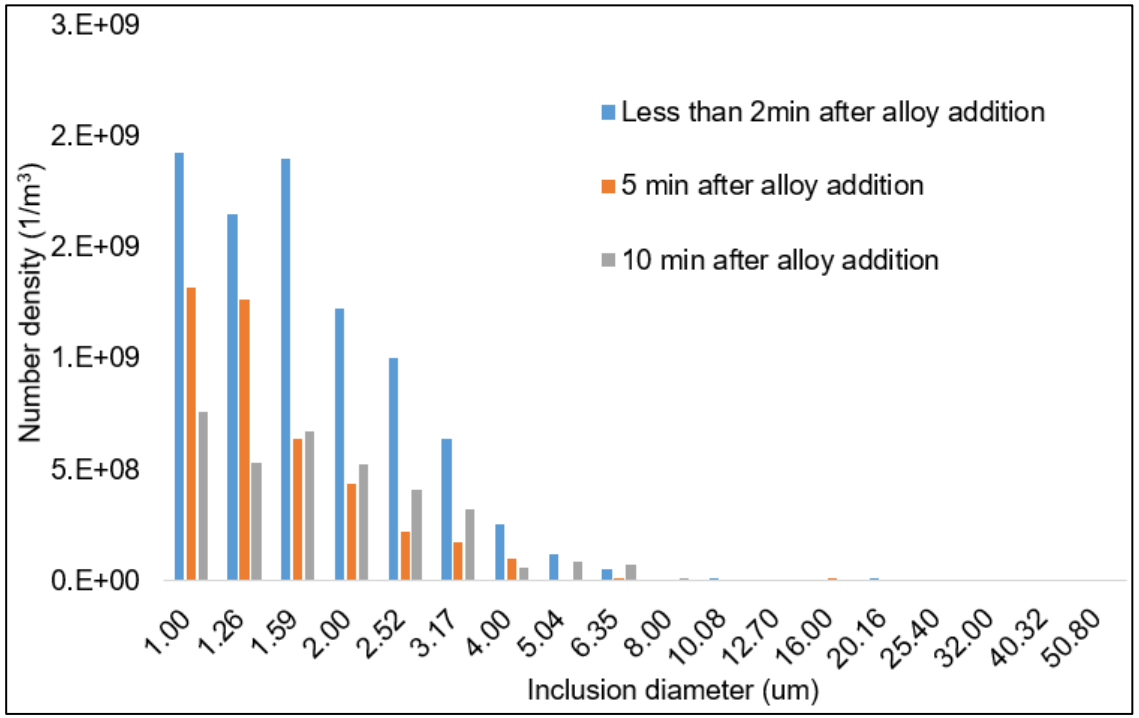


Nucor Validation Ladle Geometry

- Two layers: argon, steel
- Two plug at bottom
- Plug separation angle of 180 degrees
- Inclusion number density is shown below

