COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

Project Technical Committee (PTC):

- Joshua Anderson (AK Steel)
- Bill King (AK Steel)
- Paul Wu (AK Steel)
- Hoyong Hwang (ArcelorMittal)
- Judy Li (ArcelorMittal)
- Rui Liu (ArcelorMittal)
- Raphael Garcia da Silveira (Charter Steel)
- Taylor Zornes (EVRAZ NA)
- Kendal Dunnett (EVRAZ NA)
- Bikram Konar (EVRAZ NA)
- Jeffrey Becker (USS)
- Henrique Lize (Gerdau)
- Denise Correa de Oliveira (Gerdau)
- David Sandoval (Gerdau)
- Adam Tabor (Gerdau)
- Carlo Travaglini (Gerdau)
- Joshua Young (Gerdau)
- Michael Zuker (Gerdau)
- Joe Maiolo (Linde)
- Josh Heaton (NLMK)
- Steve Ryan (NLMK)
- Abhishek Bhansali (NUCOR)
- Helmut Oltmann (NUCOR)
- Vivek Thapliyal (NUCOR)
- Yury Krotov (SDI)
- Sunday Abraham (SSAB)
- Yufeng Wang (SSAB)
- Fernando Guerra (Stelco)
- Mitchell Klaas (Stelco)
- Sanjna Pradhan (Stelco)
- Lewyn Valladares (Stelco)
- Richard Zhang (Stelco)
- Kumar Subramanian (Tata Steel)

CIVS Team (current):

- Xipeng Guo
- Joel Godinez
- Congshan Mao
- Zhankun Luo
- Nicholas Walla
- Armin Silaen
- Chenn Zhou

"Where Ideas Become Reality"

CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

PURDUE UNIVERSITY NORTHWEST

2200 169th Street
Hammond, IN 46323

219.989.2765
civs@pnw.edu
centers.pnw.edu/civs

steelconsortium.org

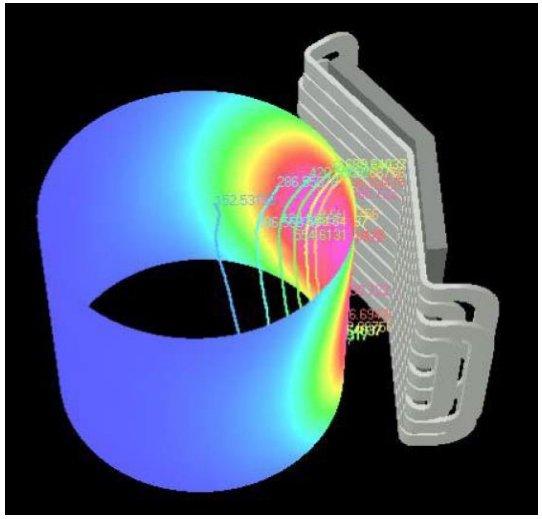
Presentation Outline

- Introduction
  - Objectives & Roadmap
  - Outcomes
  - Project Timeline
- Methodology and CFD Models
- Projects – 2020
  - Inclusion Growth & Removal
  - Chemical Model
  - Plug Clogging Study
  - EMS Ladle
  - Smart Ladle
- Summary & Future Work

Research Motivation

- **Current Issues**
  - Complex transport phenomena with multiple process variables
  - Difficulty in understanding the dynamic evolution of multiphase flow and inclusions

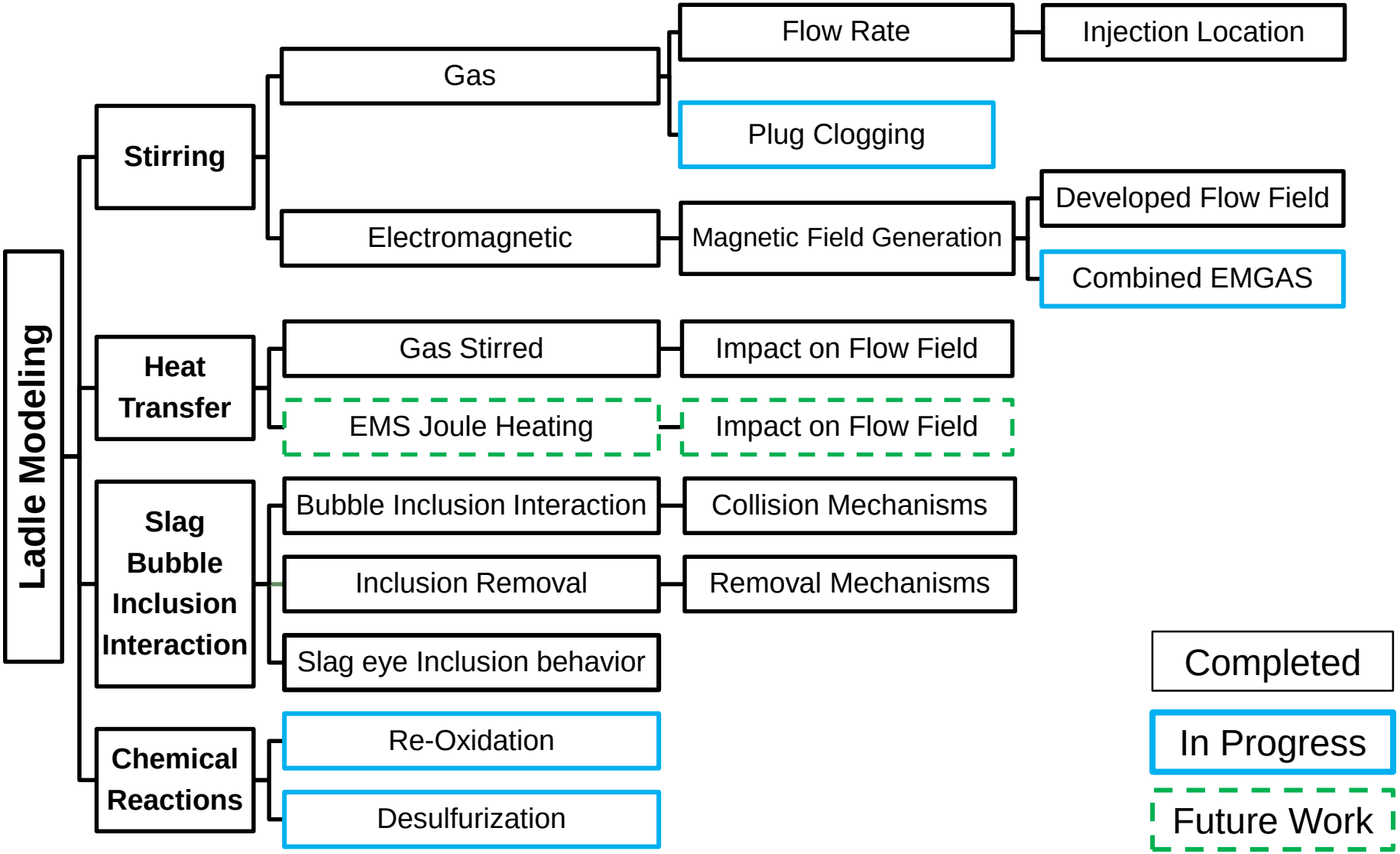
- **Potential Impacts**
  - Process design of optimized flow condition and physical properties
  - Steel cleanliness improvement and final defects reduction



Research 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, and equipment lifetime with normal operation process and with unexpected industrial problems

Research Area Roadmap



Major Outcomes – Models & Findings

Projects (2016 – 2020): 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% decrease in mixing time by increasing plug distance ratio by 0.1D
  - 25% decrease in mixing time 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 & Findings

Projects (2016 – 2020): Completed: 4, Ongoing: 5

- **Project #5:** Inclusion Removal Enhancement & Validation – Nucor Generic Ladle
  - Developed slag eye inclusion release model
  - Validated against measurements (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 3.38°F with a standard deviation of 4.35 °F
  - Implemented data-filtering based on sanity checks for physical values

Current Objectives

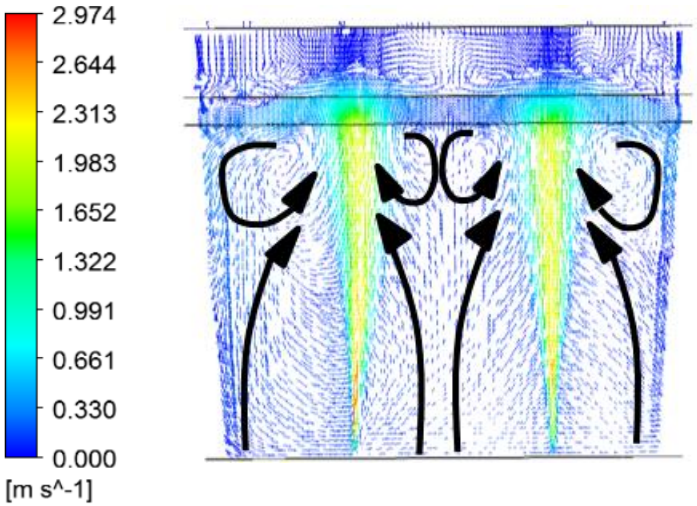
- **Investigate Inclusion Removal in Gas-stirred & EMS Ladle**
  - Improve inclusion removal model by considering inclusion removal behavior due to slag eye area
  - Validate inclusion removal results with experimental measured data
  - Apply inclusion model to EMS & EM-gas ladle
- **Investigate Chemical Reactions in Steel Ladle Refining**
  - Develop chemical reaction model including desulfurization and re-oxidation
- **Smart Ladle**
  - Develop AI engine to guide refining ladle operations

2020 Timeline

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Project 4 EMS Isothermal Ladle	Simulation of EMS with force field supplied by industry partner												
Project 5 Inclusion Removal Enhancement & Validation	Inclusion model refinements												
	Model validation												
	Simulation of inclusion removal using EMS flow field												
Project 6 Plug Clogging Study	Simulations of one plug with gentle and adjusted stirring												
Project 7 Combined Gas-Stirring and EMS	Modeling of combined EMS and gas injection flow field and inclusion modeling												
Project 8 Desulfurization and Reoxidation in Ladle	Literature Search												
	Desulfurization												
	Reoxidation												
Project 9 Smart Ladle	Development of smart ladle machine learning tool												

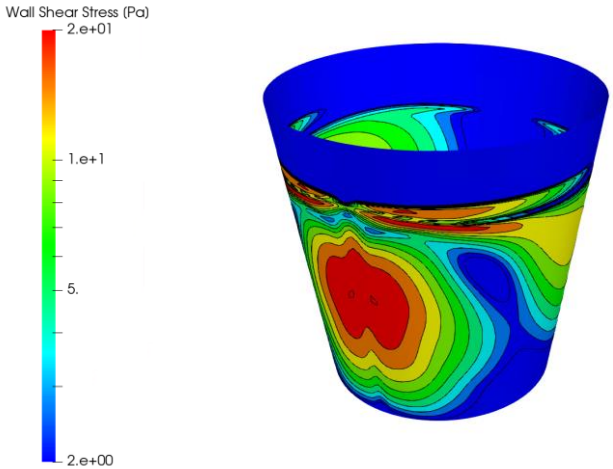
Sample Results (2016 – 2020)

