COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

Project Technical Committee (PTC):

- Joshua Anderson (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)
- Muhammad Rashid (EVRAZ NA)
- Phelipe Cecato (Gerdau)
- Henrique Lize (Gerdau)
- Denise Oliveira (Gerdau)
- David Sandoval (Gerdau)
- Adam Tabor (Gerdau)
- Carlo Travaglini (Gerdau)
- Joshua Young (Gerdau)
- Michael Zuker (Gerdau)
- Dan Brisson (NLMK)
- Abhishek Bhansali (NUCOR)
- Helmut Oltmann (NUCOR)
- Vivek Thapliyal (NUCOR)
- Allen Chan (Praxair)
- Sunday Abraham (SSAB)
- Fernando Guerra (Stelco)
- Mitchell Klaas (Stelco)
- Sanjna Pradhan (Stelco)
- Richard Zhang (Stelco)
- Kumar Subramanian (Tata Steel)

CIVS Team (current):

- Joel Godinez
- Congshan Mao
- Boping Hou
- Zhankun Luo
- Wen Ou
- Nicholas Walla
- Armin Silaen
- Chenn Zhou

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

"Where Ideas Become Reality"

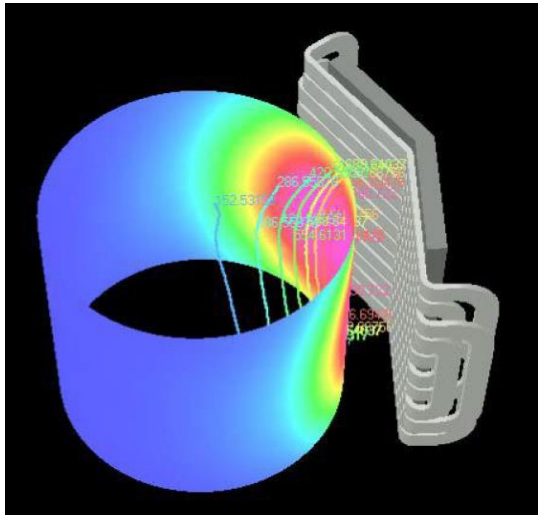
Presentation Outline

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

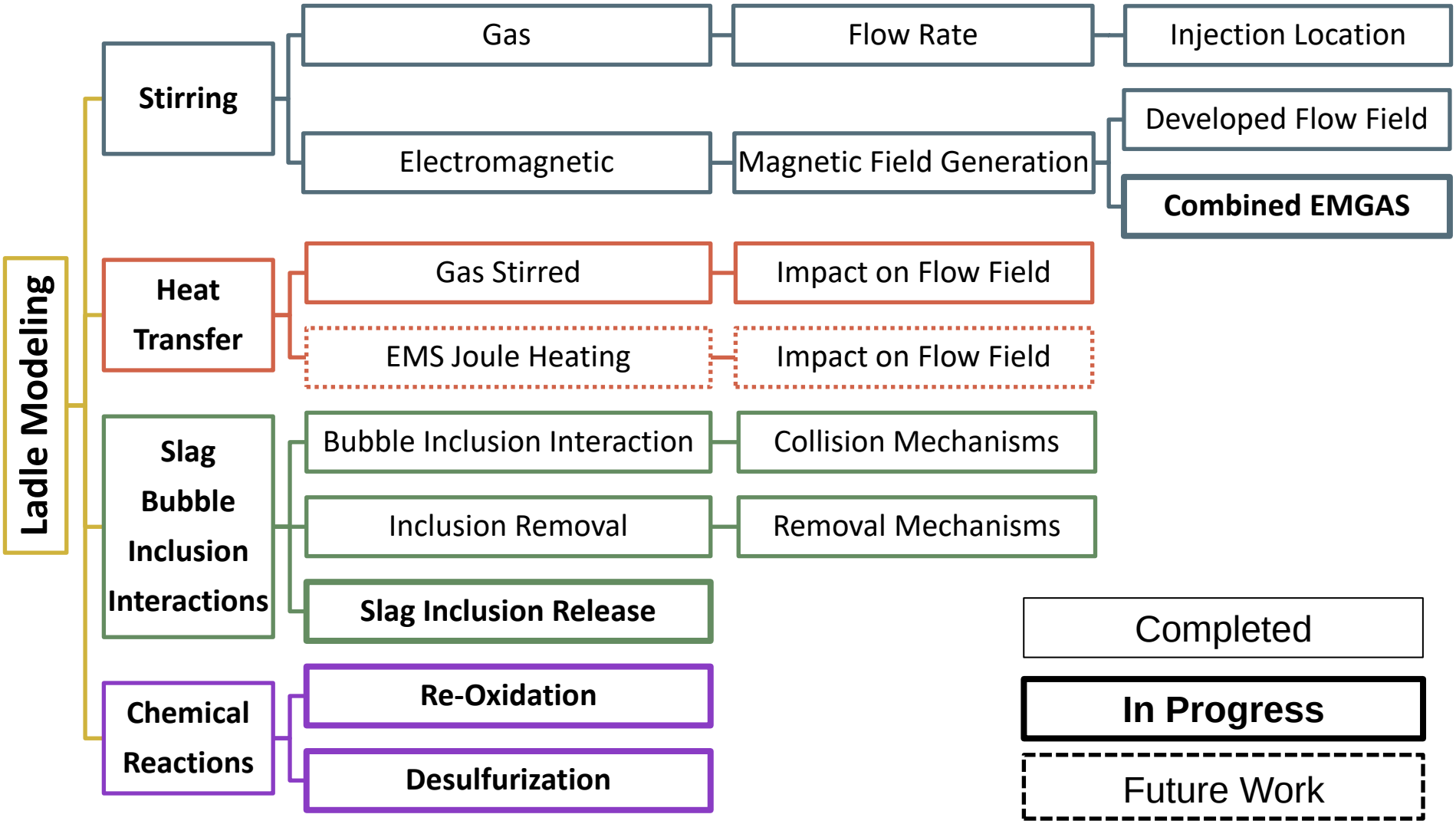
- **Potential Impacts**
  - Process design of optimized flow condition and physical properties
  - Steel cleanliness improvement and final defects reduction



Research Objectives

- **Long-term Objectives (5+ Years):**
  - Develop a validated comprehensive multiphase CFD model of a steel ladle using three stirring methods: Gas stirring, EMS and combined EM-Gas stirring
  - Optimize ladle stirring conditions for steel cleanliness, productivity, and equipment lifetime with normal operation process and with unexpected industrial problems
- **Current Objectives – 2020:**
  - **Investigate Inclusion Removal in Gas-stirred & EMS Ladle**
    - Add inclusion release effect at slag eye
    - Investigate plug clog phenomenon
    - Investigate impacts of EMS and EMS-Gas combined stirring on inclusion growth & removal rate
  - **Investigate Chemical Reactions in Steel Ladle Refining**
    - Develop chemical reaction model including desulf. & reoxidation
  - **Smart Ladle**
    - Develop AI engine to guide refining ladle operations