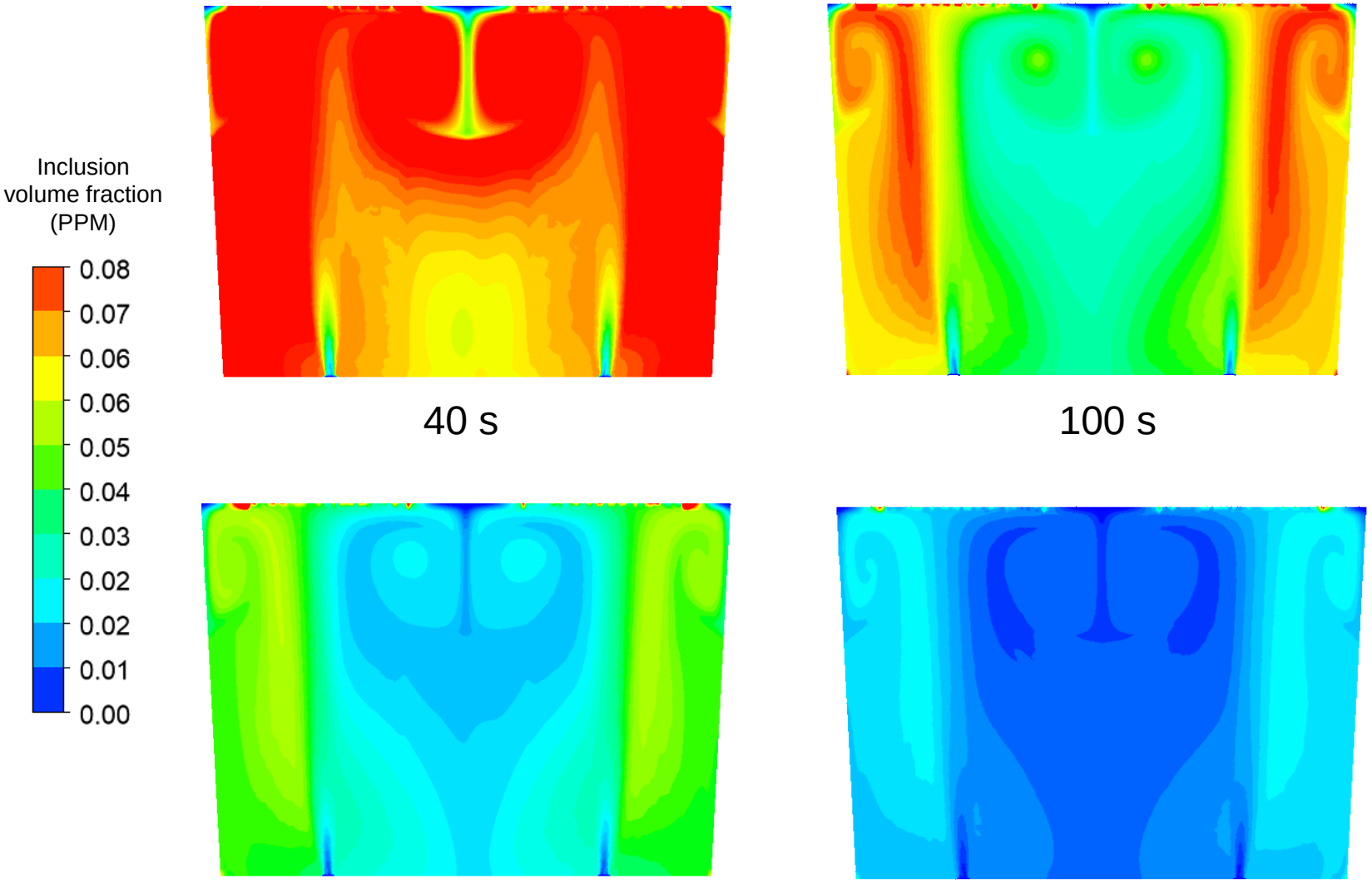


Schematic of ladle geometry



Number density distribution

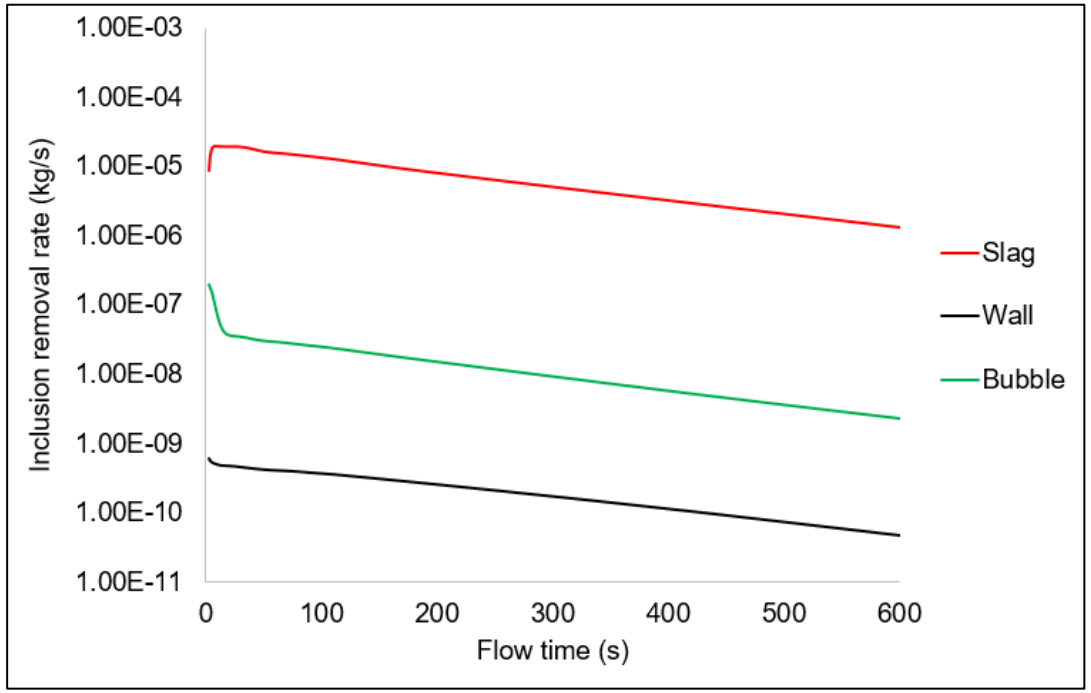
Inclusion Volume Fraction



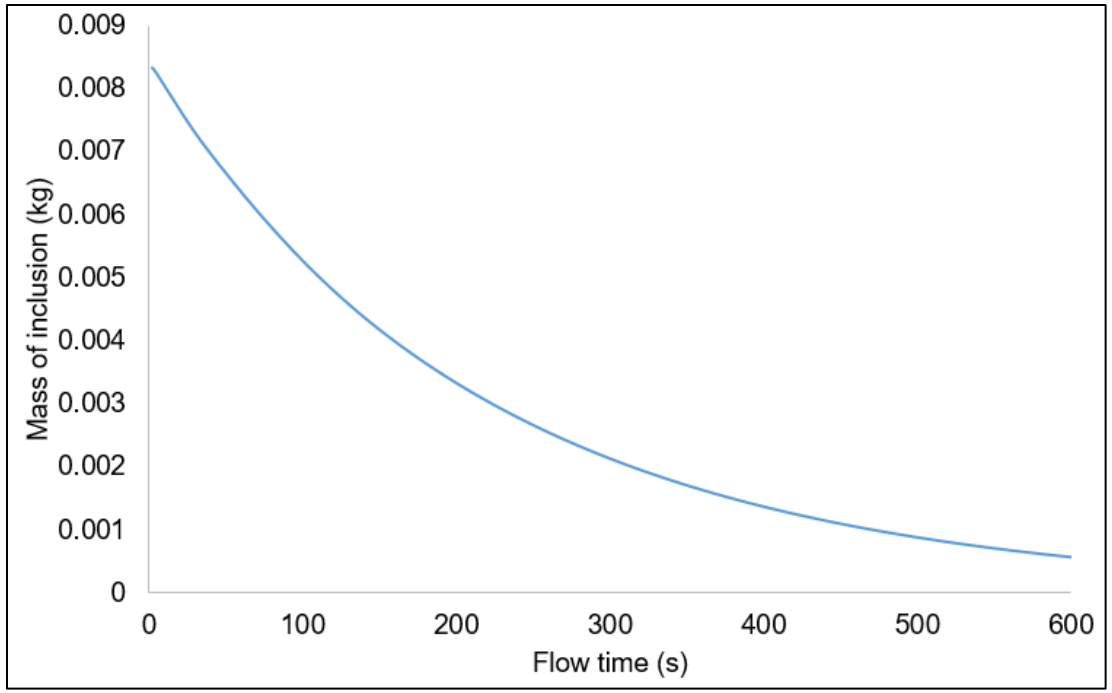
- Inclusion volume fraction decreases over time
- Inclusion volume fraction in the region between two plume decreases faster then the region near the wall
- The trajectory of the inclusion movement is closely related to the flow field

Inclusion Removal Validation

- Inclusion removal mechanisms: Slag > Bubble > Wall
- Inclusion removal rate due to different mechanisms decreases over time
- 10 minutes after alloy addition, inclusion removal rate is 92.1%



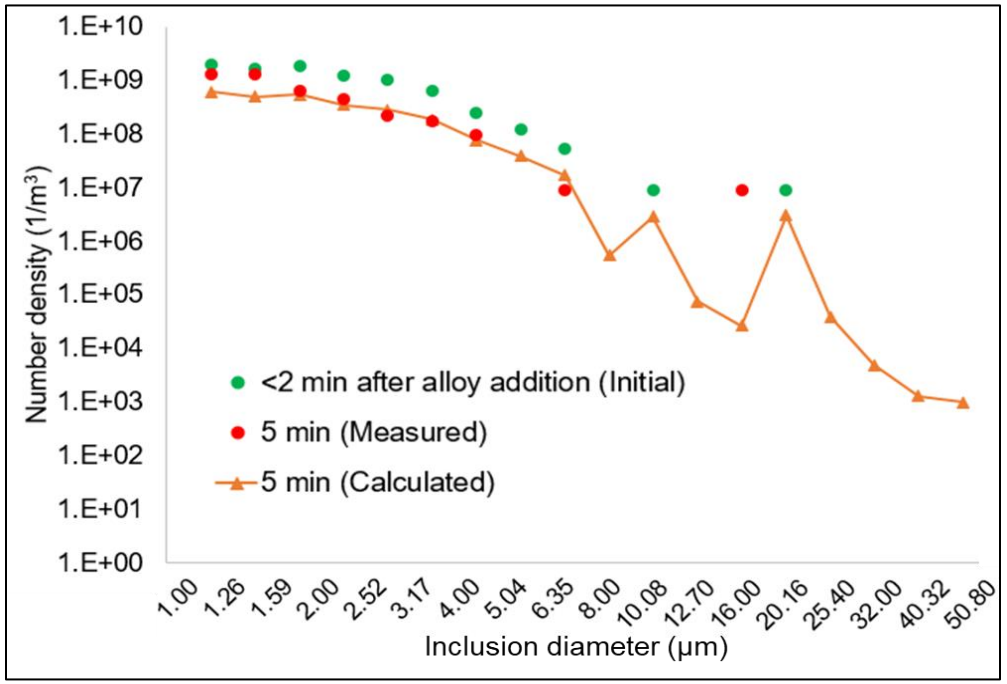
Inclusion removal mechanisms



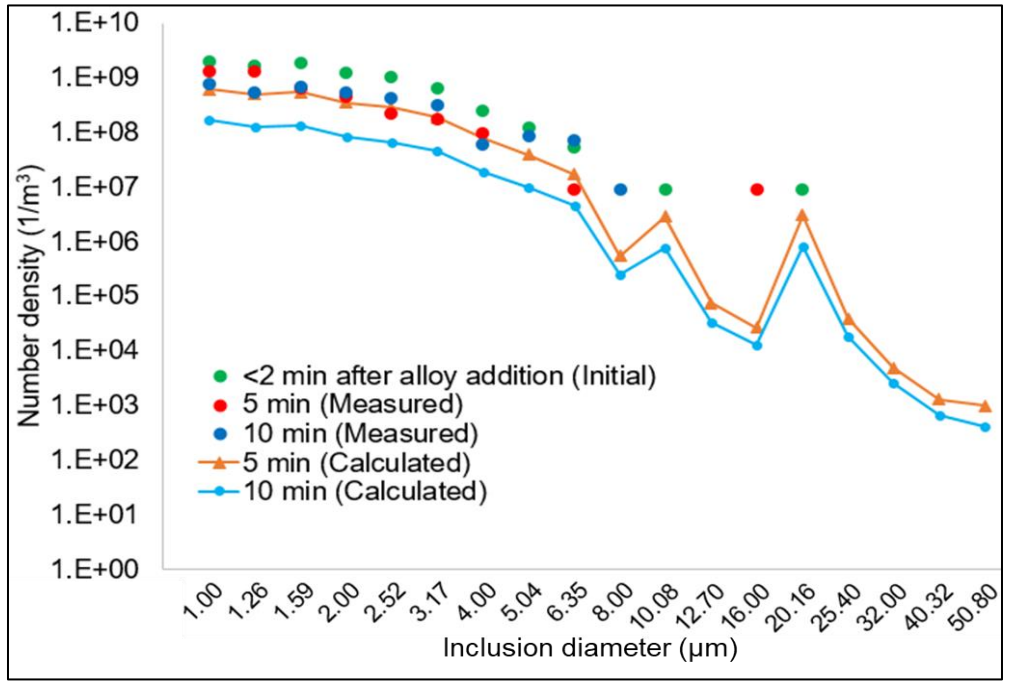
Mass of inclusion in the ladle

Inclusion Removal Validation

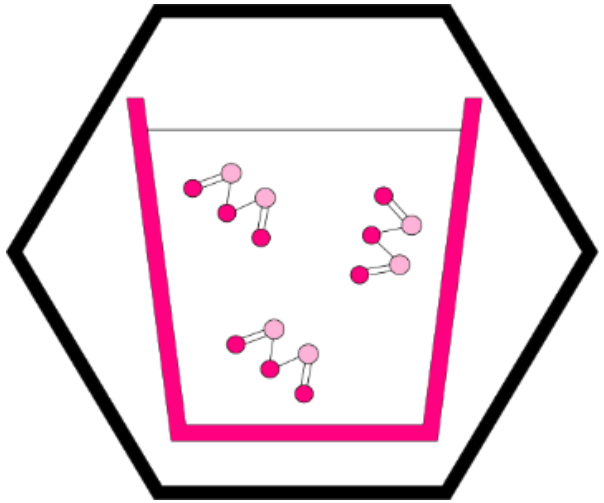
- Inclusion sizes in model range from 1.00 μm to 50.80 μm
- Measured data taken from Nucor Decatur ladle operations
- Simulation results are sensitive to initial inclusion size distribution
- Good trend agreement between CFD results and measured data



Inclusion Number Density Validation



Initial Number Density



Project 8:
Ladle Desulfurization and Re-oxidation
Start: March 2020

Desulfurization and Re-oxidation

- **Motivation:**
  - Sulfur increases due to re-sulfurization from oxidizing slag and steel scrap
  - Sulfur can be removed by chemical reactions between steel and slag
- **Objective**:
  - Develop model for desulfurization and re-oxidation process
  - Verify the model with references and validate it with industry sampling
- **Potential Impact:**
  - Improved product quality and castability

New Methodology

1. Simulation of flow field

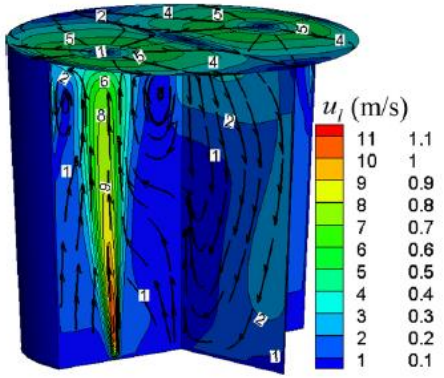
- Objective: to find the turbulence dissipation rate and velocity
- Method: Fluent model & UDF code

2. Calculation of chemical parameter

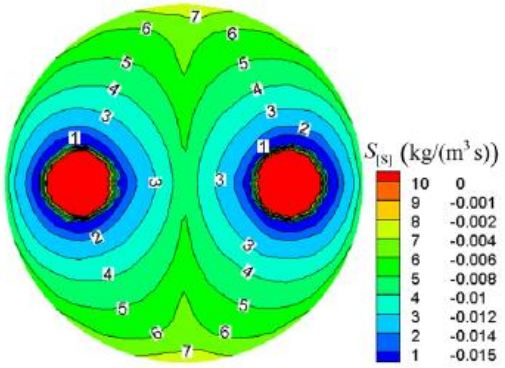
- Objective: to determine the mass transfer coefficient, distribution ratio and oxygen activity
- Method: UDF code