Project 1: Gas-Stirring Flow Simulation

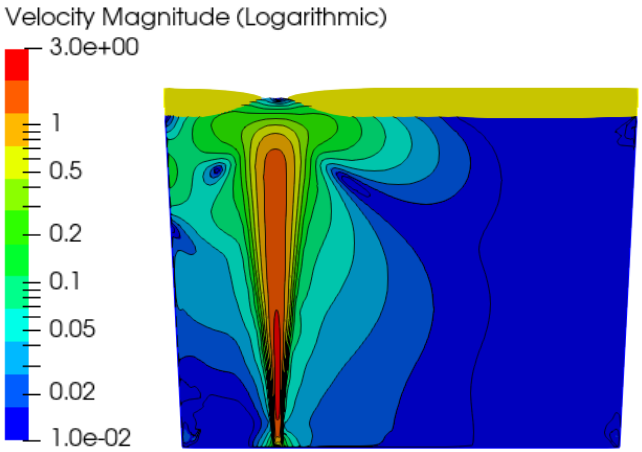


Cases	Investigation Factor	Eye diameter (m)		
		CFD	Experiment data	Percent diff.
Case 1 (Base Case)	-	0.150	0.142	5.69 %
Case 2	Low flow rate	0.135	0.125	7.55 %
Case 3	High flow rate	0.158	0.157	0.65 %
Case 4	Thin top layer	0.202	0.189	6.67 %
Case 5	Top liquid density and viscosity (mustard oil)	0.204	0.227	10.05 %
Case 6	Top liquid density and viscosity (coconut oil)	0.192	0.175	9.95 %

Project 4: Upwards EMS wall shear stress

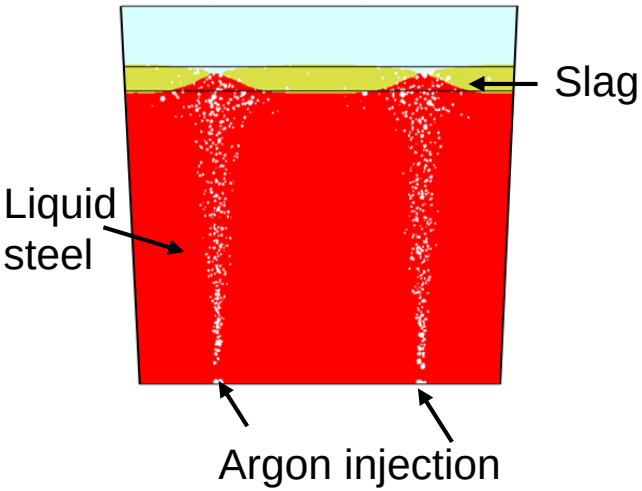


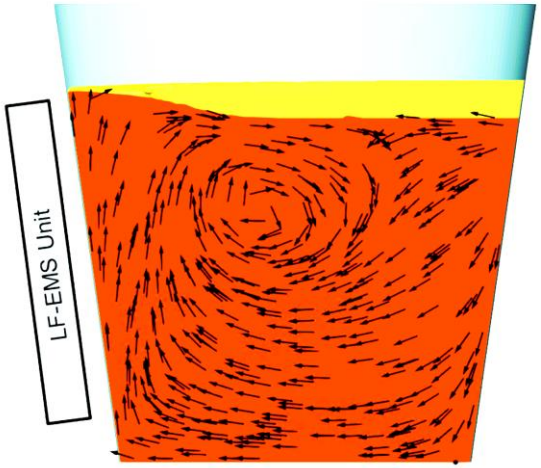
Project 6: 5 SCFM flow field, one plug



CFD Models

- **Gas-stirred and EMS Model**
  - Multiphase turbulent flow
  - Discrete tracking of argon bubbles
  - Bubble breakup and coalescence
  - Momentum source terms for Lorentz force (EMS)
- **Inclusion Model**
  - Population balance model
  - Inclusion aggregation and removal due to wall, slag and bubble
- **Chemical Reaction Model**
  - Species transport
  - Simultaneous reaction model





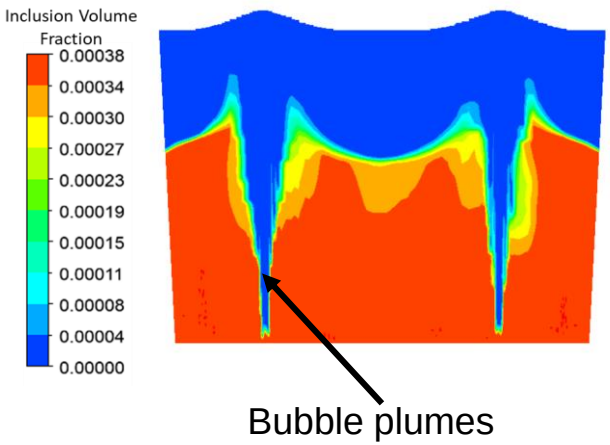
Results since April 2020

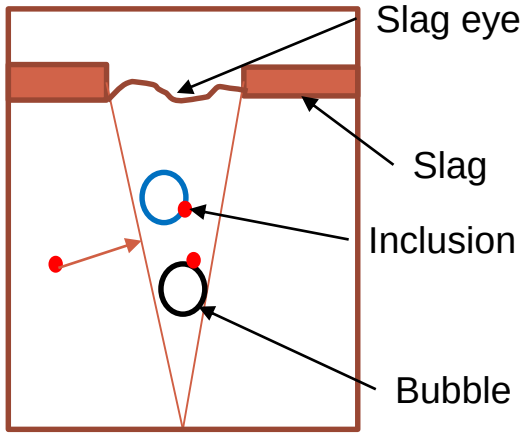
Project 5:
Inclusion Removal Model Enhancement and Validation

Site: Nucor Generic Ladle/Nucor Decatur
Start: November 2019

Inclusion Removal Modeling

- **Objective:**
  - Refine inclusion model (including inclusion release at slag eye)
  - Validate model with laboratory experiment
- **Issue of previous model:**
  - Assumes inclusions are removed by bubbles immediately rather than transported
  - Overpredicts inclusion removal
- **Improved model:**
  - Inclusion transport by bubbles
  - Inclusion re-release at slag eye
  - Inclusion removal at slag-steel interface and walls



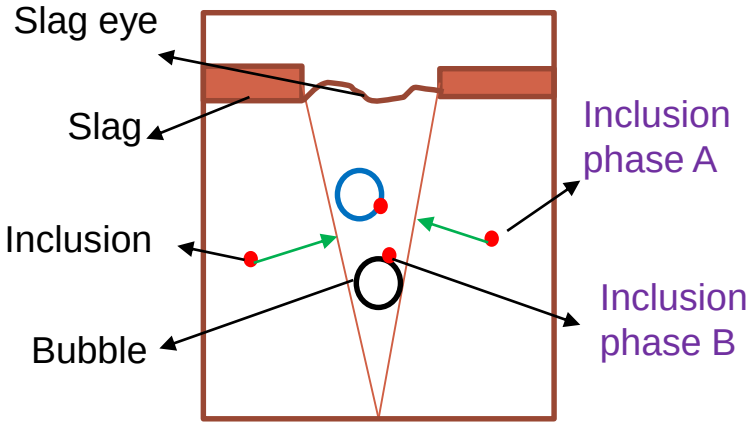


Methodology

1. Flow field of gas-stirring ladle

- Fluid zones (steel and argon)
  - Eulerian-Eulerian multiphase flow
  - Standard k-ε turbulent model
  - Bubble induced turbulence

Velocity ($u_{x,y,z}$), turbulence k & ε, pressure, etc.

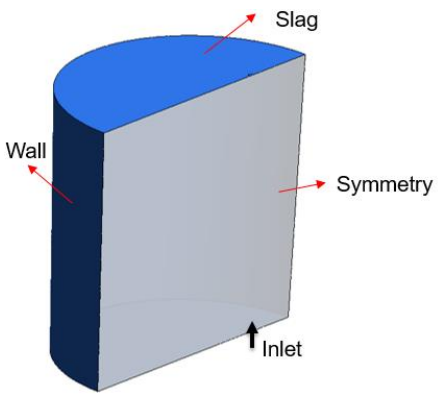


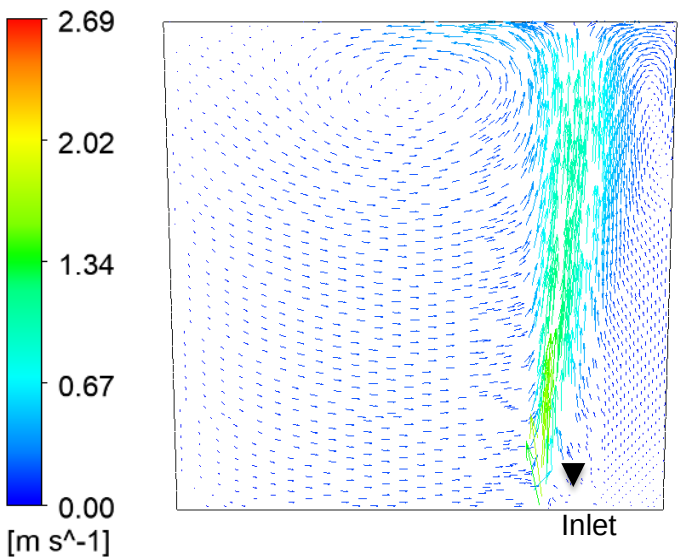
2. Inclusion removal and aggregation model

- 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

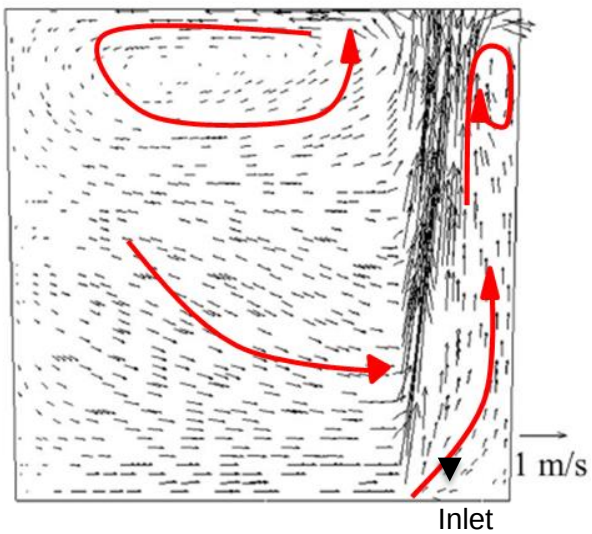
Ladle Geometry and Flow Field

- Geometry from Chen et al. 2019 for validation*
- Assume: top flat free surface as slag
- Results:
  - Gas plume: incline towards wall
  - Flow field: two near-slag recirculation zones