Research Area Roadmap



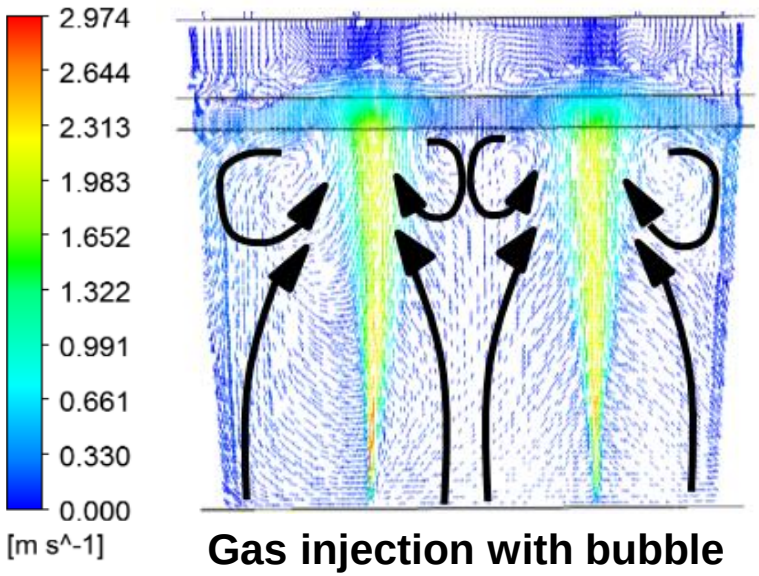
Major Outcomes – Models & Findings

Projects (2016 – 2020): Completed: 3, Ongoing: 6

- **Project #1:** Isothermal Gas-stirred Ladle Flow Simulation - Nucor Decatur
  - Validated CFD models against measurements (avg. 8.7% slag eye size difference)
  - Increasing plug distance ratio by 0.1D reduced mixing time by 18%
  - At 0.6D plug distance ratio, 60° separation angle yield 25% faster mixing vs. 180°
- **Project #2:** Heat Transfer Effect in Gas-stirred Ladle - Nucor Decatur
  - Effects of initial wall temperature on steel temperature stratification (29% faster temperature lost on cold wall ladle)
- **Project #3:** Gas-Stirred Isothermal Inclusion Growth and Removal – Nucor Generic Ladle
  - Developed inclusion growth and removal model to predict inclusion removal efficiency
  - 180° plug separation increased removal efficiency by 5%
- **Project #4:** EMS Isothermal Ladle – AM Generic Ladle
  - Investigated wall shear stress, bulk velocity & slag-eye size
- **Project #5:** Inclusion Removal Enhancement & Validation – Nucor Generic Ladle
  - Accuracy improvements in inclusion growth and removal rates
- **Project #6:** Plug Clogging Study - Nucor Generic Ladle
  - Effect of single plug on flow field and wall shear
- **Project #7:** Combined Gas-EMS Ladle Model Study – AM Generic Ladle
  - Developing model
- **Project #8:** Desulfurization and Reoxidation in Ladle
  - Developing
- **Project #9:** Smart Ladle
  - Developed deep learning algorithm using SDI data
  - Prediction of LMF-to-caster temperature drop and tundish temperature
  - In implementation stage

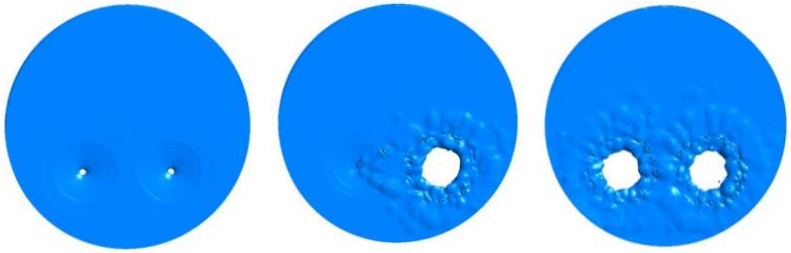
Sample Results (2016 – 2019)

Project 1: Gas-Stirring Flow Simulation



Gas injection with bubble breakup and coalescence

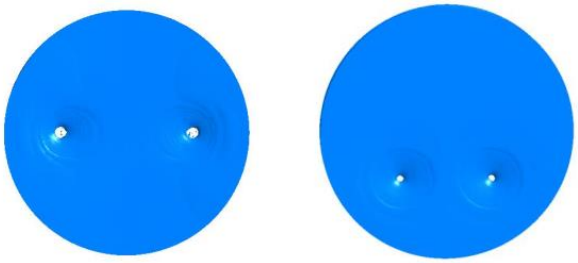
Comparison of flow rates at 90° separation angle



5/5 SCFM 5/20 SCFM 20/20 SCFM

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 %

Comparison of separation angle



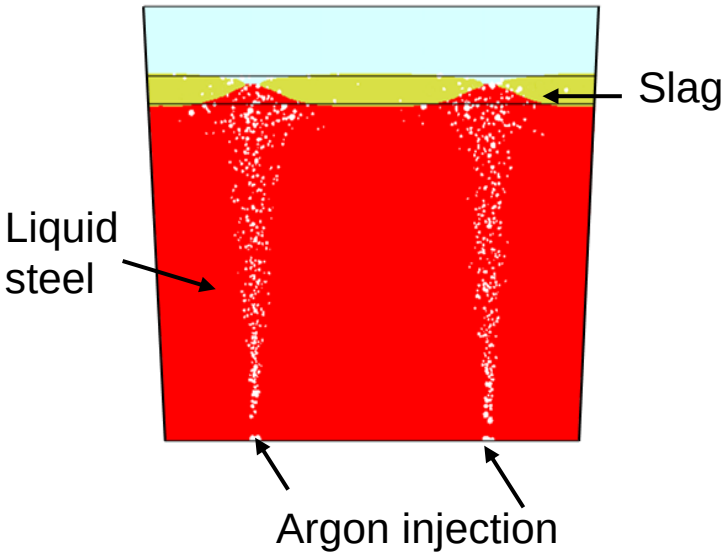
5/5 SCFM(180°) 5/5 SCFM(90°)