3. Calculation of chemical reaction rate

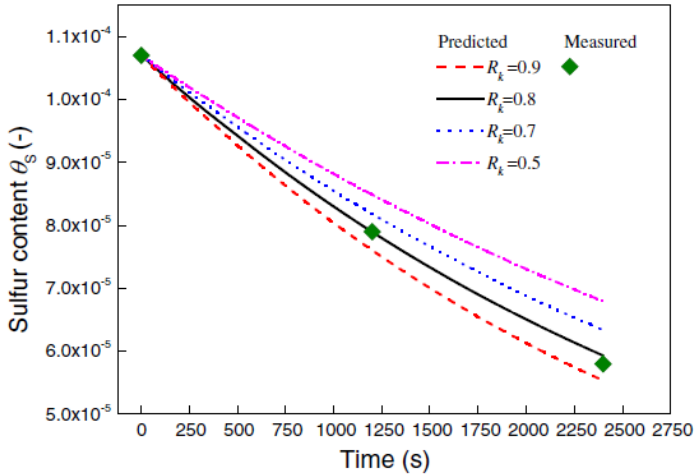
- Objective: to calculate the source terms of elements in ladle
- Method: UDF code



Velocity distribution



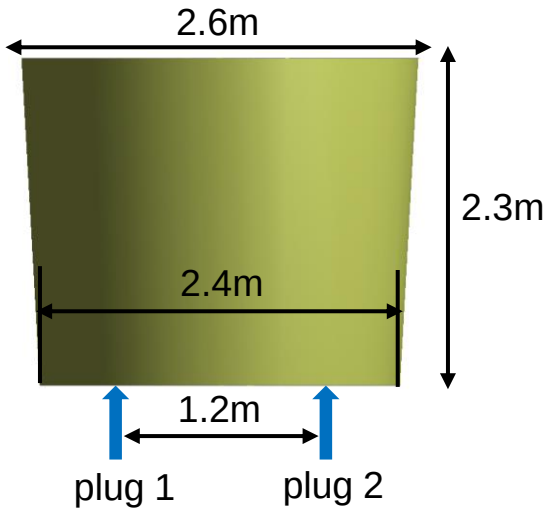
Sulfur removal rate

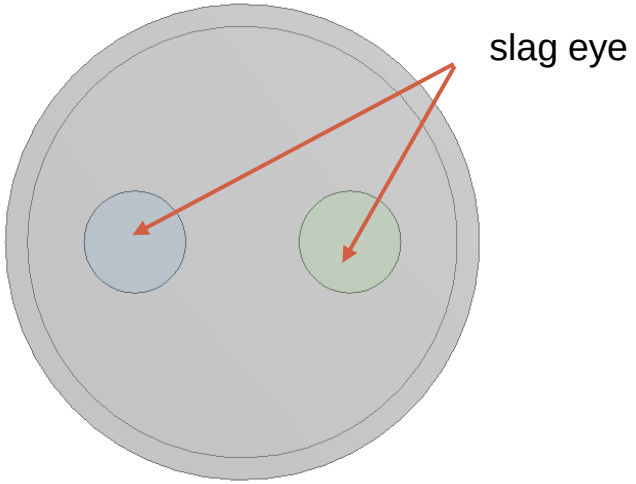


Sulfur content

Geometry & Assumption

- Geometry
  - An 80-ton ladle is selected from reference [1]
- Assumptions
  - Top surface (slag & slag eye) as flat free-surface
  - Slag eye is fixed, with the diameter determined by argon injection rate[1]
  - Reaction occurs at slag-metal interface, no reactions in slag eye area
  - Oxygen dissolution from slag eye is not considered

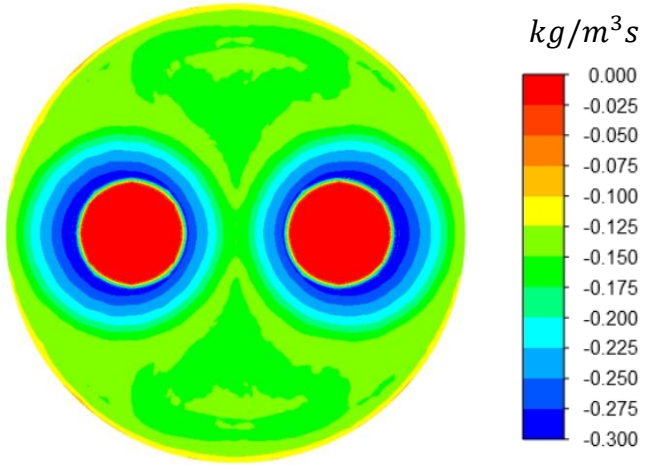




[1] Lou, Wentao, and Miaoyong Zhu. "Numerical simulation of desulfurization behavior in gas-stirred systems based on computation fluid dynamics–simultaneous reaction model (CFD–SRM) coupled model." *Metallurgical and Materials Transactions B* 45.5 (2014): 1706-1722.

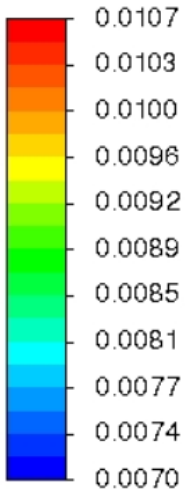
Sulfur Mass Fraction

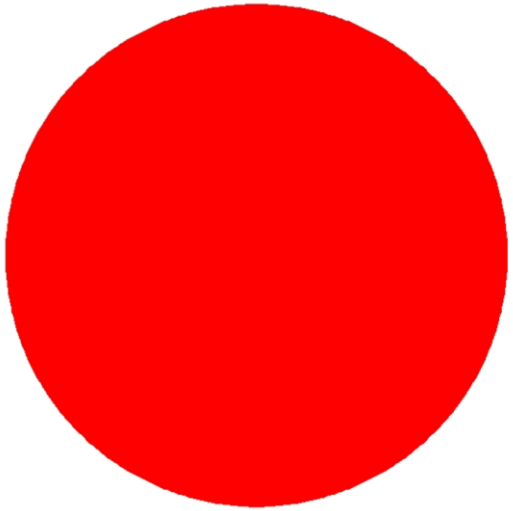
- Preliminary results
  - Sulfur mass fraction reduced at slag-metal interface
  - Desulfurization rate decreases closer to the slag eye location
    - Slag eye region has no desulfurization, so sulfur defuses into neighboring areas
  - Trend similar to reference work



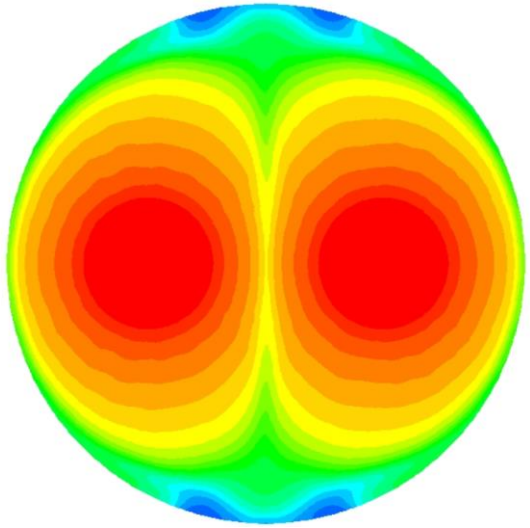
Contours of desulfurization rate

Sulfur mass fraction (%)

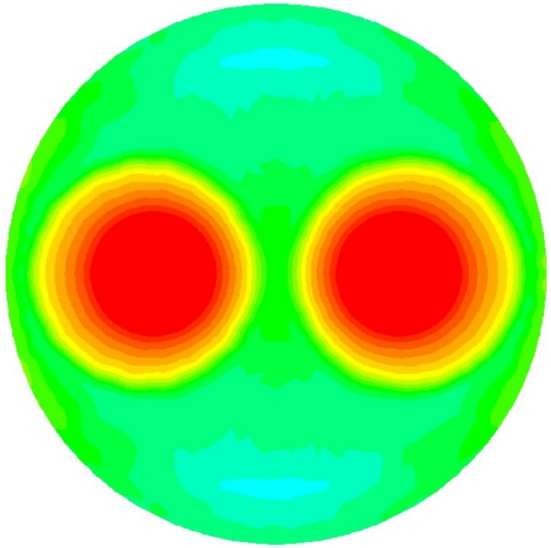




Sulfur mass fraction at t = 0.0s



Sulfur mass fraction at t = 5.0s



Sulfur mass fraction at t = 14.0s

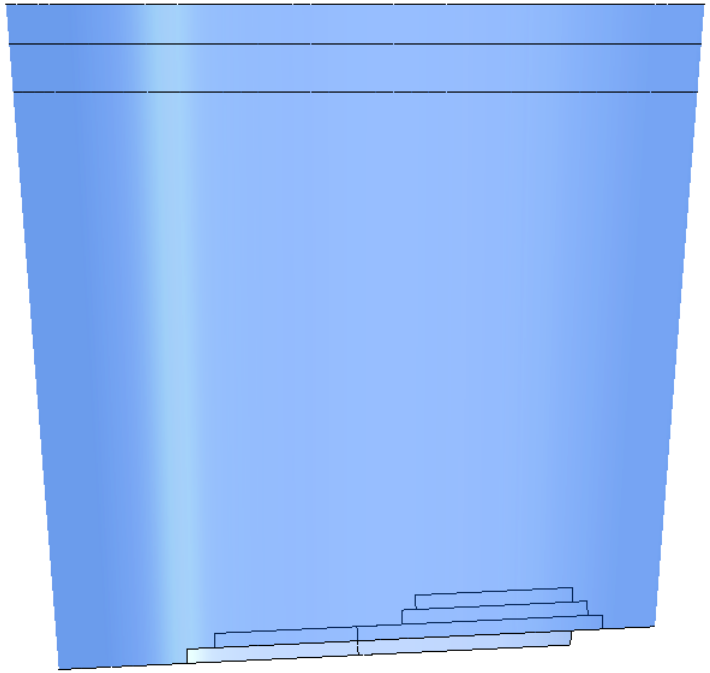
Project 10:
Cleveland Cliffs Gas Stirring Application
Site: Cleveland Cliffs - Mansfield
Start: January 2021