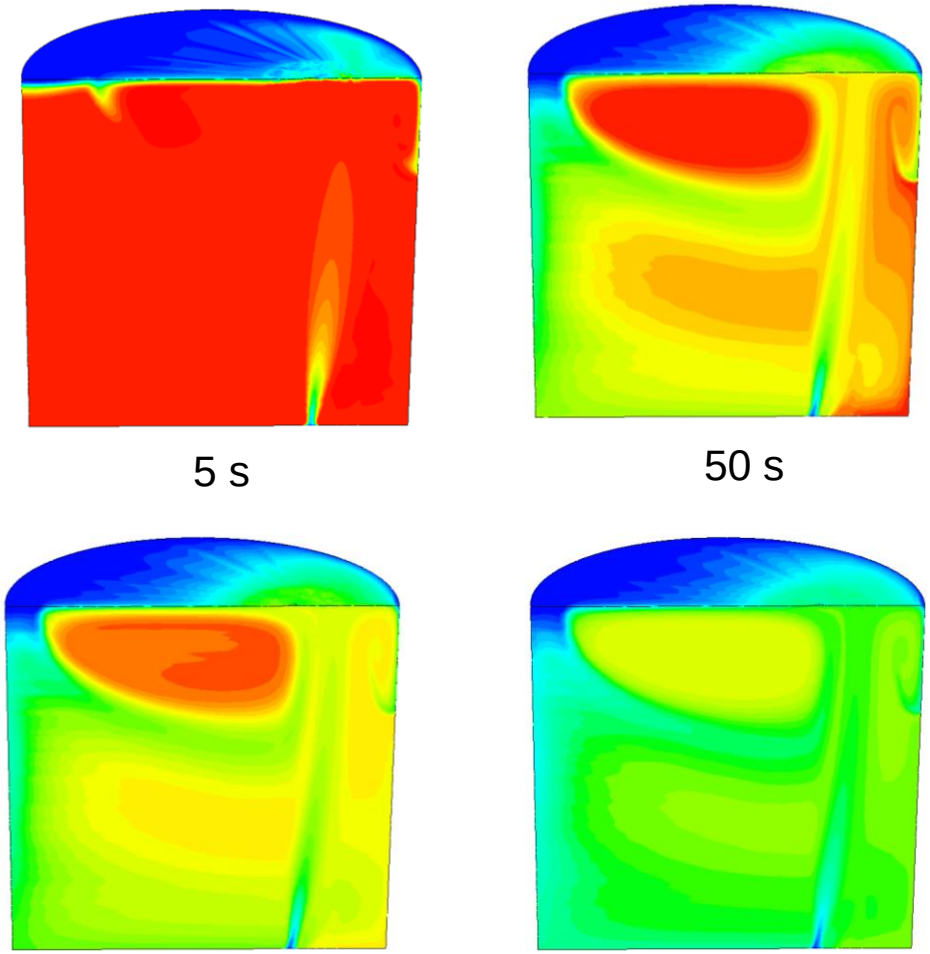
SMSVC Flow Field

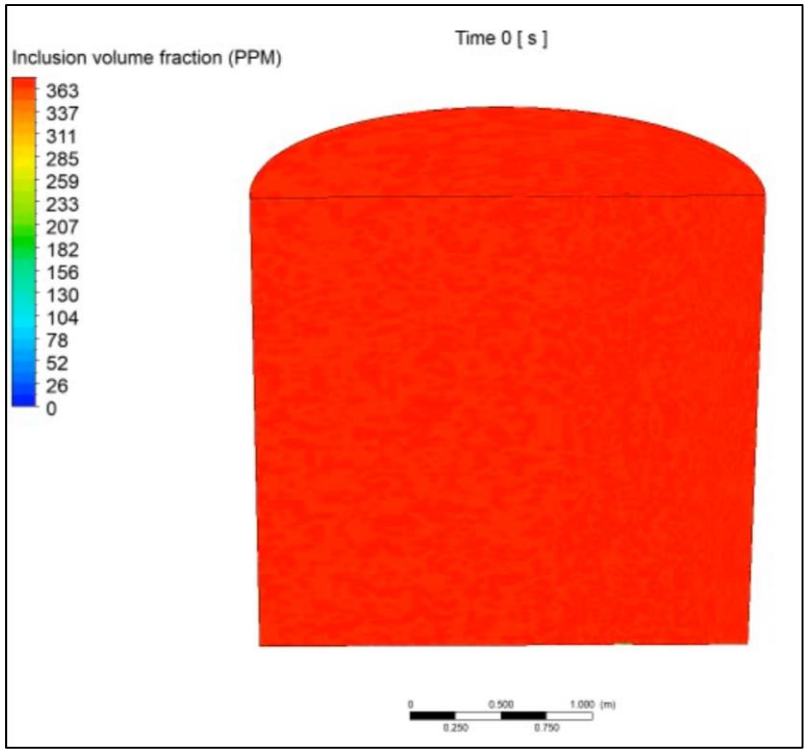


Chen et al.'s Flow Field

- *Chen, Gujun, and Shengping He. "Application of Inhomogeneous Discrete Method to the Simulation of Transport, Agglomeration, and Removal of Oxide Inclusions in a Gas-Stirred Ladle." *JOM* 71.11 (2019): 4206-4214.

Inclusion Volume Fraction

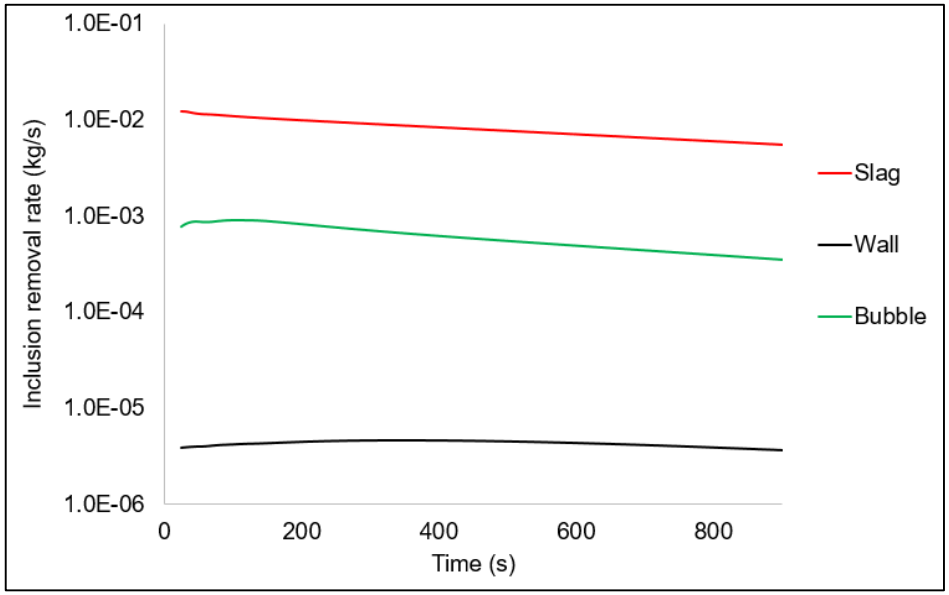




- Inclusions can become trapped in recirculation zones

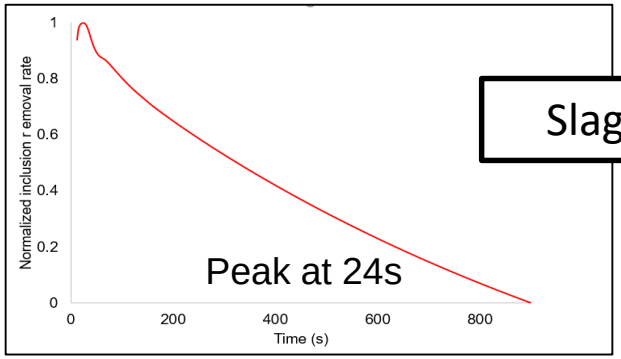
Inclusion Removal Rate

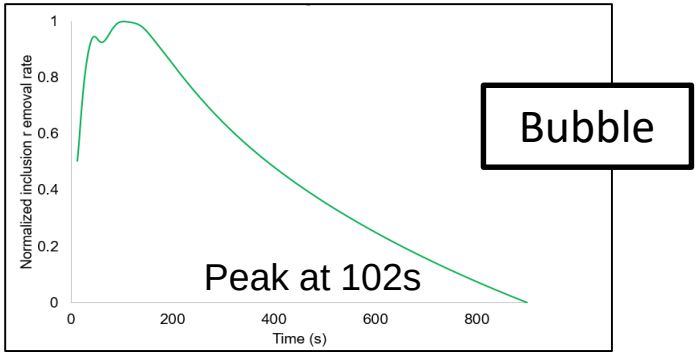
Inclusion Removal Mechanisms

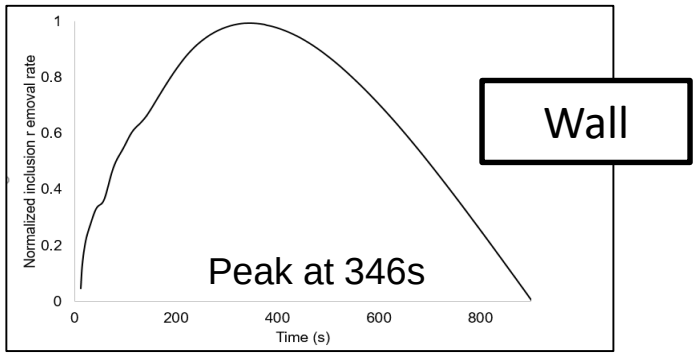


- Removal rate is 51.8% at 900s (15 min)
- Removal rate: Slag > bubble > wall
- All removal rates increase then decrease for each mechanism
  - Different peak time for different mechanisms