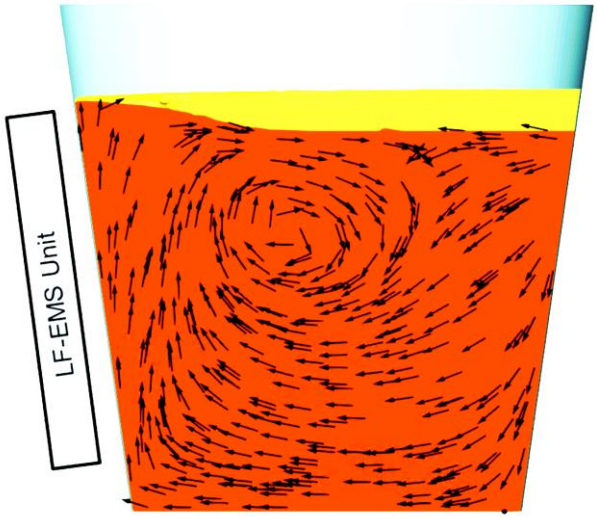
Timeline for 2020

	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												
	Simulation of inclusion removal using EMS flow field												
Project 5 Inclusion Removal Enhancement & Validation	Inclusion model refinements												
	Model validation and applications												
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 with inclusion modeling												
Project 8 Desulfurization and Reoxidation in Ladle	Literature Search												
	Desulfurization												
	Reoxidation												
Project 9 Smart Ladle	Development of smart ladle machine learning tool												

Methodology & CFD Models

- **Gas-stirred Model :**
  - Multiphase turbulent flow
  - Discrete tracking of argon bubbles
  - Bubble breakup and coalescence
- **EMS Model:**
  - Multiphase turbulent flow
  - Momentum source terms for Lorentz force
- **Inclusion Model:**
  - Population balance model
  - Inclusion growth
  - Inclusion transport by bubbles
  - Inclusion removal by slag and wall





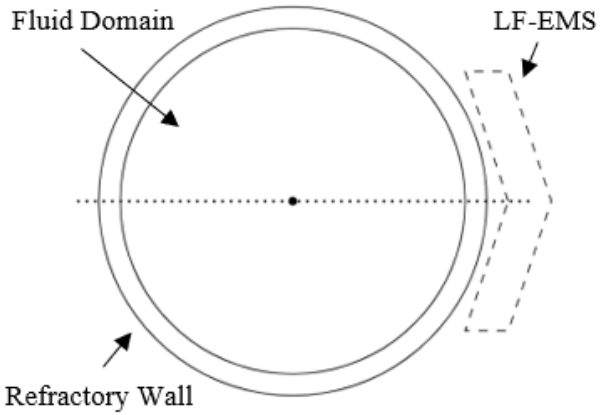
Project 4:
EMS Isothermal Flow

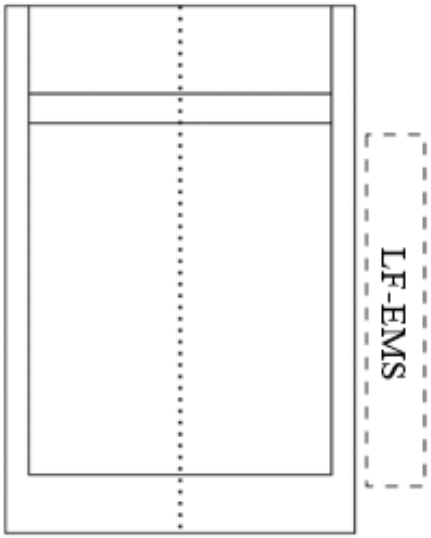
Site: Generic ArcelorMittal Ladle

Start: June 2018
(Force density started November 2019)