Cleveland Cliffs Ladle Application

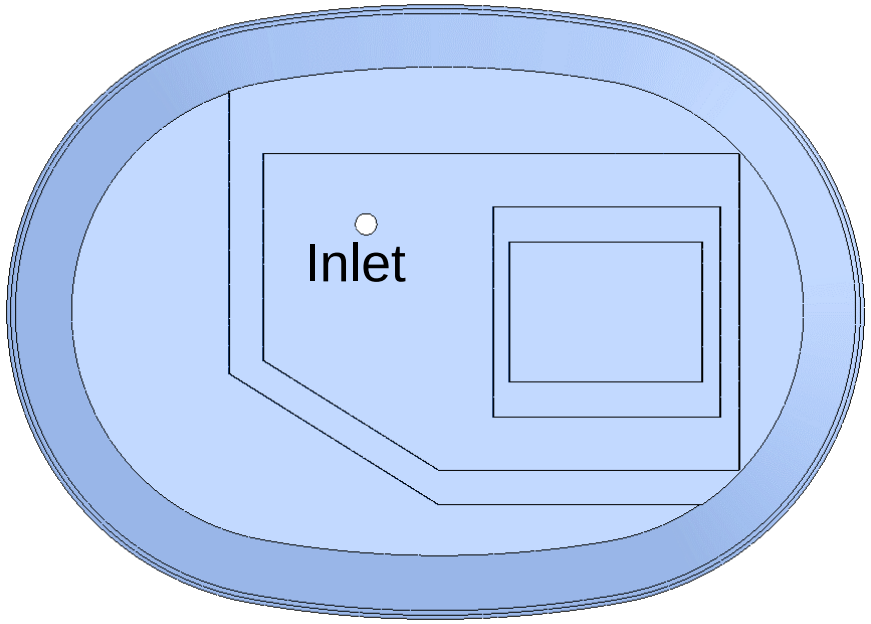
- **Objective:**
  - To utilize SMSVC stirring and inclusion models to help solve problem in real plant operations
  - To help Cleveland-Cliffs obtain an improved understanding of daily routine stirring practices at Mansfield Works
  - To find out location of maximum wall shear stress and velocity distribution at slag-metal interface under different stirring conditions
- **Approach:**
  - Recreate Mansfield Works ladle geometry and perform isothermal multiphase mixing study
  - Analyze and compare the mixing efficiency of several stirring flow rates
  - Examine additional effects such as wall shear stress

Mansfield Ladle Geometry

- Ellipse ladle with three layers: air, slag, steel
- One off-center plug at bottom
- Heat size is 150 tons, with 10" of slag
- Four flow rate scenarios: 2 SCFM, 5 SCFM, 15 SCFM and 26 SCFM



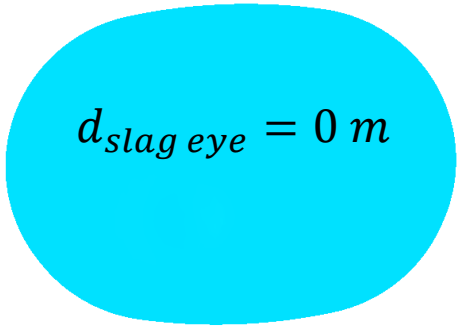
Side view



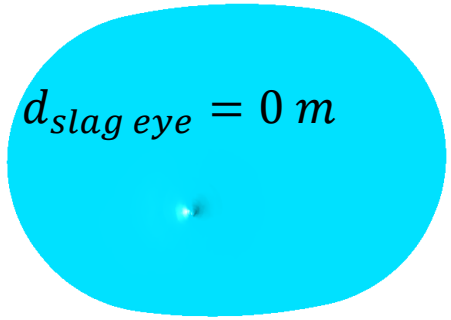
Bottom view

Slag Eye and Flow Field Comparison

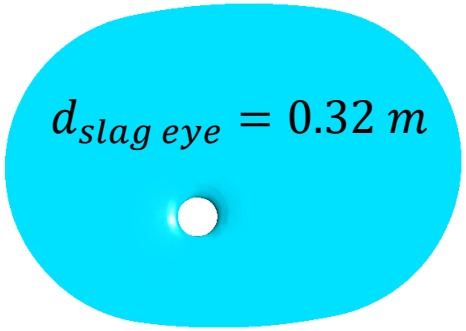
- Comparison slag eye diameter



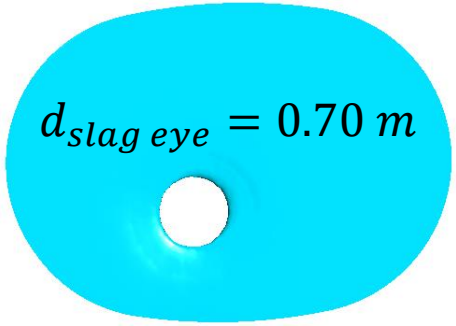
2 SCFM



5 SCFM

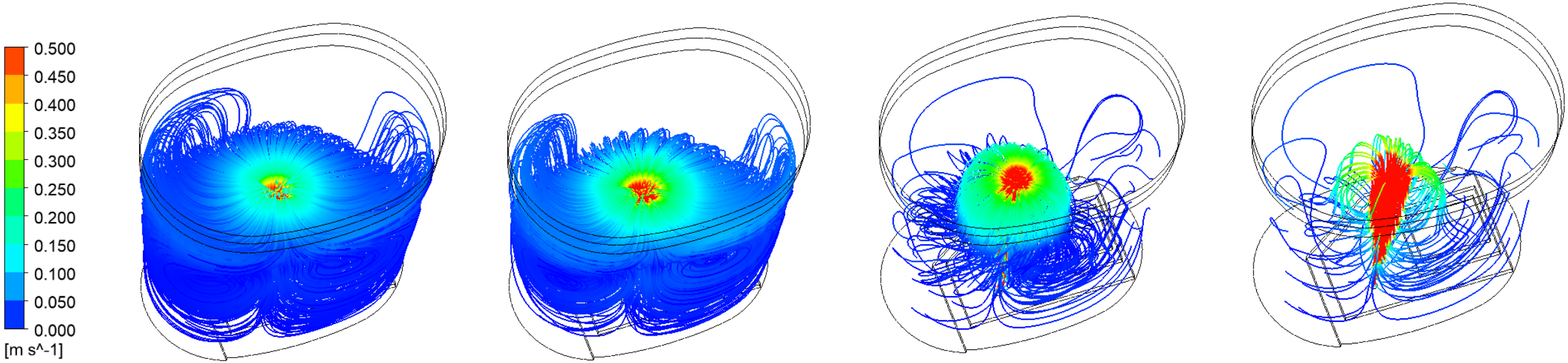


15 SCFM



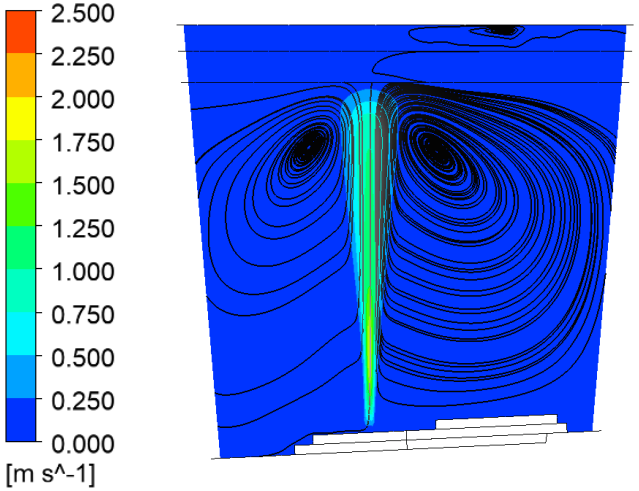
26 SCFM

- Comparison streamline in the ladle

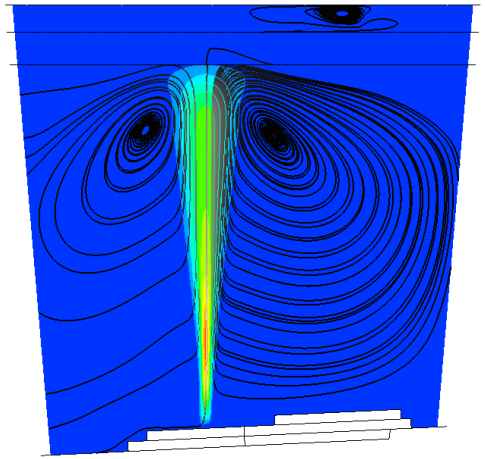


2 SCFM 5 SCFM 15 SCFM 26 SCFM

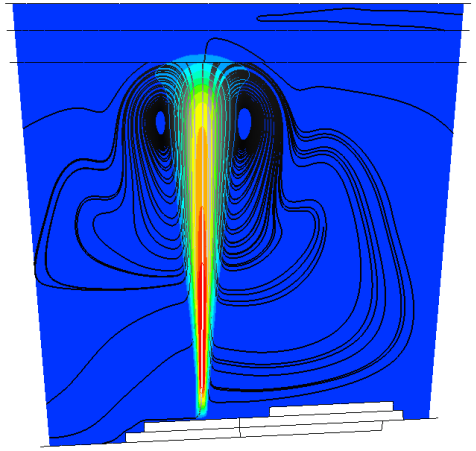
Flow Field Comparison



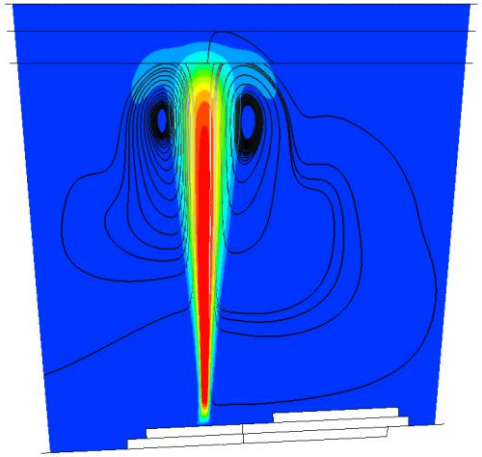
2 SCFM (Plane 1)