Normalized Inclusion Removal Rate

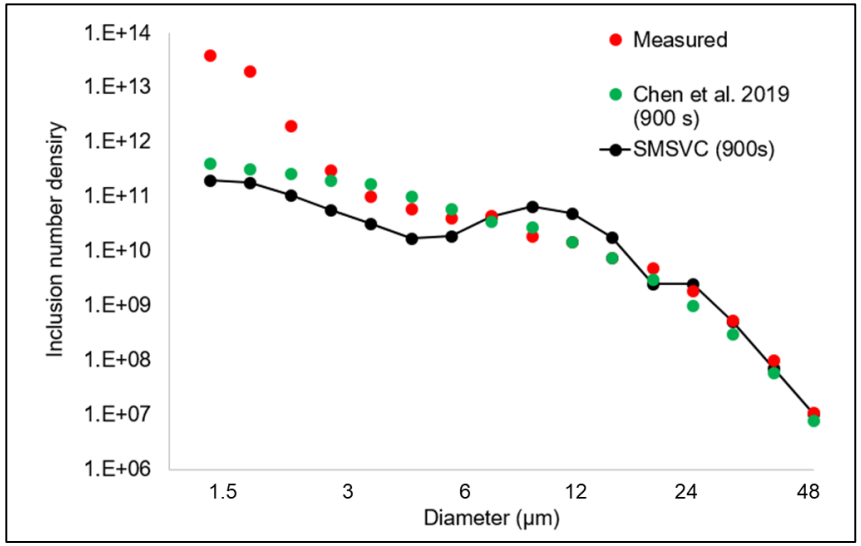




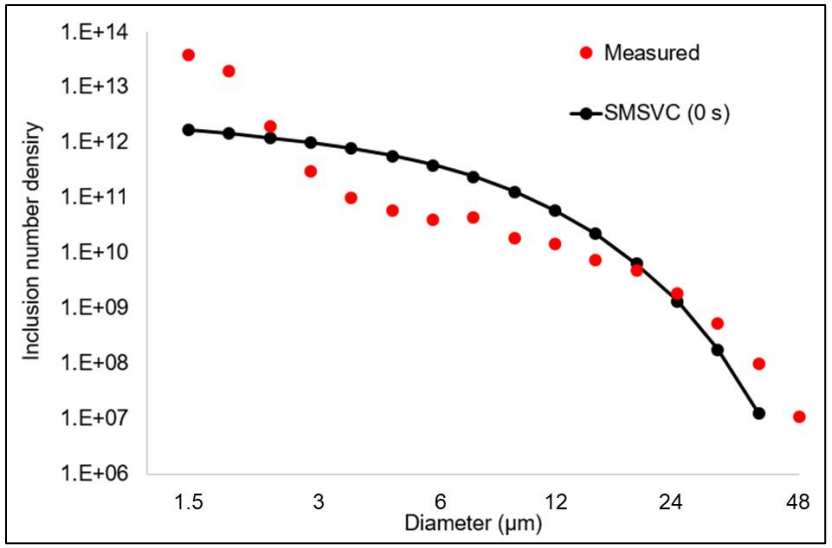


Inclusion Removal Validation

- Inclusion sizes range from 1.5 μm to 48 μm
- Measured data from Laboratory experiment by Y. Miki et al, 1999*
- Good agreement: avg. number density difference 12.1%
- Prediction deviation for small inclusion: model neglects rapid re-oxidation and solidification during sampling



Inclusion Number Density Validation



Initial Number Density**

* Chen, Gujun, and Shengping He. "Application of Inhomogeneous Discrete Method to the Simulation of Transport, Agglomeration, and Removal of Oxide Inclusions in a Gas-Stirred Ladle." *JOM* 71.11 (2019): 4206-4214.

* * Miyashita, Yoshio, and Katsuhiko Nishikawa. "Measurement of the Size Distribution of Nonmetallic Inclusions in Steel." *Transactions of the Iron and Steel Institute of Japan* 8.3 (1968): 181-185.

Project 8: Desulfurization and Reoxidation in Ladle

Objective: Develop desulfurization and reoxidation model in ladle

Start: March 2020

Desulfurization and Re-oxidation

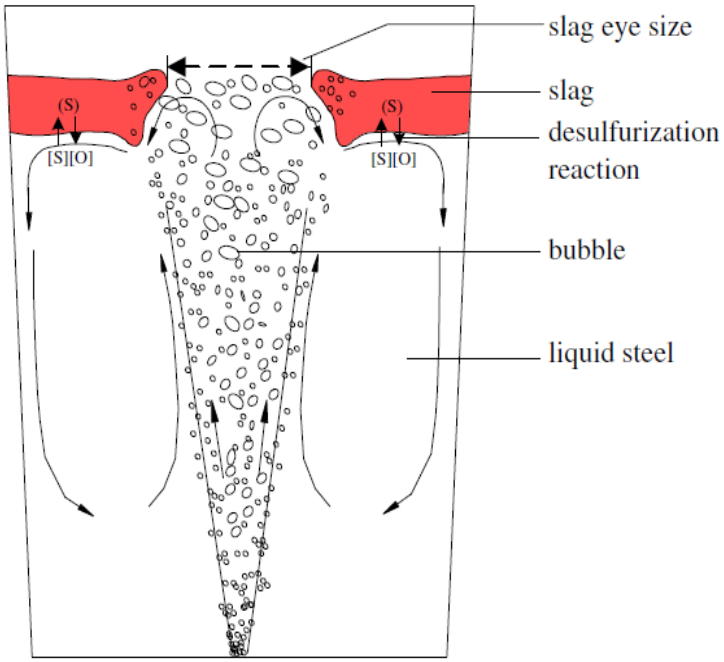
- **Motivation:**
  - Sulfur increases due to re-sulfurization from oxidizing slag and steel scrap
  - Sulfur can be removed by chemical reactions between steel and slag
- **Objective**:
  - Develop model for desulfurization and re-oxidation process
  - Verify the model with references and validate it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

Methodology

- Coupled computational fluid dynamics–simultaneous reaction model (CFD-SRM)

1. Flow field and species concentration
   - Eulerian-Eulerian multiphase model
   - Standard k-epsilon model
   - Species transport model

2. Chemical reaction rate
   - Reaction rate of each element in steel



Chemical Reaction Modeling

- Chemical reactions at slag-metal interface
  - Desulfurization reaction

$$[S]+\left(O^{2-}\right)=\left(S^{2-}\right)+[O]$$

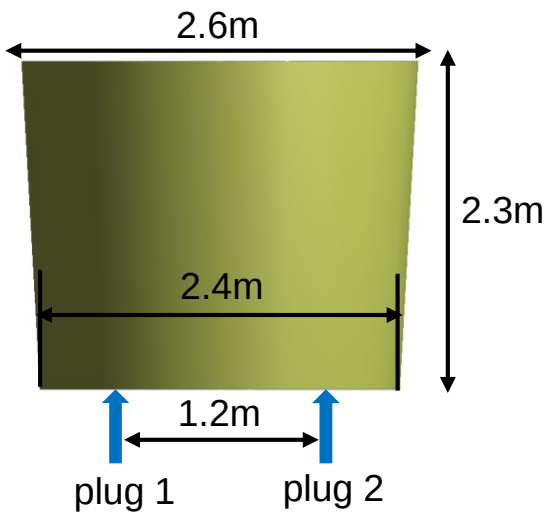
  - Alloy oxidation

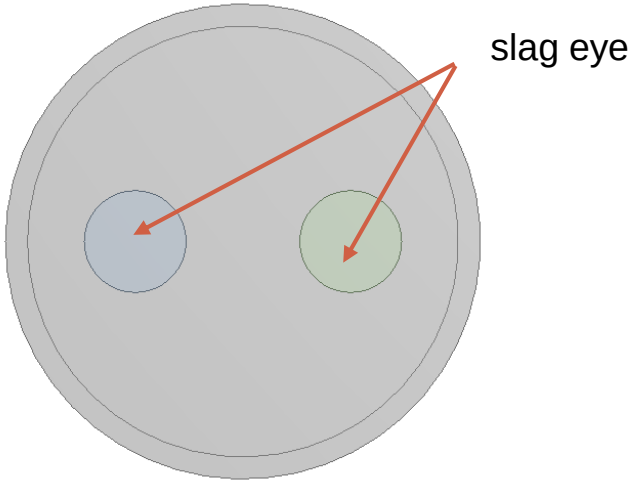
$$[Al]+1.5[O]=\left(AlO_{1.5}\right)$$
$$[Si]+2[O]=\left(SiO_2\right)$$
$$[Mn]+[O]=(MnO)$$

- Influential factors on reaction rate
  - Initial mass fraction of each element
  - Argon injection rate
  - Steel temperature
  - Slag basicity

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

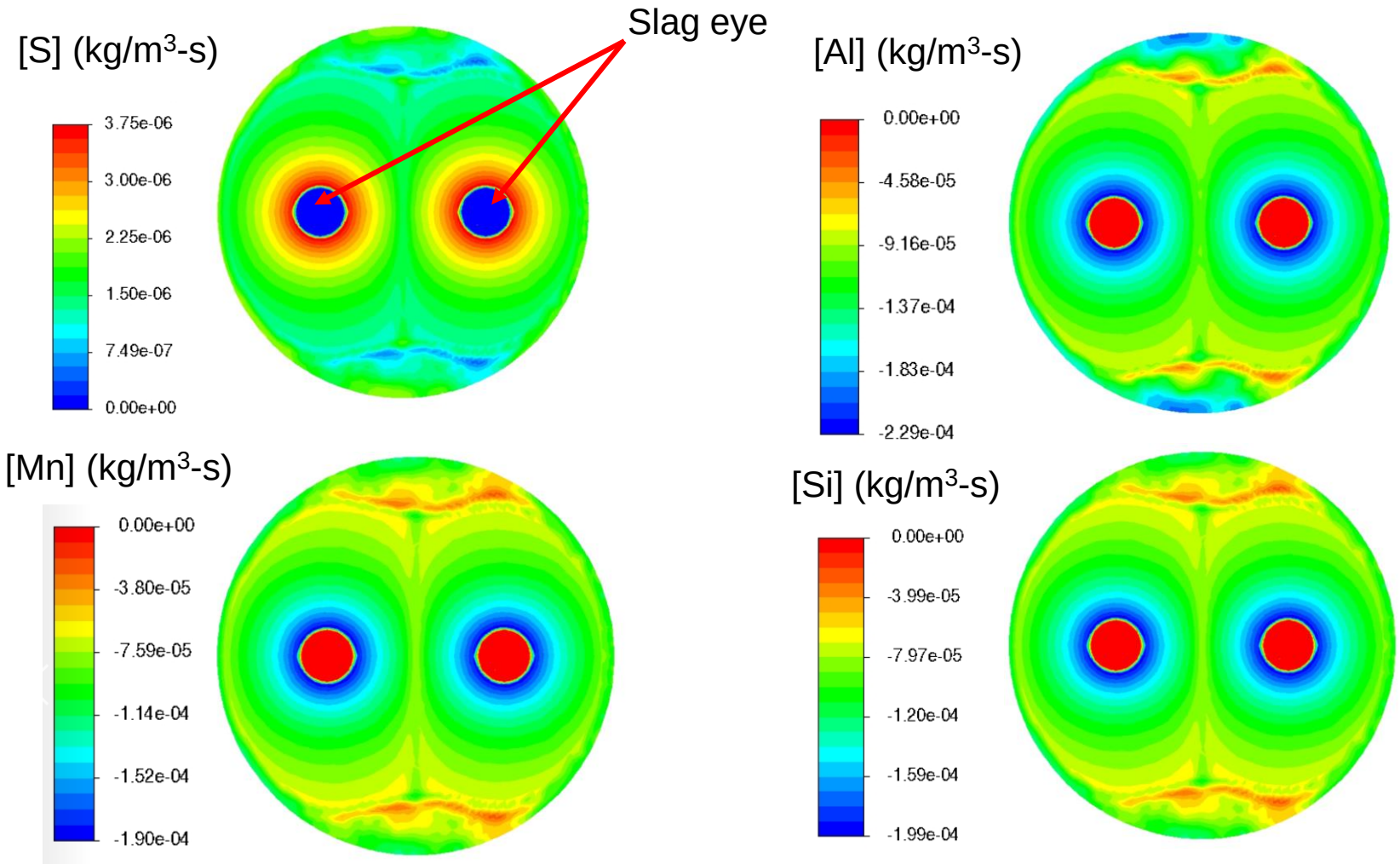




[1] Lou, Wentao, and Miaoyong Zhu. "Numerical simulation of desulfurization behavior in gas-stirred systems based on computation fluid dynamics–simultaneous reaction model (CFD–SRM) coupled model." *Metallurgical and Materials Transactions B* 45.5 (2014): 1706-1722.