EMS Ladle Modeling

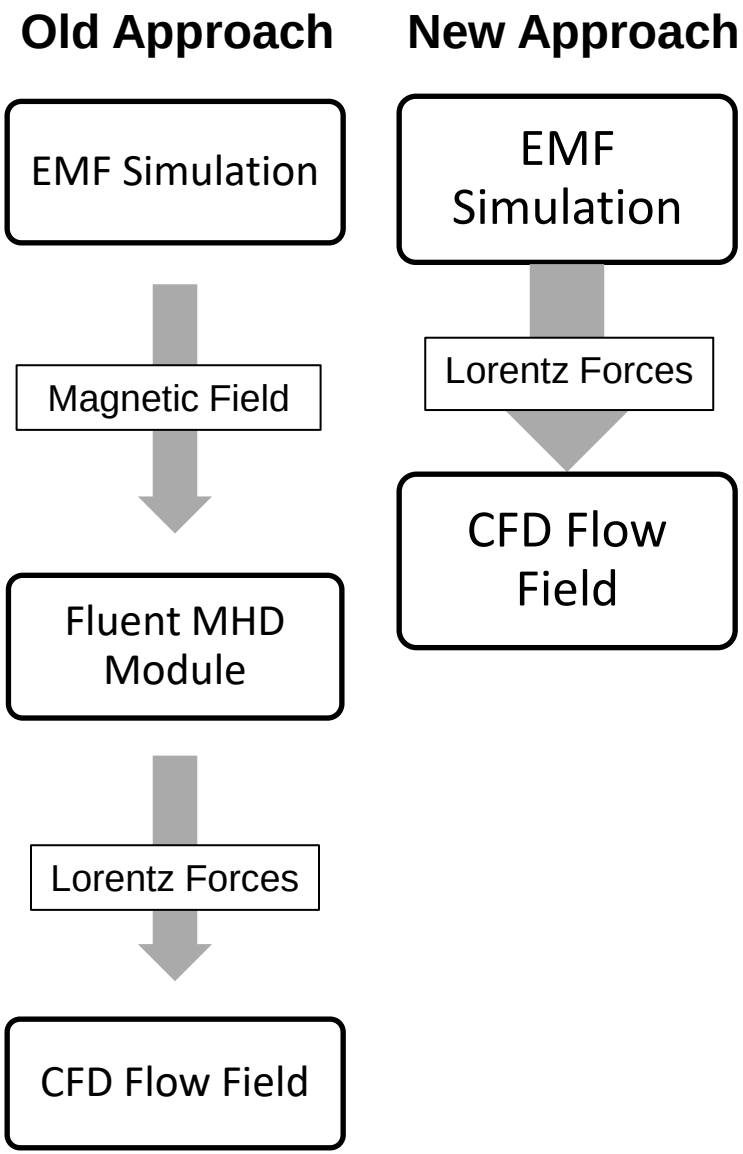
- Objective:
  - Simulate liquid steel flow field caused by induction stirring
    - Stirring time
    - Inclusion removal
    - Wall shear stress
  - Validate flow field with industry data
- Current model:
  - Uses Fluent MHD Module and imported magnetic field data
- New Approach:
  - Import Lorentz force data directly
  - Generate flow field using force data as momentum source term