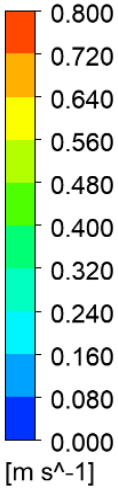
5 SCFM (Plane 1)

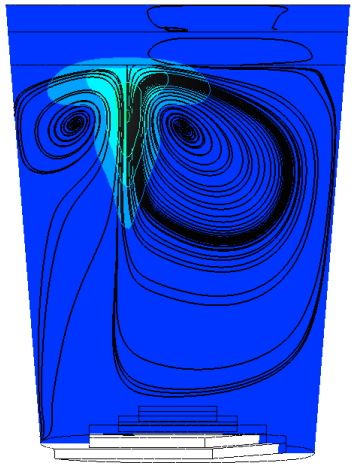


15 SCFM (Plane 1)

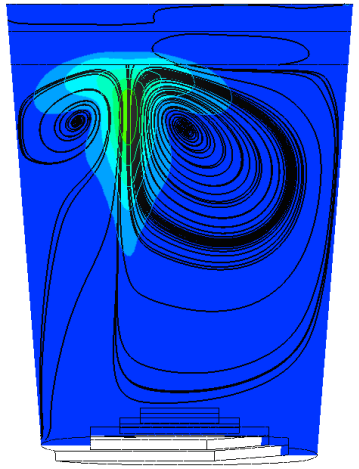


26 SCFM (Plane 1)





2 SCFM (Plane 2)



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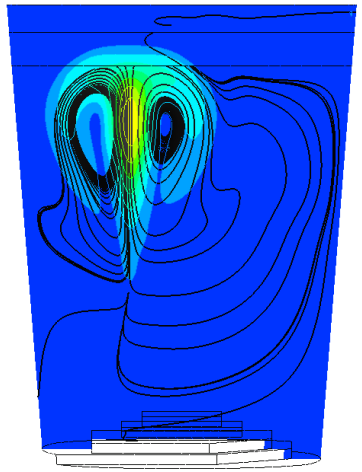
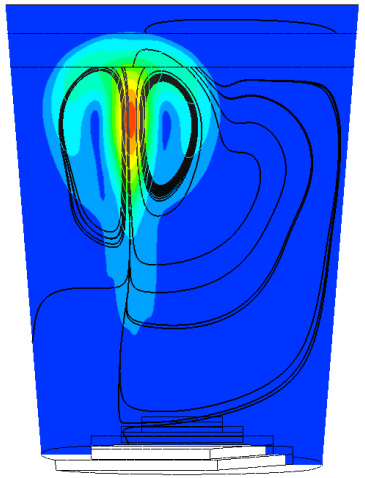
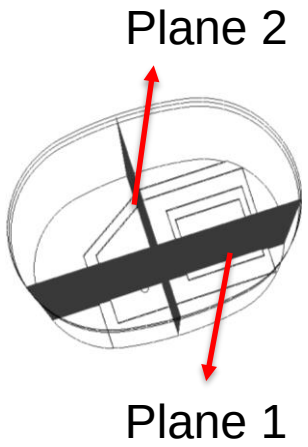


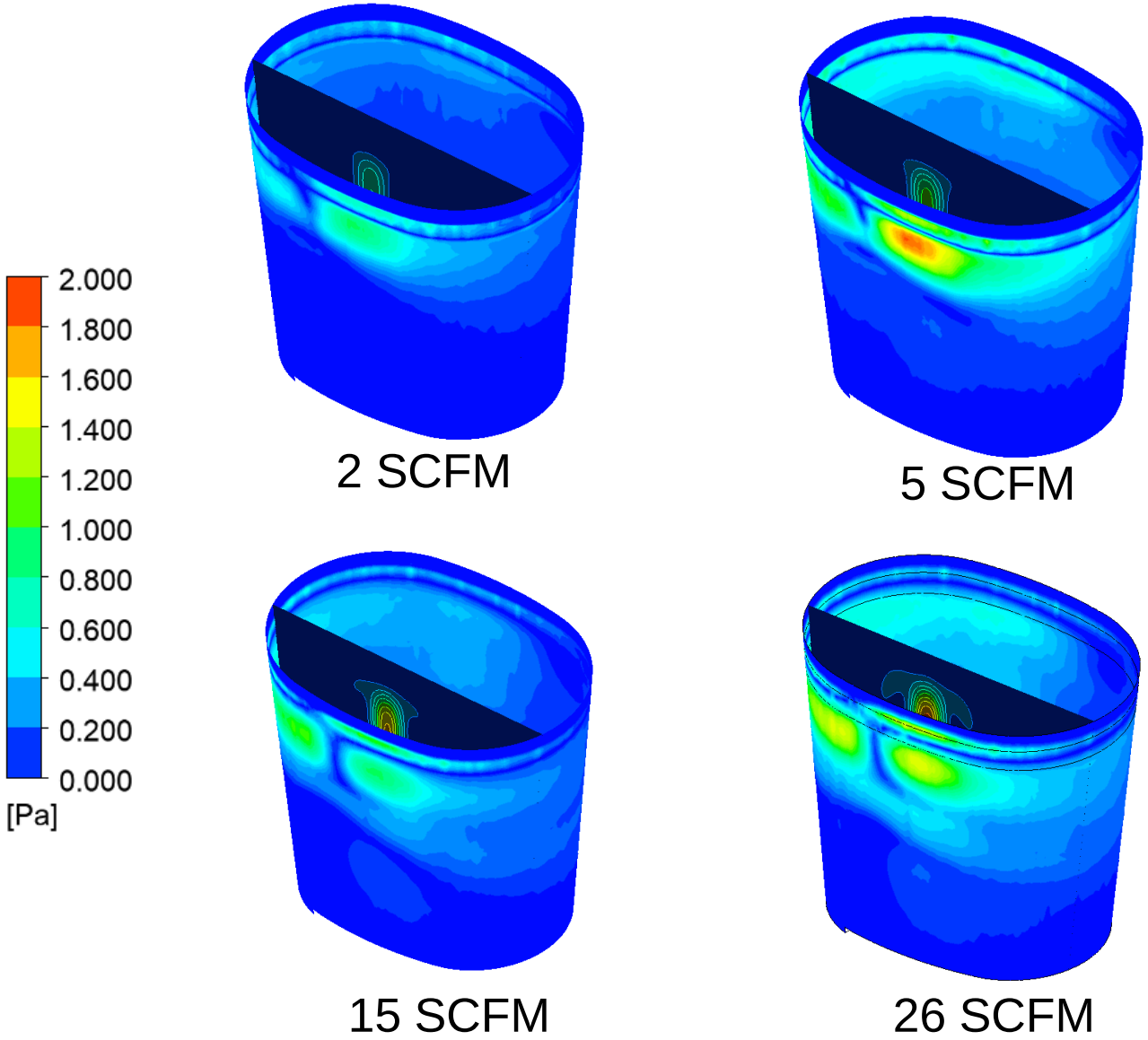
15 SCFM (Plane 2)



26 SCFM (Plane 2)



Wall Shear Stress Comparison

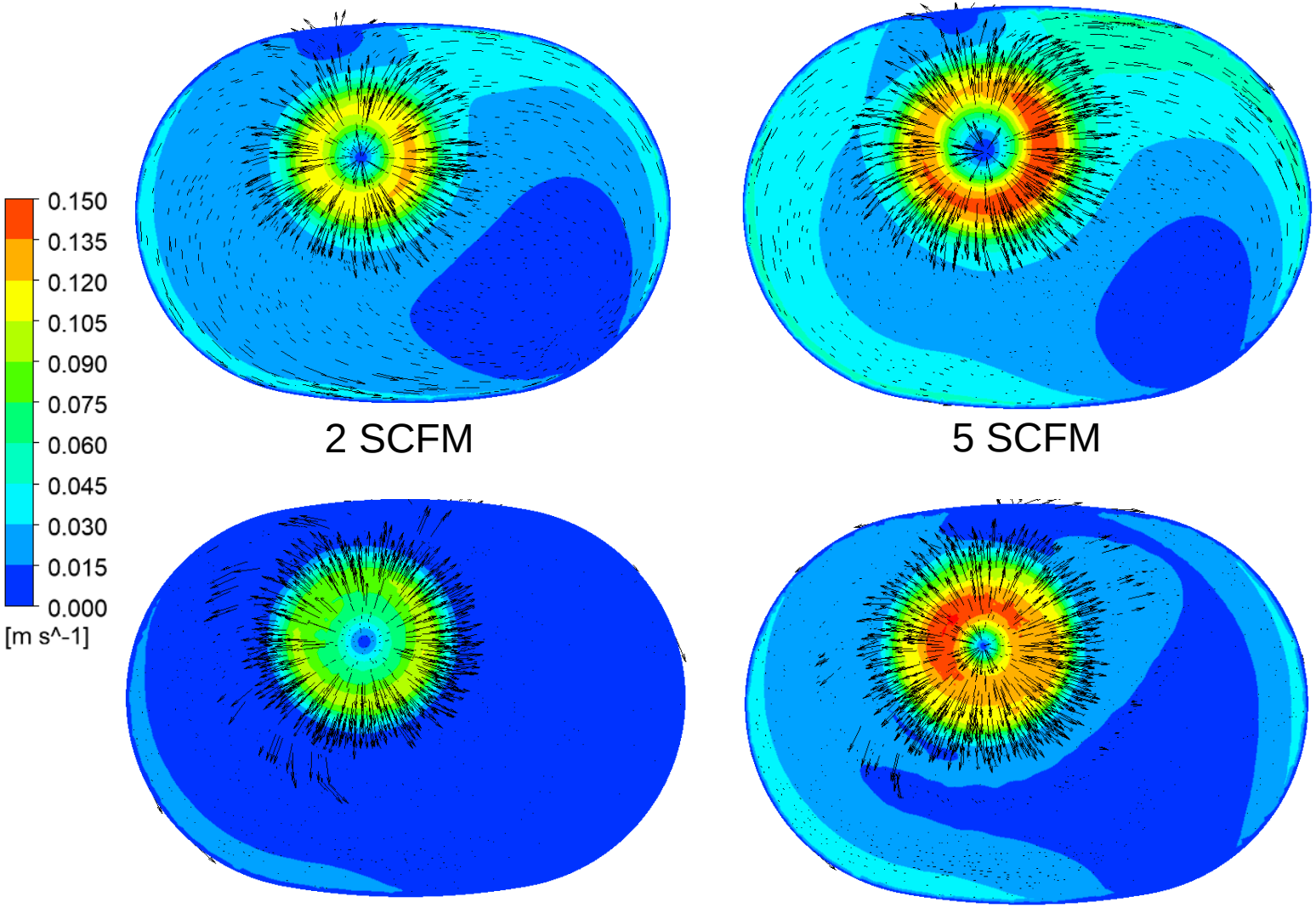


Case	Maximum wall shear stress (Pa)
2 SCFM	0.93
5 SCFM	1.88
15 SCFM	1.08
26 SCFM	1.45