Chemical Reaction Rate Results

- The chemical reaction rates of each element at the slag-metal interface at 18 seconds



Chemical Reaction Rates Results

- The average chemical reaction rate at the slag-metal interface at 18 seconds:

Element in Steel	Reaction Rate (kg/m^3-s)
[S]	2.03e-06
[Al]	-1.32e-04
[Mn]	-1.03e-04
[Si]	-1.08e-04

  - Sulfur transfers from steel to slag while alloy elements are generated and move into steel
  - The reaction rate of sulfur is much lower than alloy element reaction rates
  - The reaction rates of alloy elements are similar

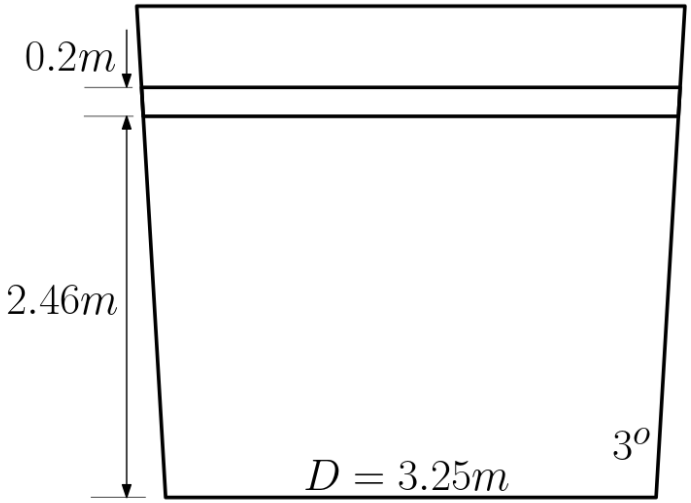
Project 6:
Plug Clogging Study

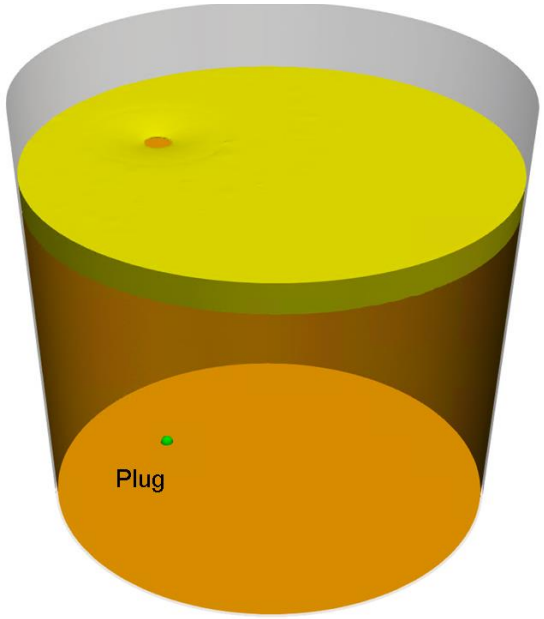
Objective: Investigate solutions for plug clogging operations

Start: February 2020

Plug Clogging Study

- **Issue:**
  - Plug failure on stirring start due to clog or other issue
- **Potential solutions:**
  - Maintain same gas flow rate through plug
  - Inject more gas to offset loss of plug
- **Approach:**
  - Simulate generic ladle with one plug off at 5 SCFM
  - Compare with doubled flowrate (10 SCFM)

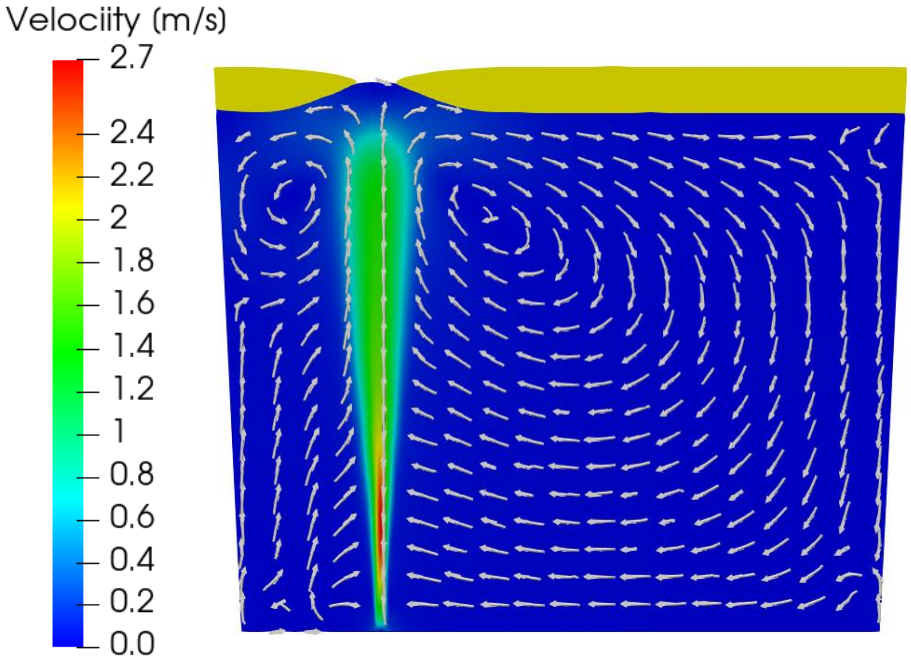


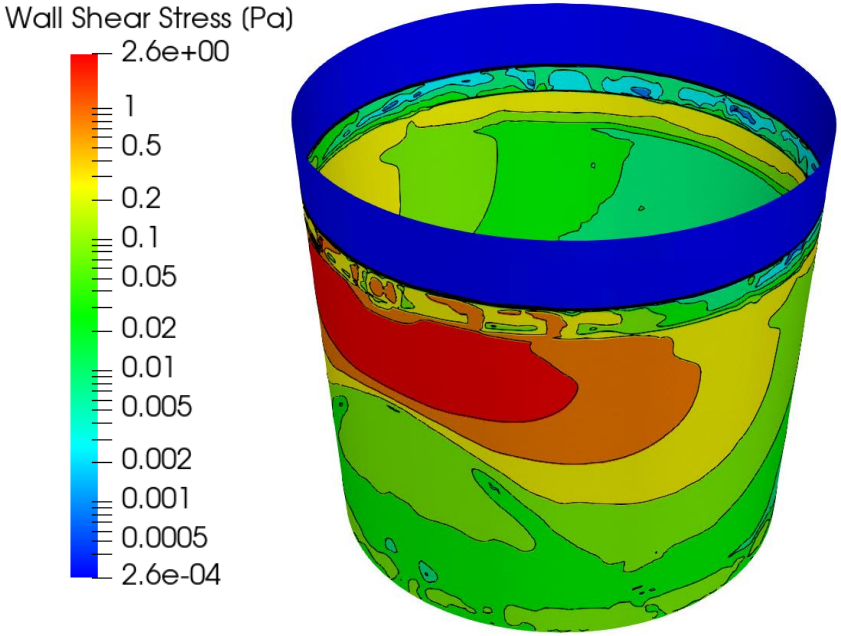


Single Plug at 5 SCFM

- Typical single-plug flow pattern
  - Two recirculation zones near slag surface
  - Wall shear stress highest on wall near the bubble plume

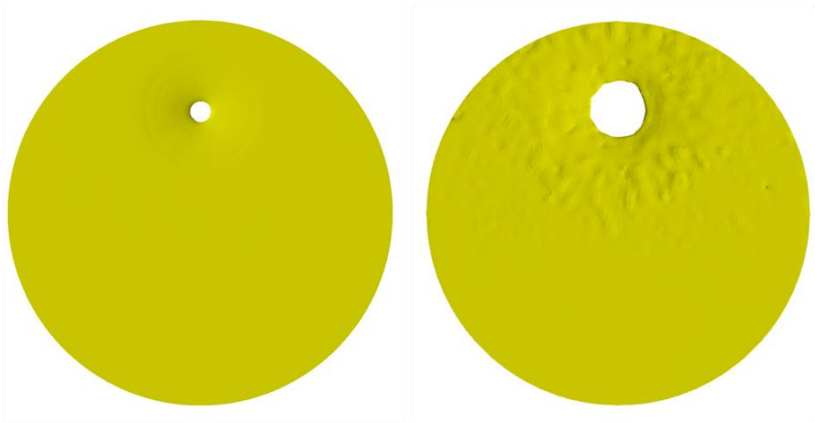
0.2m slag eye opening in 5 SCFM case





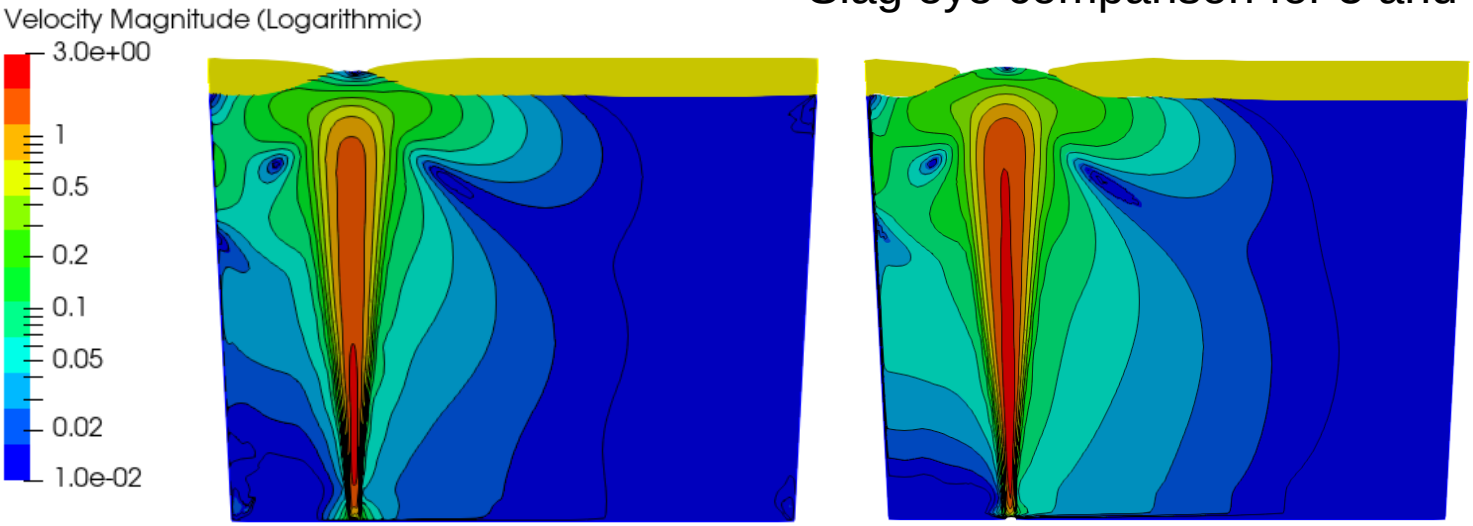
Effect of Doubled Flowrate

- Flow patterns similar to 5 SCFM case
  - Larger slag eye formed: 0.54m vs. 0.2m with 5 SCFM