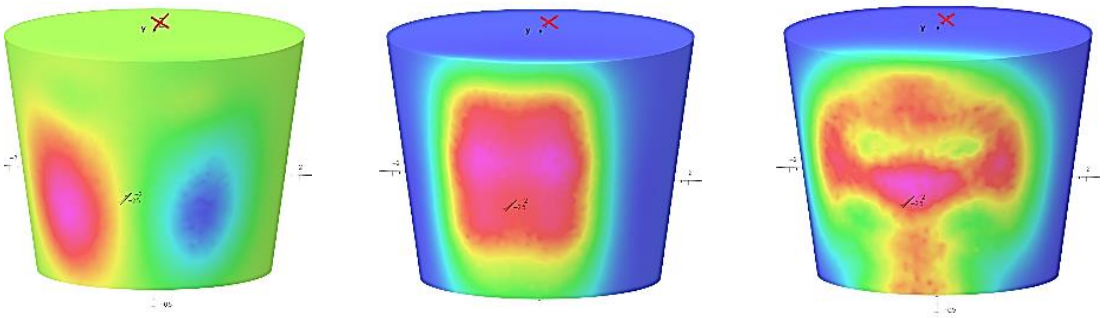
New Approach: EMS Force Density Data

- To simulate magnetic stirring, need MHD capability in Fluent
  - Convert magnetic field into Lorentz forces to induce steel momentum changes
  - Built-in Fluent MHD module required constant that could not be generalized
- New approach is to import Lorentz forces directly without using MHD module
  - Remaining methodology is the same
- ArcelorMittal provided force data for a stirring unit on one of their ladles

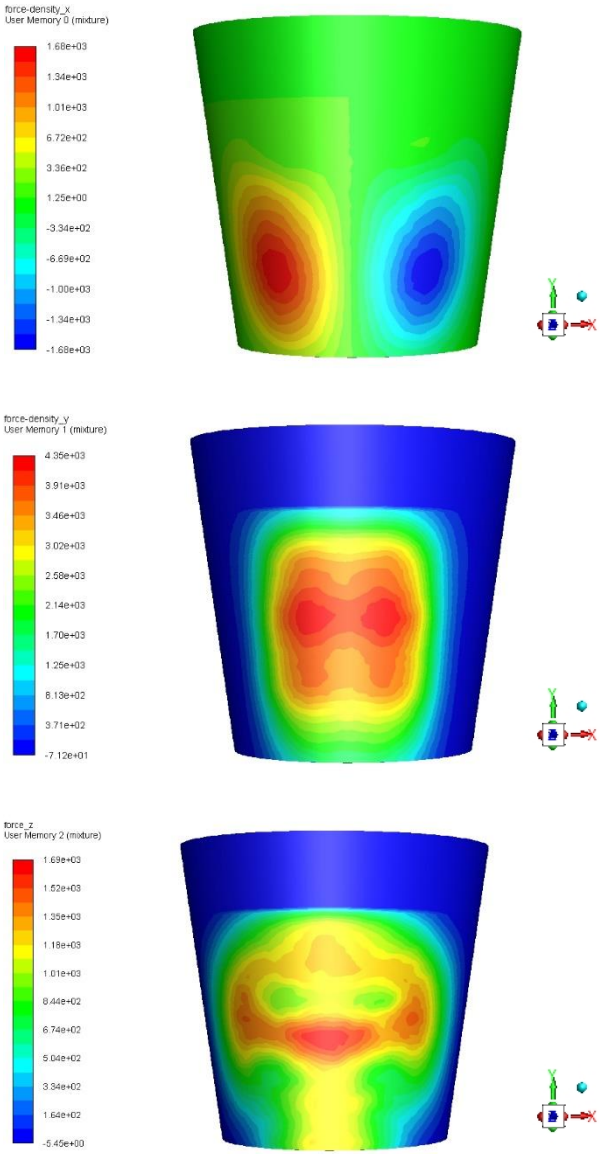


EMS Force Density Distribution

- Simplified ArcelorMittal geometry
  - Top Radius: 2.19m
  - Bottom Radius: 1.60m
- Using tolerance of 20mm, 96% of force density data range was captured
- Force density data can be applied as direct momentum source terms in Fluent to bypass MHD module