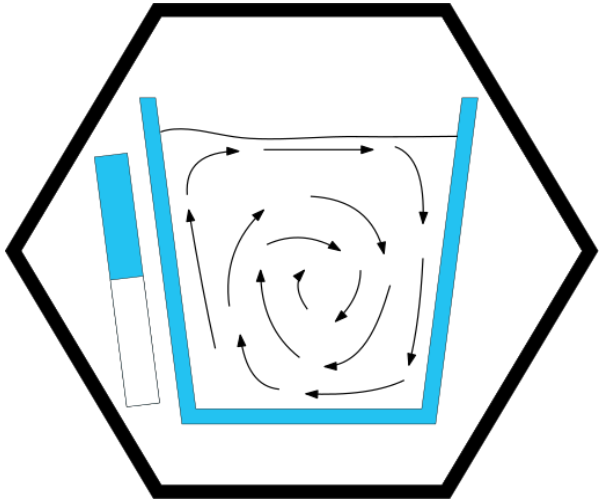
- At lower flow rate without a slag eye, shear stresses increase as flow rate increases
- After slag eye appears between 5 and 15 SCFM, wall shear stresses decrease
  - Increased flow then raises wall shear stress again

Interface Velocity Distribution Comparison

- Slag-steel interface



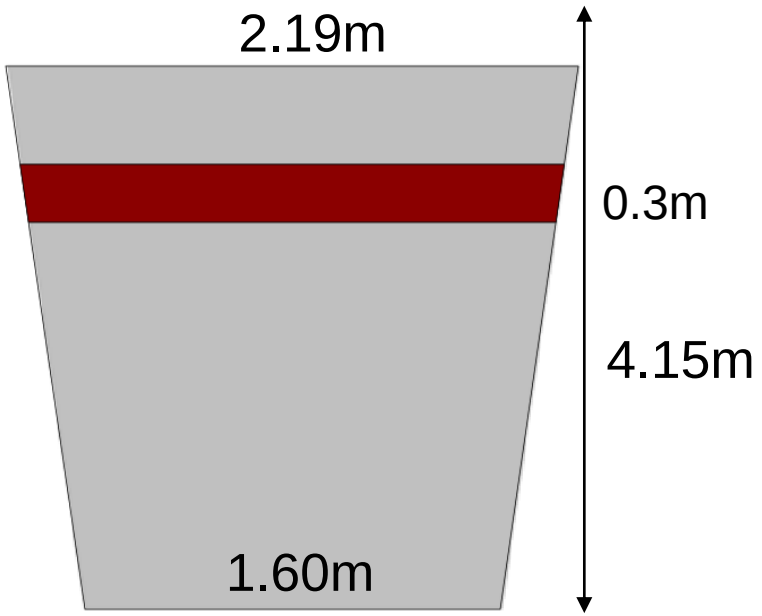
- Contour shows tangential velocity at slag steel interface
- The bubble plume pushes slag outwards
- Before and after slag eye appear, increase flow rate, the average velocity will increase
- When slag eye just appear, the interface velocity decreases



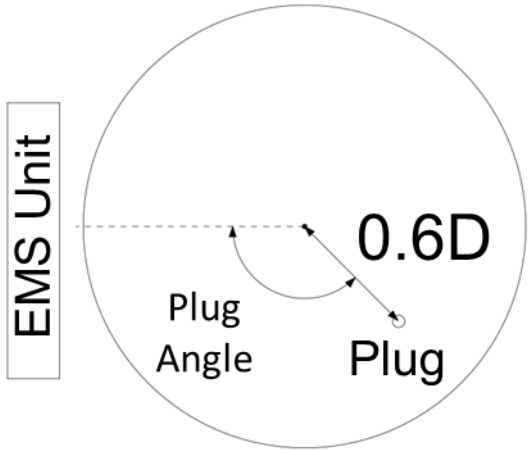
Project 7:
EMS and Combined Gas-EMS Study
Site: Indiana Harbor Ladle
Start: April 2020

EM-Gas Simulation

- **Objective:**
  - Simulate combined stirring of EMS field and argon injection
  - Compare resulting flow fields for three different plug placements
- **CFD Model:**
  - Isothermal transient model of EMS Lorentz forces and single 5 SCFM bottom plug
- **Approach:**
  - Use directly-imported Lorentz forces to bypass magnetic field simulation
  - Investigate and compare behavior for 0, 90, and 180 degrees between LF-EMS and plug
  -



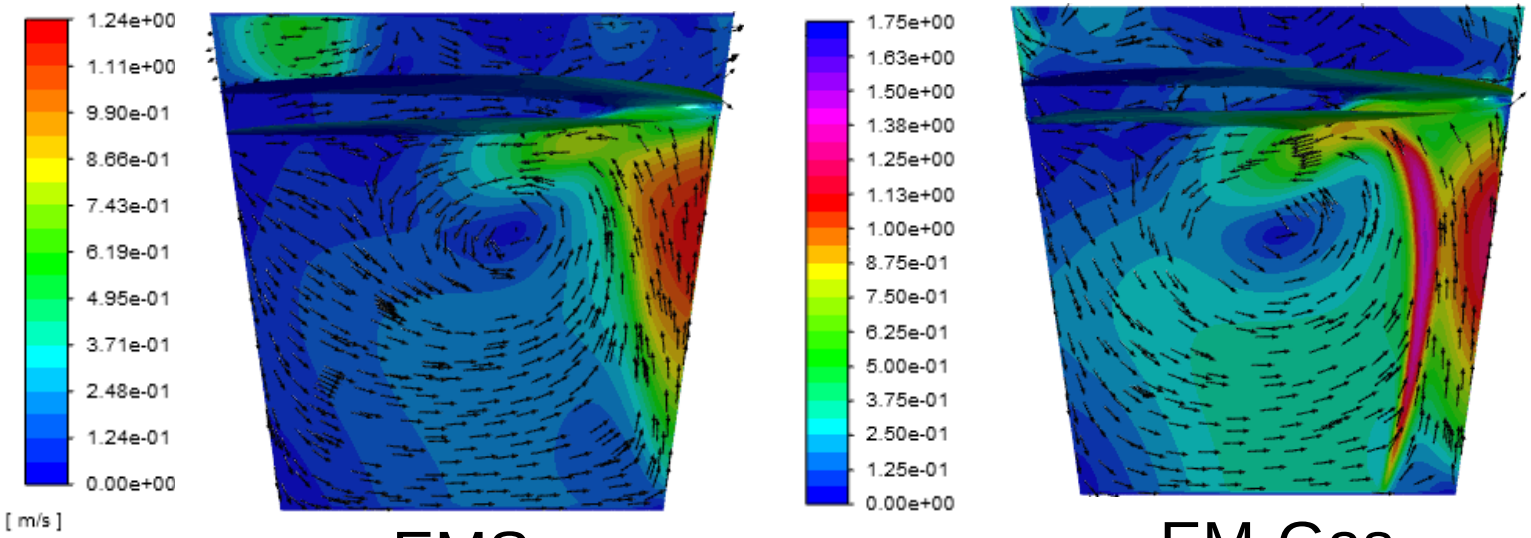
EMS/EM-Gas Ladle



Relative positions of plug and stirring unit

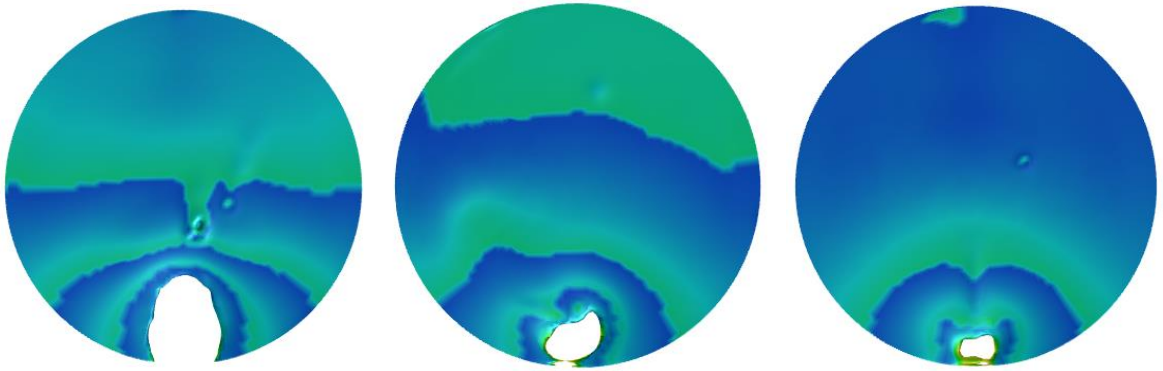
Comparison of Plug Flow Slag Eye

- Plume & EMS flow forces influence one another near top slag-steel interface
- EMS velocity:
  - Peak: 1.24 m/s
  - Average: 0.25 m/s
- EM-Gas velocity:
  - Peak: 1.59 m/s
  - Average: 0.35 m/s
- Case with 0º plug position shows much larger slag eye than other cases
  - Flow is accelerated due to “same direction” plug placement



EMS EM-Gas

Velocity flow fields



0º 90º 180º

EM-Gas slag opening (Top view)