5 SCFM (0.2m eye) 10 SCFM (0.54m eye)

Slag eye comparison for 5 and 10 SCFM



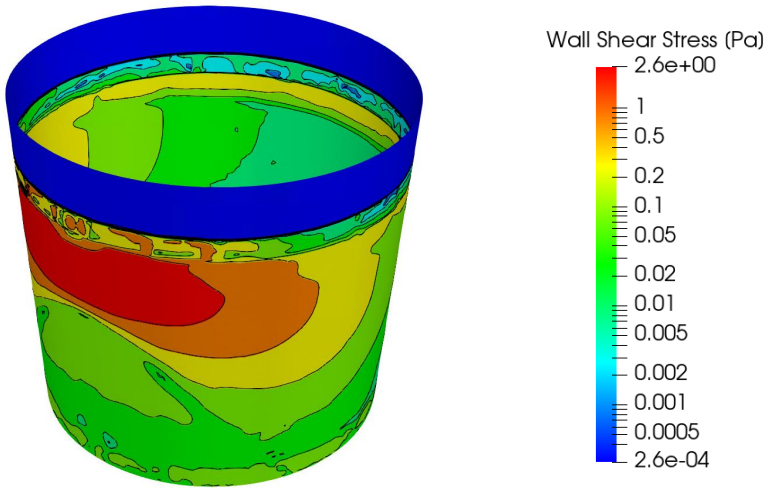
5 SCFM 10 SCFM

Logarithmic plot of velocity for 5 SCFM (left) and 10 SCFM (right)

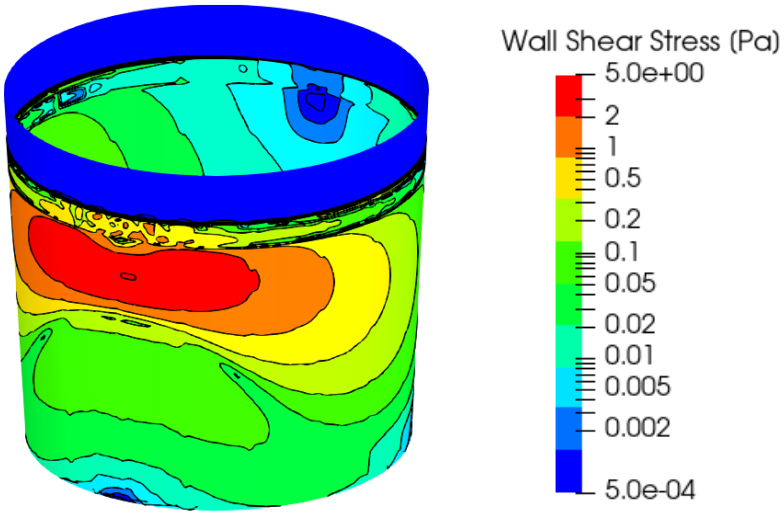
Wall Shear Stress

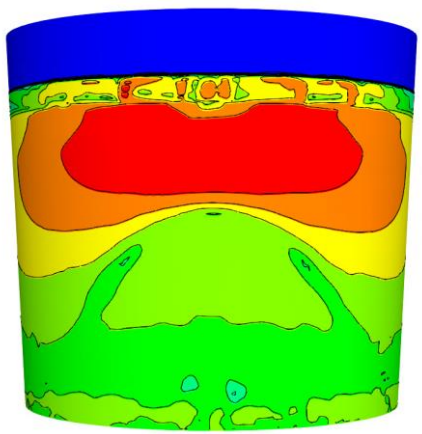
- Wall shear in 10 SCFM case nearly doubled

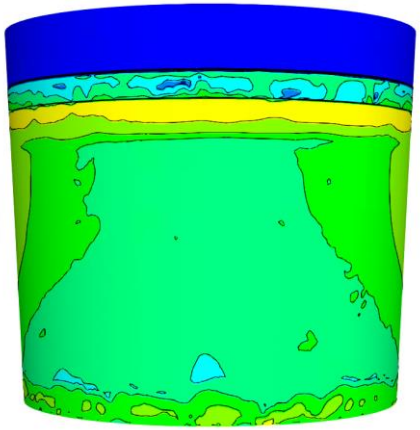
5 SCFM Wall Shear Stress

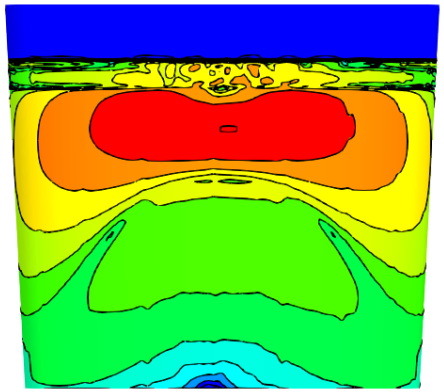


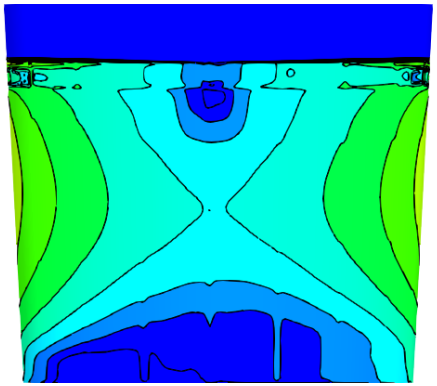
10 SCFM Wall Shear Stress











Effects of Flow Rate Increase

- Losing one plug results in a 38% increase in mixing time
- Increasing that single plug to 10 SCFM brings mixing time to within 1% of two plug 5/5 SCFM
- Wall shear stresses nearly double for 10 SCFM single plug versus 5 SCFM single plug stirring
  - 82% increase in peak shear stress, 60% in average

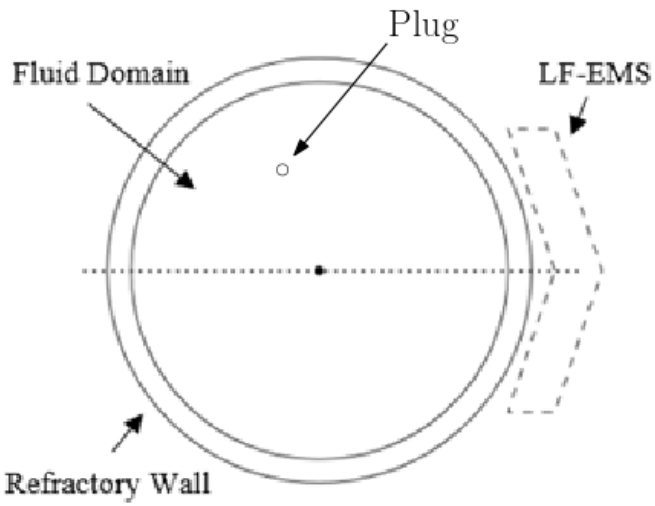
	Mixing Time (sec)	Wall Shear Stress (Pa)		Mixing Time Increase
		Peak	Avg	
90deg 5/5	349	2.969	0.217	-
1Plug 5	483	2.594	0.1428	38%
1Plug 10	352	5.39	0.229	1%

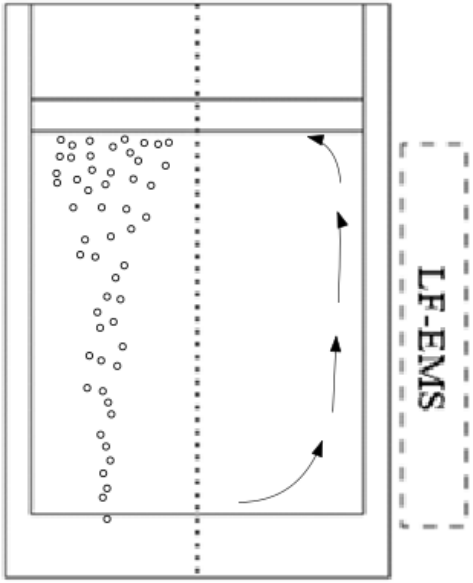
Project 7:
Combined Gas-EMS Ladle Model Study

Site: Generic ArcelorMittal Ladle
Start: April 2020

EM-Gas Combined Stirring

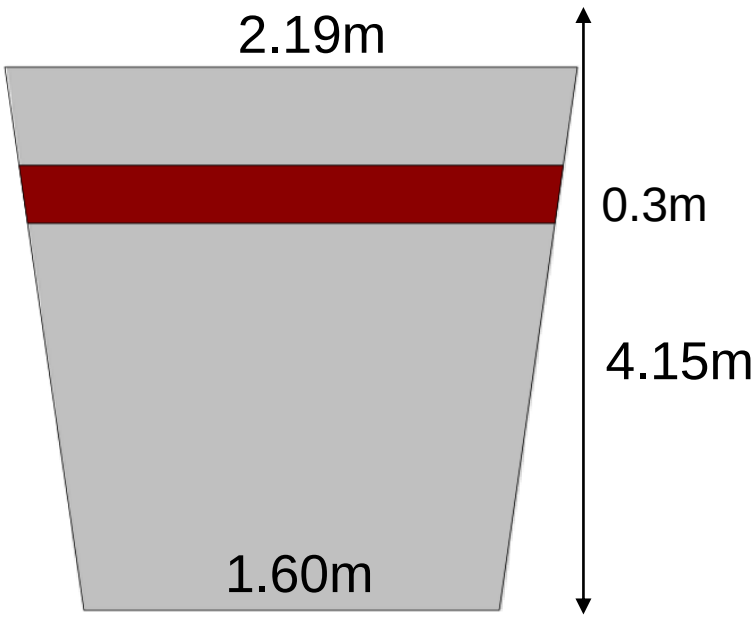
- **Objective:**
  - Simulate combined stirring of EMS field and argon injection
  - Compare resulting flow field to individual methods
- **CFD Model:**
  - Isothermal transient model of EMS Lorentz forces and single 5 SCFM bottom plug
- **Approach:**
  - Use directly-imported Lorentz forces to bypass magnetic field simulation
  - Compare results to gas-only and EMS-only simulations



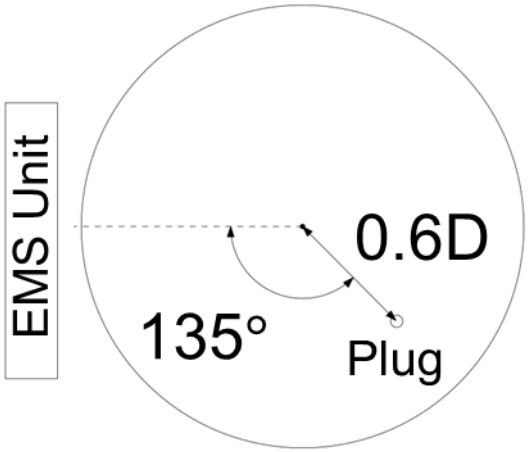


EM-Gas Simulation

- Single 3-inch diameter plug on ladle bottom at 5 SCFM
- CFD Model:
  - VOF multiphase with DPM
  - Transient, isothermal
  - K-epsilon turbulence
- Using imported Lorentz Forces field as momentum source term for upward stirring
  - ArcelorMittal provided force data for a stirring unit on one of their ladles