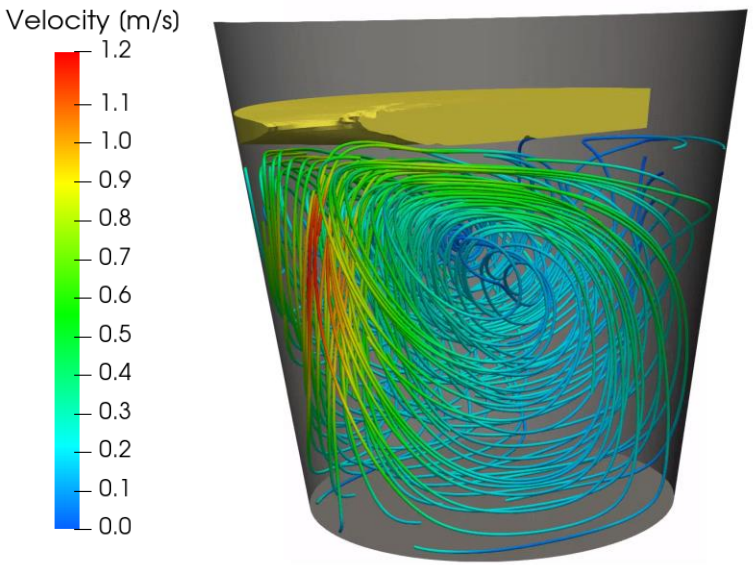


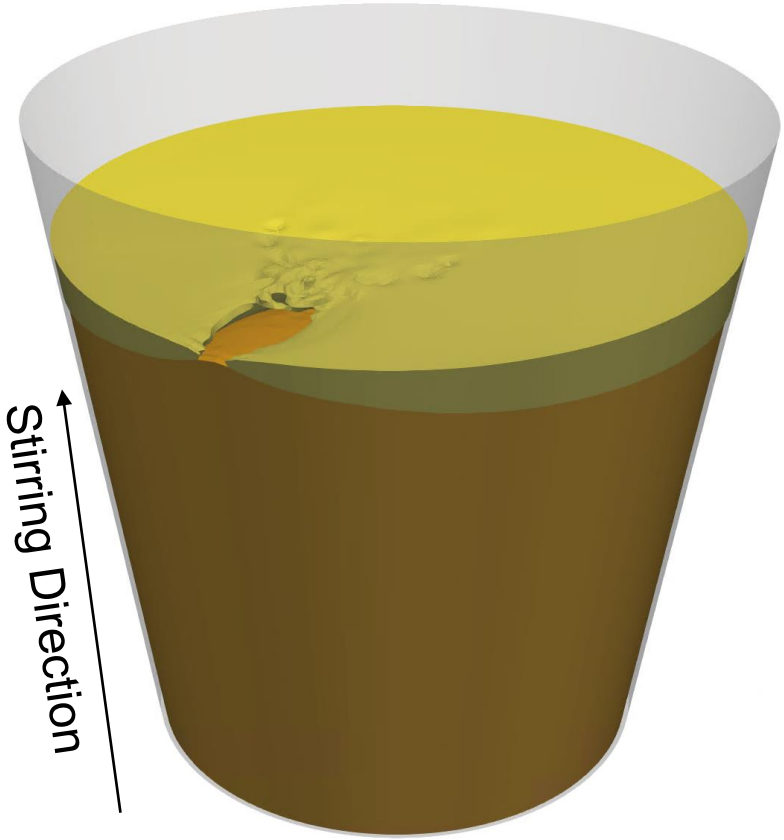
Above: Lorentz force values from EMF simulation software.
Right: Imported Lorentz force values in Fluent



EMS Ladle Flow Field Results

- Flow reached quasi-steady at 40 seconds
- Developed flow field shows small slag opening formation
- Large singular recirculation region across upper-center of ladle