EM-Gas Mixing Time and Wall Shear Stress

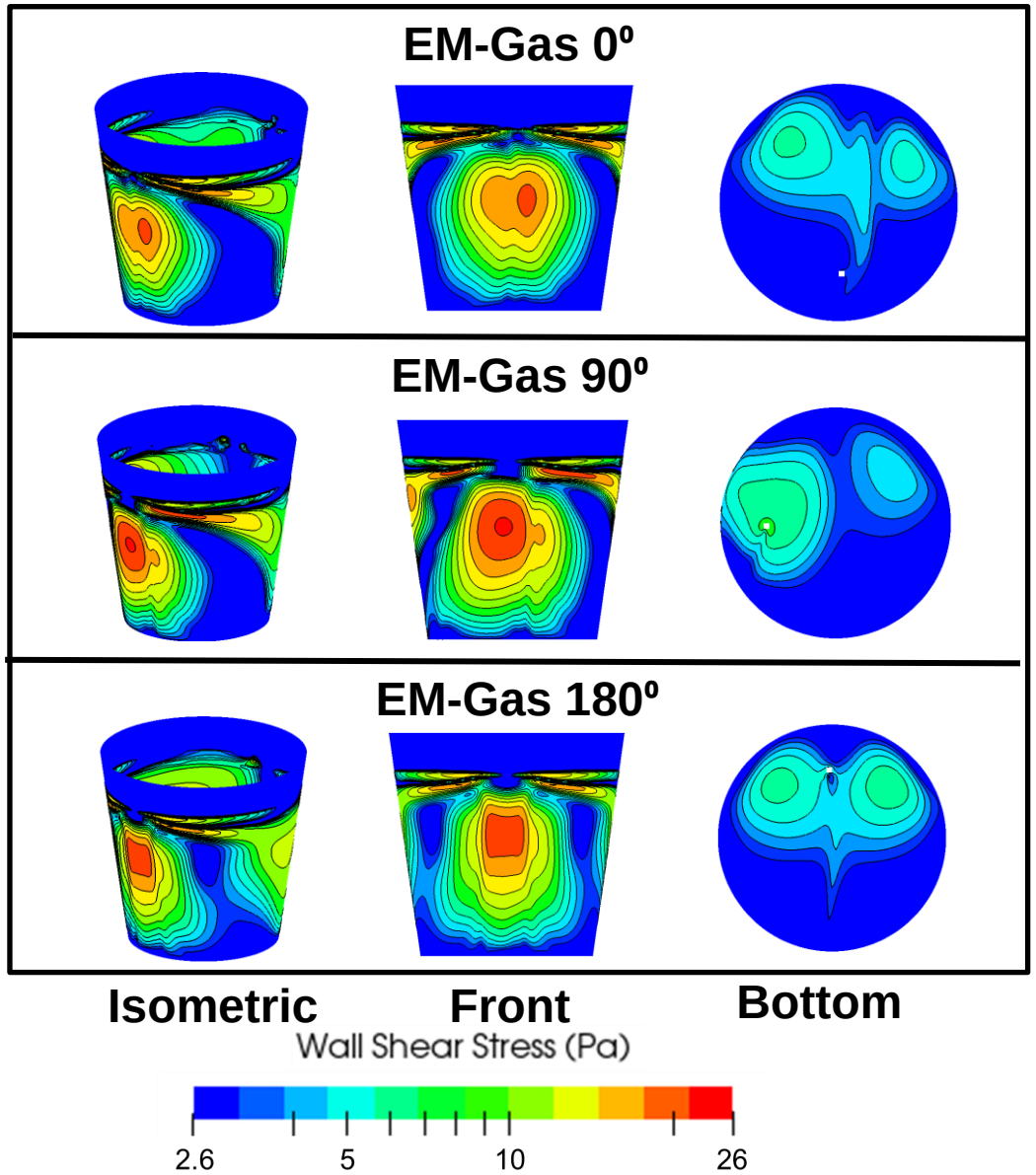
- EM-Gas shows slower mixing time than EMS-only
  - Best performer at 0° plug position

Mixing Time	**EMS**	**0º**	**90º**	**180º**
SMSVC	58	188	245*	240

* One point excluded due to placement issue. With point, time is >310 s

- Wall shear stresses are 16.7% higher for 90º than 0º but 180º has highest peak stress

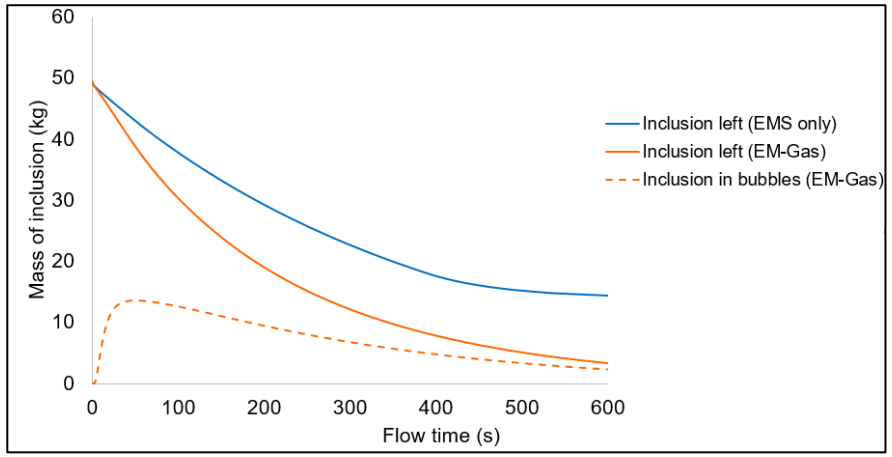
	Wall Shear Stress (Pa)	
	Peak	**Average**
EM-Gas 0º	22.7	4.316
EM-Gas 90º	26.5	4.848
EM-Gas 180º	23.8	4.960



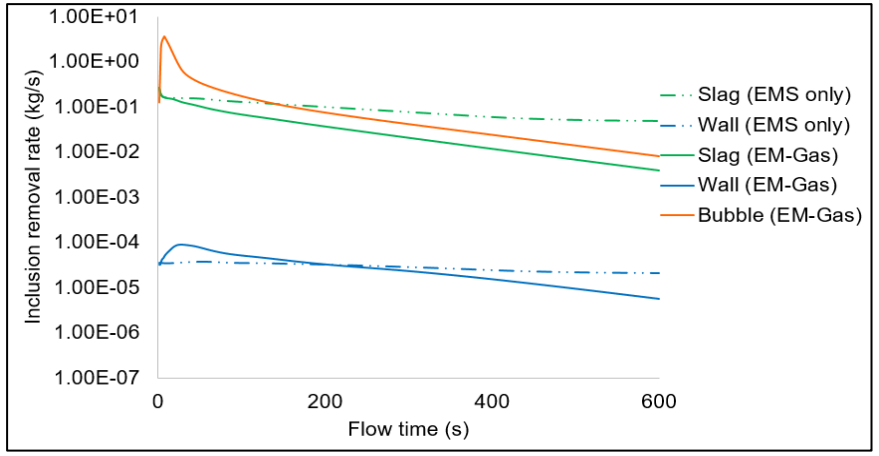
Inclusion Removal

- Inclusion sizes included range from 1.5 μm to 48 μm
- After 600 seconds, EM-Gas has more-thorough inclusion removal than EMS alone
- Strongest removal method in EM-Gas is bubbles, followed by slag and wall.
- EMS-only has primarily slag-based inclusion removal
- Bubble and slag removal in gas case reduces in effectiveness over time, while EMS shows more consistent removal rate (though by slag only)

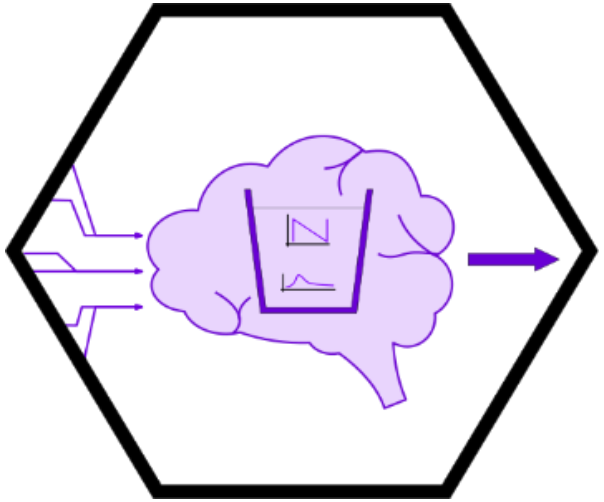
Case	EMS only	EM-Gas
Inclusion removal rate (600s)	71.0%	93.3%
Inclusion in bubbles (600s)	-	4.6%



Mass of Inclusion in Different Ladle



Removal Rate Due To Different Mechanisms



Project 9:
Smart Ladle AI-Based Tool
Site: SDI Butler Division
Start: September 2019

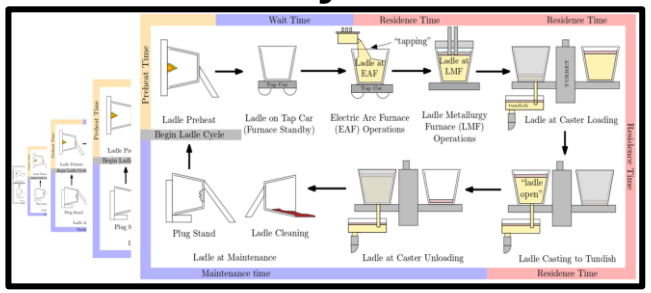
Smart Ladle

- **Issue:**
  - Operators must predict future temperature requirements using limited information
- **Methodology:**
  - Machine learning model trained using ladle and casting process history data
  - Trained model applied to ladle at the LMF to predict temperature during casting
- **Potential Impacts:**
  - Improved operational responses for casting temperature control
  - Recognition of special circumstances