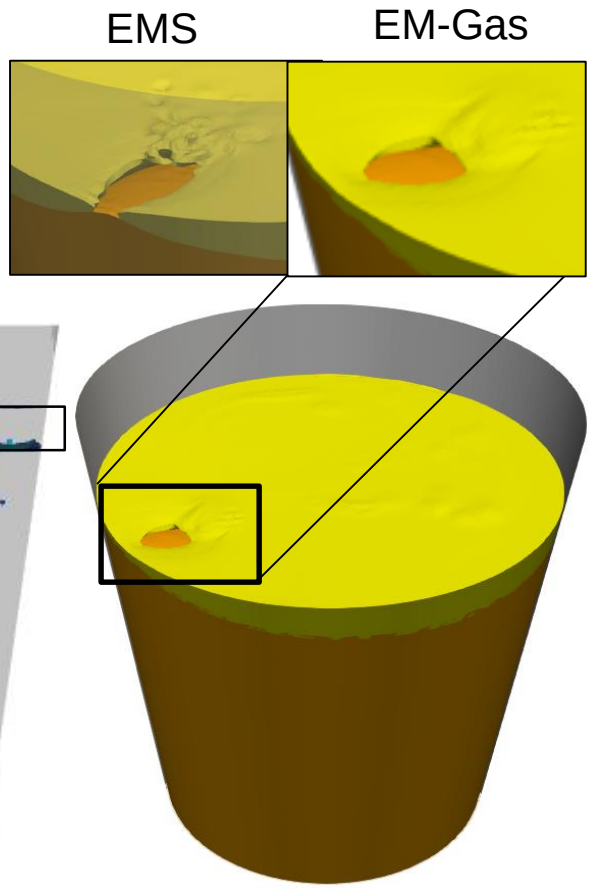
EMS/EM-Gas Ladle

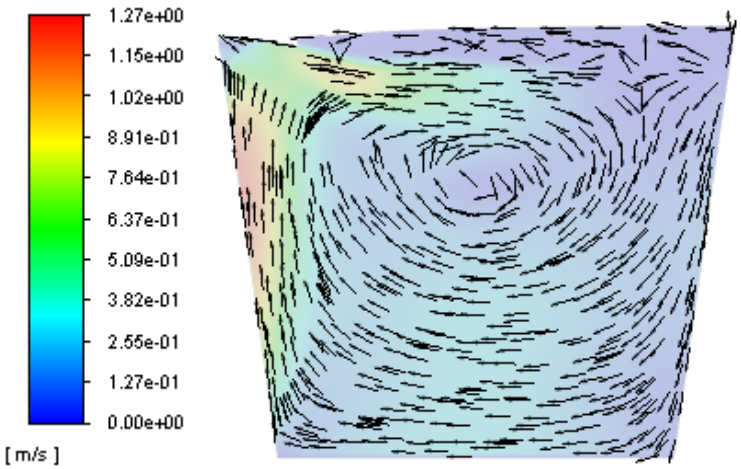


Relative positions of plug and stirring unit

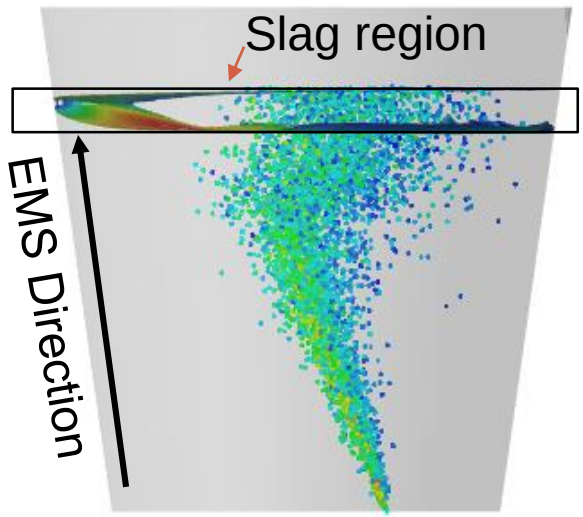
EM-Gas Flow Field

- Gas plume is pushed by EMS flow forces
- Higher tangential velocities in near-slag steel, scattering bubble plume
  - Smaller impact of plume on slag
- EM-Gas has smaller opening than EMS





Steel vectors and contour of velocity magnitude



Side view of bubble plume at 80 seconds

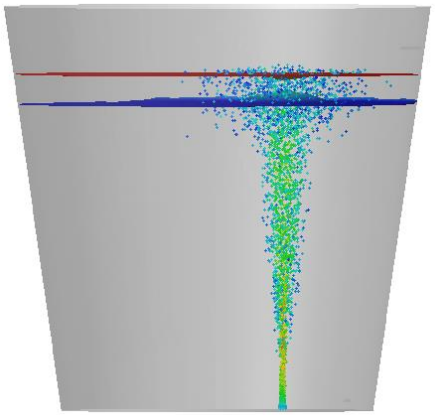
EM-Gas slag opening

EM-Gas Flow Field & Mixing

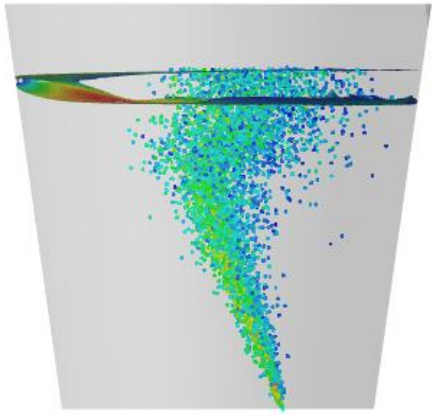
- EM-Gas Mixing time slower than EMS alone.
  - Both show improvement over gas-only mixing
  - Sand et al. shows similar trend

Mixing Time	**Gas**	**EMS**	**EM-Gas**
SMSVC	448	58	117
Sand et al.*	>400	160	190

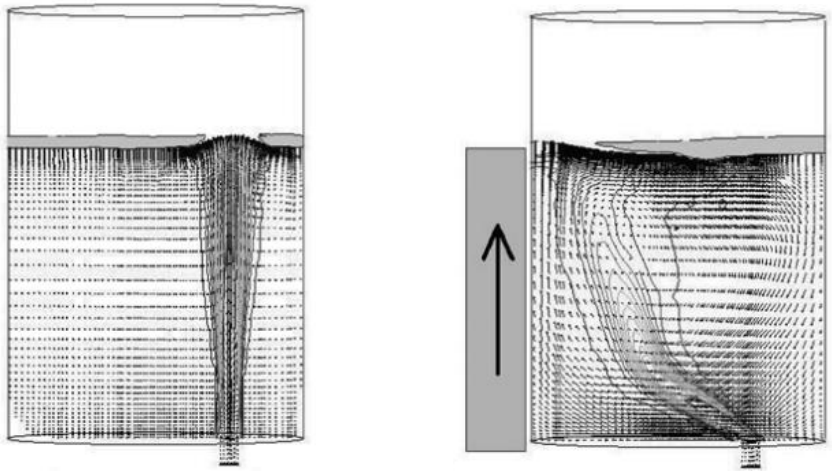
Gas Only



EM-Gas



SMSVC



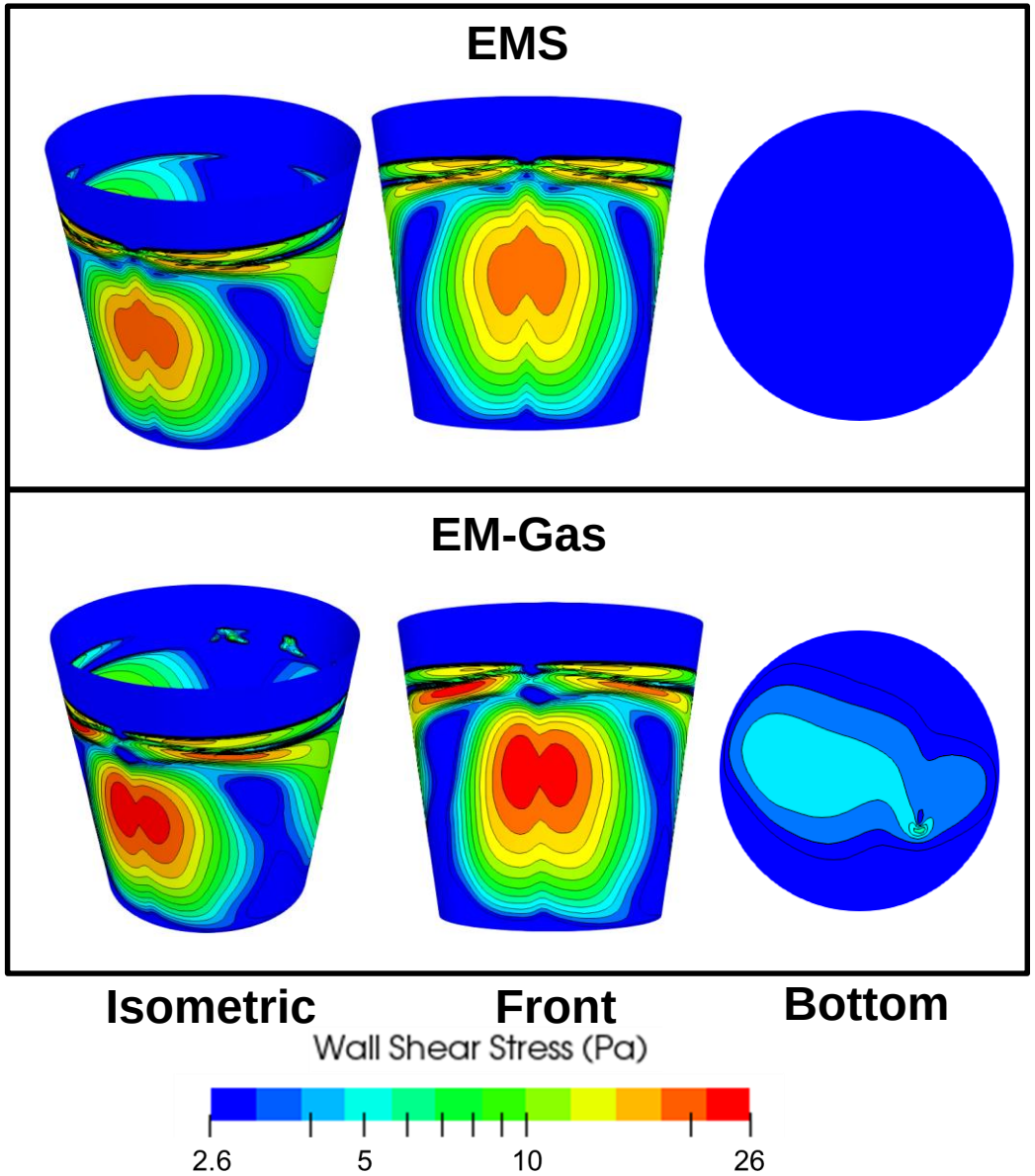
Sand, et al.