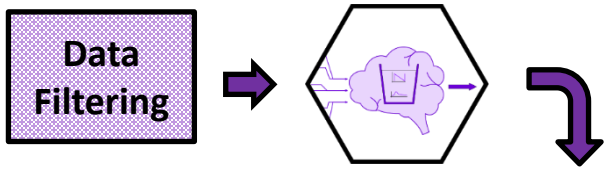
Smart Ladle

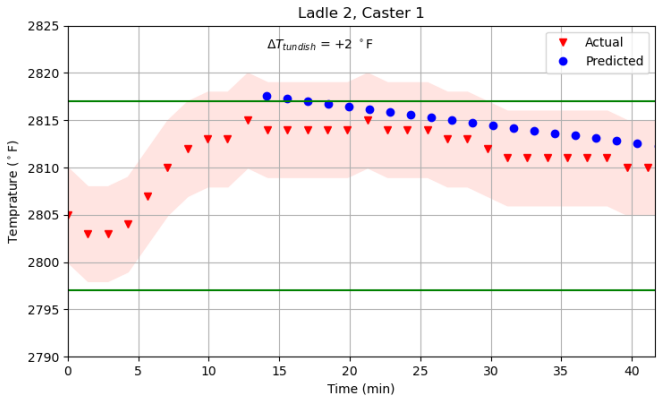
- After an LMF temperature measurement is taken, Smart Ladle code processes ladle data
  - Steel contact time, number of heats on ladle, temperature measurement, etc.
- Using a machine learning algorithm trained by SDI Butler Division historical data, model makes two predictions:
  - Tundish midpoint temperature
  - Temperature slope at midpoint
- Inputs and results displayed to operator in user interface

Ladle Process & History Data



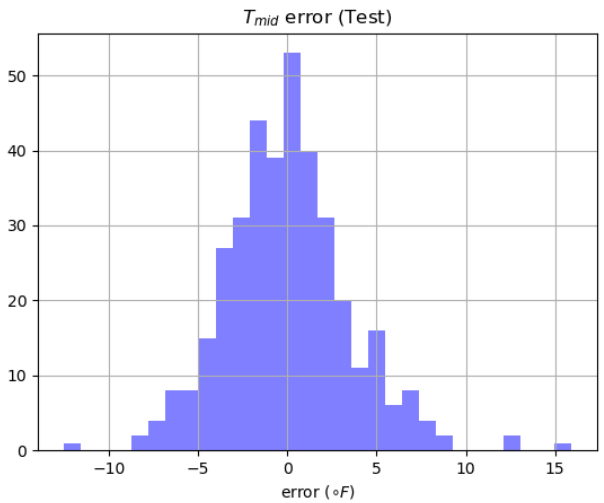
Smart Ladle



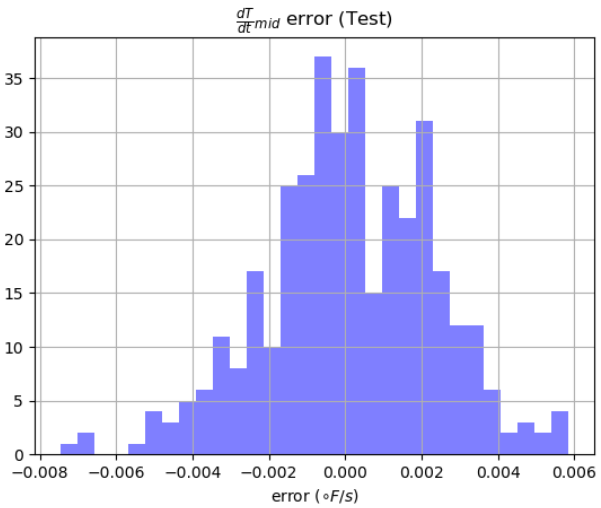


Results

- LightGBM model shows great performance for accuracy of midpoint temperature and slope
  - Test dataset shows an average error below **3°F**, with a standard deviation of **3.51°F**
  - Three heats outside outlier range of 15°F error



Midpoint Temperature Error Distribution

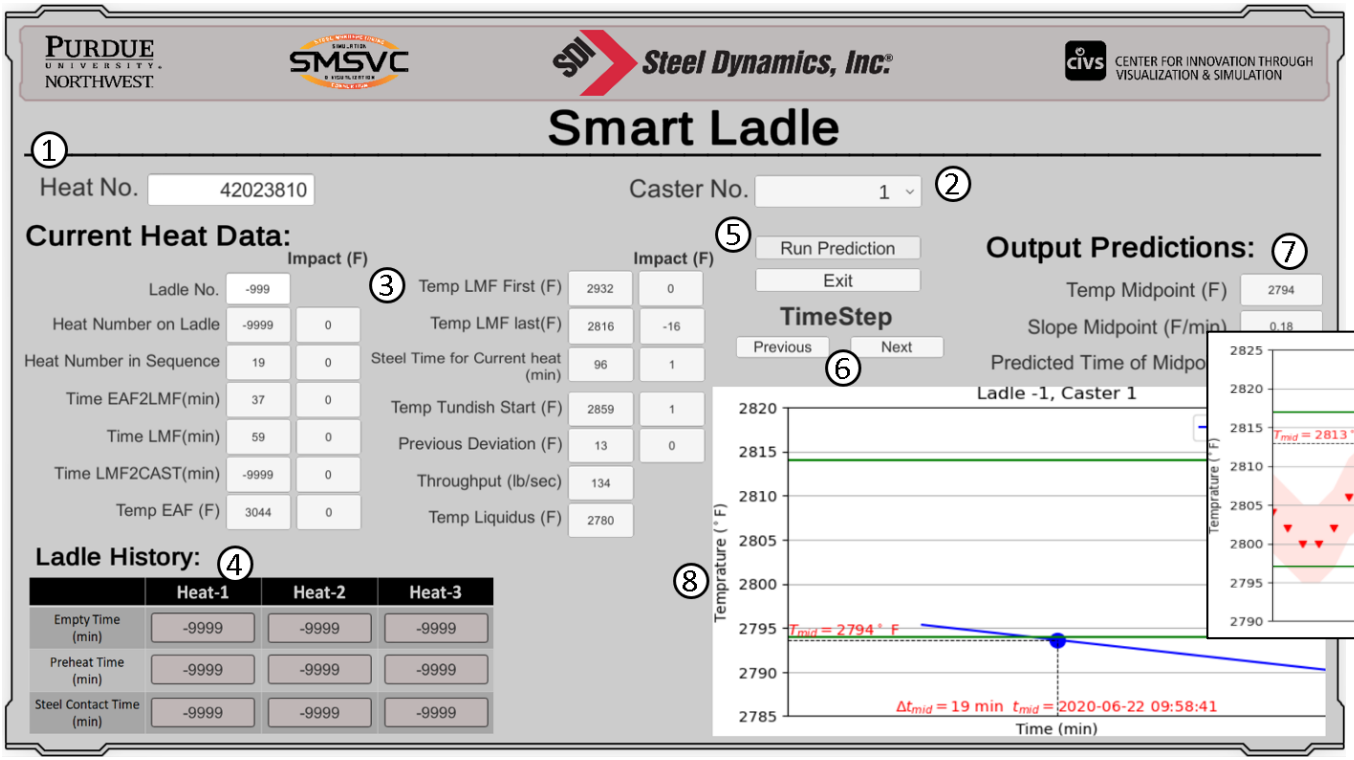


Midpoint Slope Error Distribution

	Midpoint Temperature (F)		Midpoint Slope (F/min)		Temperature Outliers (F)	
Dataset	**MAE**	**RMSE**	**MAE**	**RMSE**	**Lowest**	**Highest**
Training	1.48	1.92	0.09	0.120	-9.86	8.84
Validation	3.09	3.99	0.108	0.138	-10.81	15.97
Test	2.62	3.49	0.108	0.132	-12.54	15.93
Previous Model's Best	8.18	10.66	0.156	0.222	-21.36	71.47

Smart Ladle Interface

1. Target Heat Number
2. Caster Number
3. Current Heat Data with Impact
4. Ladle History
5. Run Prediction/Exit
6. Next/Previous
7. Prediction Outputs
8. Prediction Plot



History & Prediction Plot

- Clicking “Run Prediction” will use input heat number to create prediction for both casters and show expected behavior in a plot
- Clicking “Next/Previous’ will step through sequence data history for target caster. Plot will overlay actual data over prediction

Smart Ladle Implementation

- Implementation testing in progress at SDI Butler Division’
- Next step is to implement at other facilities:
  - Ladle and caster data samples
  - Data table formats for Smart Ladle input/output
  - Interface requirements
  - Re-train model on new data and package standalone interface for testing and feedback

Summary

Summary

- **Project 5: Inclusion Removal Enhancement & Validation**
  - Results from optimized inclusion model is validated well with industrial measurements
- **Project 7: Combined Gas/EMS Ladle Study**
  - Same side upward combined stirring has larger stress & slag penetration but lower mixing times than combined stirring with plug placement on the opposite side
- **Project 8: Desulfurization and Re-oxidation**
  - Updated flow field including turbulence dissipation rate and velocity
  - Updated mass transfer coefficient and desulfurization rate based on the flow field
- **Project 9: Smart Ladle**
  - Changes in model have increased accuracy of the predictions
  - Standalone interface has been implemented and is being tested

Future Work

- **Project 5: Inclusion Removal Enhancement & Validation**
  - Further validation with more industrial data
  - Evaluate inclusion removal for various stirring conditions
- **Project 7: Combined Gas/EMS Ladle Study**
  - Simulate EM field with gas injection in top lance ladle
- **Project 8: Desulfurization and Reoxidation**
  - Improvement of the flow field especially dissipation rate
  - Desulfurization rate verification with literature work
- **Project 9: Smart Ladle**
  - Adapt standalone interface to work with data from other facilities
  - Implementation testing at other plants
- **Project 11: Shipping Temperature and Superheat Control**
  - Non-isothermal gas-stirred ladle simulation
  - EMS joule heating and arcing reheating
- **Project 12: Minimization of Ladle Erosion and Wear**
  - Mechanical and chemical erosion effects

Comments from Industry Collaborator

Thank You
Questions and Comments

Thank You

Q&A