*U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, "Control of Gas Bubbles and Slag Layer in a Ladle Furnace by Electromagnetic Stirring," *Iron Steel Technol.*, no. July 2009, 2009.

EM-Gas Wall Shear Stress

- EMS wall shear stresses are 10x higher than gas-stirring
- EM-Gas increases shear stress by 30% over EMS alone

	Wall Shear Stress (Pa)	
	Peak	**Average**
Gas Only (5 SCFM)	2.88	0.138
EMS	20.155	3.859
EM-Gas	26.308	4.694



Project 9:
Smart Ladle AI-Based Tool

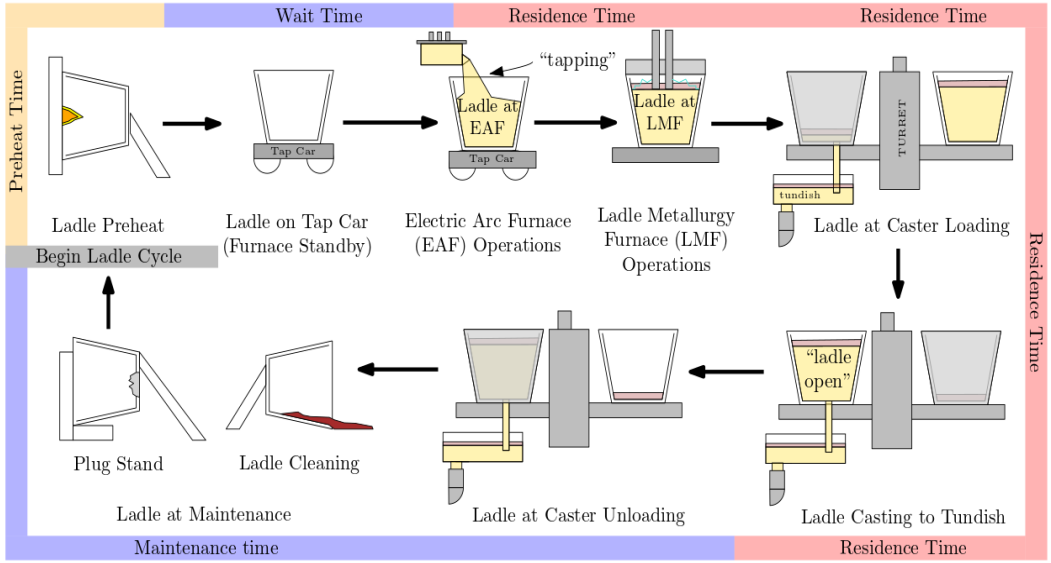
Start: September 2019
Site: Steel Dynamics, Inc – Butler, IN

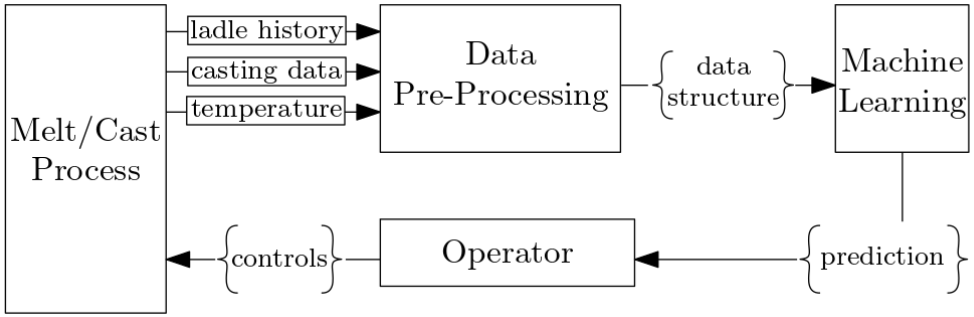
Smart Ladle

- **Issue:**
  - Operators must predict future temperature requirements using limited information
- **Approach:**
  - AI model using real-time and historic process data to predict future casting temperature
- **Potential Impacts:**
  - Improved operational responses for casting temperature control
  - Recognition of special circumstances

Methodology

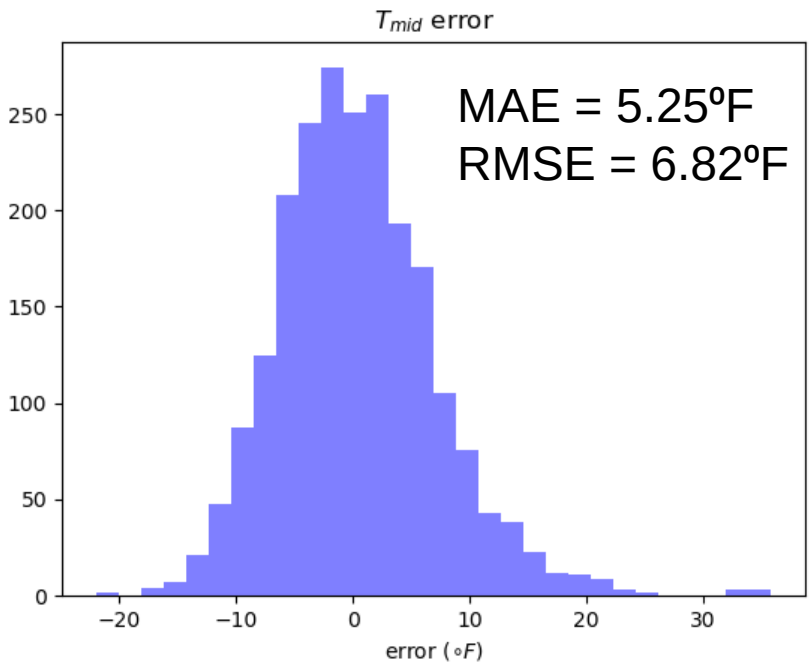
- Data taken from ladle and casting processes
- Ladle and tundish "history" data structure created
  - Time intervals, ladle history, temperature data, throughput, liquidus temperature
- Predict midpoint temperature and slope of tundish temperature for future heat

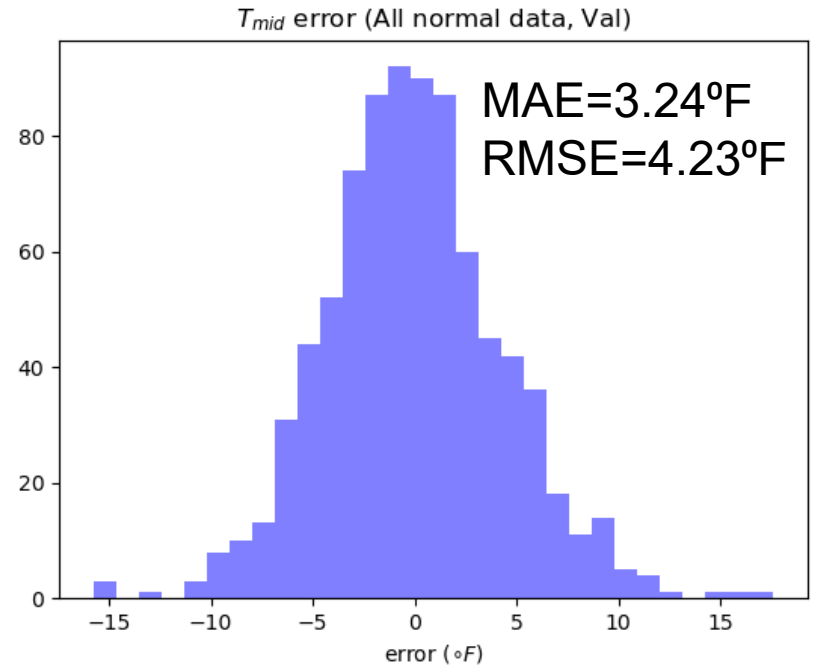




Smart Ladle Accuracy Improvements

- **June**
  - Dataset increased by 3x
  - Model used ladle history data, LMF temperature sample, tundish temperature data
- **November**
  - Filtered heats with invalid or missing data
  - Improved architecture
  - Added liquidus temperature and casting throughput to model





Smart Ladle Future Work

- Current model is based on data from one site
- To be more universal, model must be able to work with variety of data sources
- Inputs needed for Smart Ladle:
  - Process description – From tap to cast
  - Data sampling – Where and how is data collected
  - Database info – Access methods, database type
  - Operator interaction – Desired form of model output (e.g. HMI)

Summary

Summary

- **Project 5: Inclusion Removal Enhancement & Validation**
  - Inclusion removal model including inclusion behavior at slag eye area is developed
  - Results from optimized inclusion model is validated with measured data
- **Project 6: Plug Clogging Study**
  - Doubling flow rate reduces mixing time but increases wall shear stress
- **Project 7: Combined Gas/EMS Ladle Study**
  - Adding gas to EM stirring reduces slag opening, but also increases wall shear stress and slows mixing time
- **Project 8: Desulfurization and Reoxidation**
  - Simulation of chemical reaction rates at the beginning of the desulfurization process
- **Project 9: Smart Ladle**
  - Changes in model architecture and data usage have increased accuracy of the predictions

Future Work

- **Project 5: Inclusion Removal Enhancement & Validation**
  - Evaluate inclusion removal for various stirring conditions
  - Validation of model using industrial data
- **Project 6: Plug Clogging Study**
  - Adjust inputs to offset lost efficiency while minimizing added wall shear stress/erosion rates of refractory walls
- **Project 7: Combined Gas/EMS Ladle Study**
  - Simulate EMS and gas injection in top lance ladle and different plug positions/flow rates
- **Project 8: Desulfurization and Reoxidation**
  - Develop and validate desulfurization and reoxidation models
  - Apply models to industry ladles
- **Project 9: Smart Ladle**
  - Further model development and implementation

Feedback from PTC

- Applications of interest:
  - Minimization of slag emulsification
  - Stir setting for shortest time to achieve highest inclusion removal prior to diminishing return
  - Recommendation for ladle shipping temperature and superheat control
  - Re-establishing homogenization as the heat waits for cast delays
- Suggestions for new models:
  - Effects of chemistry on inclusion movement
  - Effects of electrode heating and natural /forced convection
  - Real time algorithms and models for mill application

Additional Potential Applications

- **Refining Process Improvements:**
  - Stirring time minimization
  - Gas flow rate selection
  - Ladle heat loss reduction
  - Refractory life extension/wall shear stress reduction
  - Inclusion removal effectiveness/speed
  - Slag opening minimization

- **Ladle Design:**
  - Ladle shape
    - Height, diameter, wall taper angle
  - Plug parameters
    - Plug number, separation angle, distance
  - Lance positioning/flow

- **AI Process Control:**
  - LMF ship temperature for casting improvement
  - Scheduling/timing

Comments from Industry Collaborator

Thank You
Questions and Comments