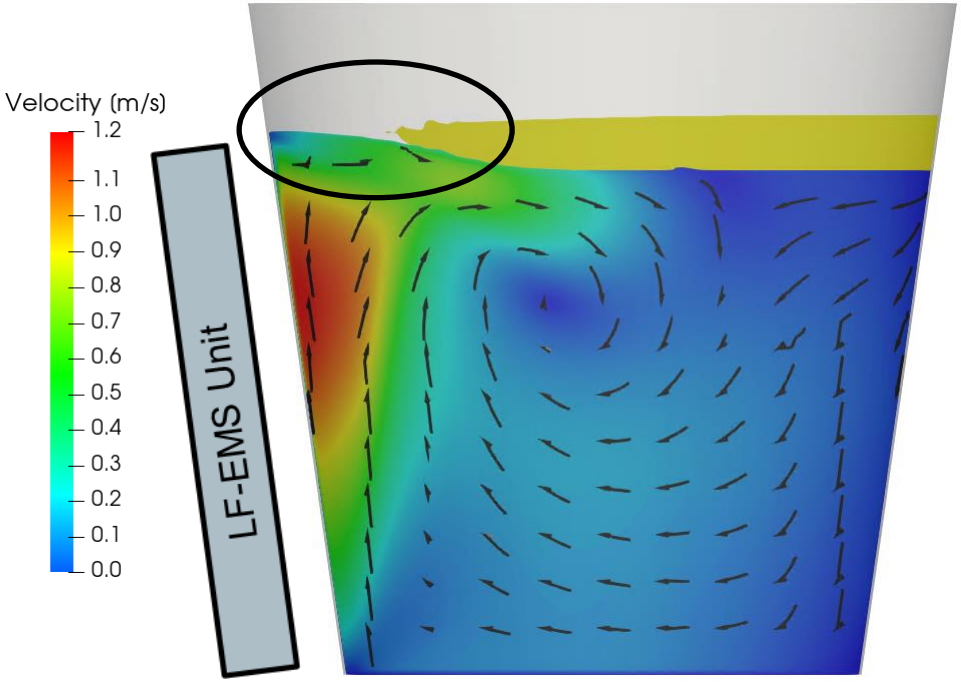




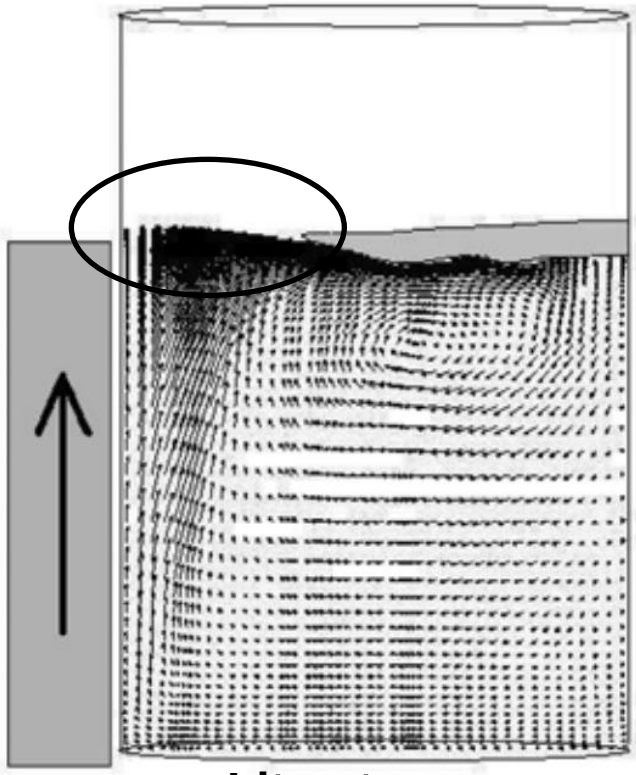
Left: Streamlines of steel velocity
Above: Slag opening formation from EMS stirring

Comparison with Literature

- Flow shows strong central vortex
- Resulting pattern similar to literature



SMSVC Simulation
Vectors of steel flow and contour of velocity at center plane

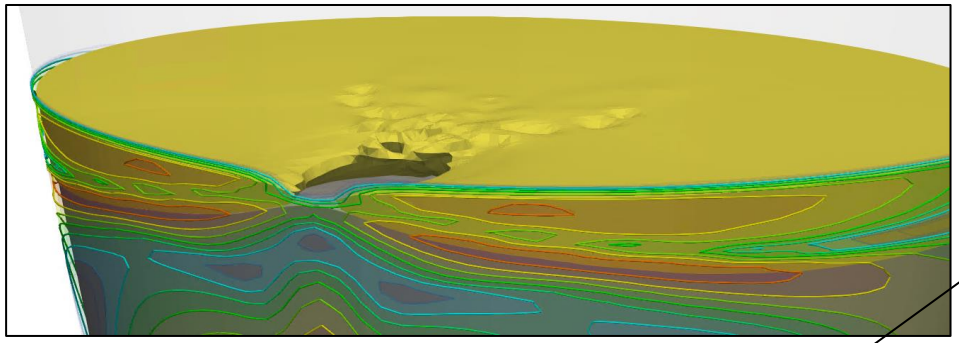


Literature
Vectors for similar upwards EMS

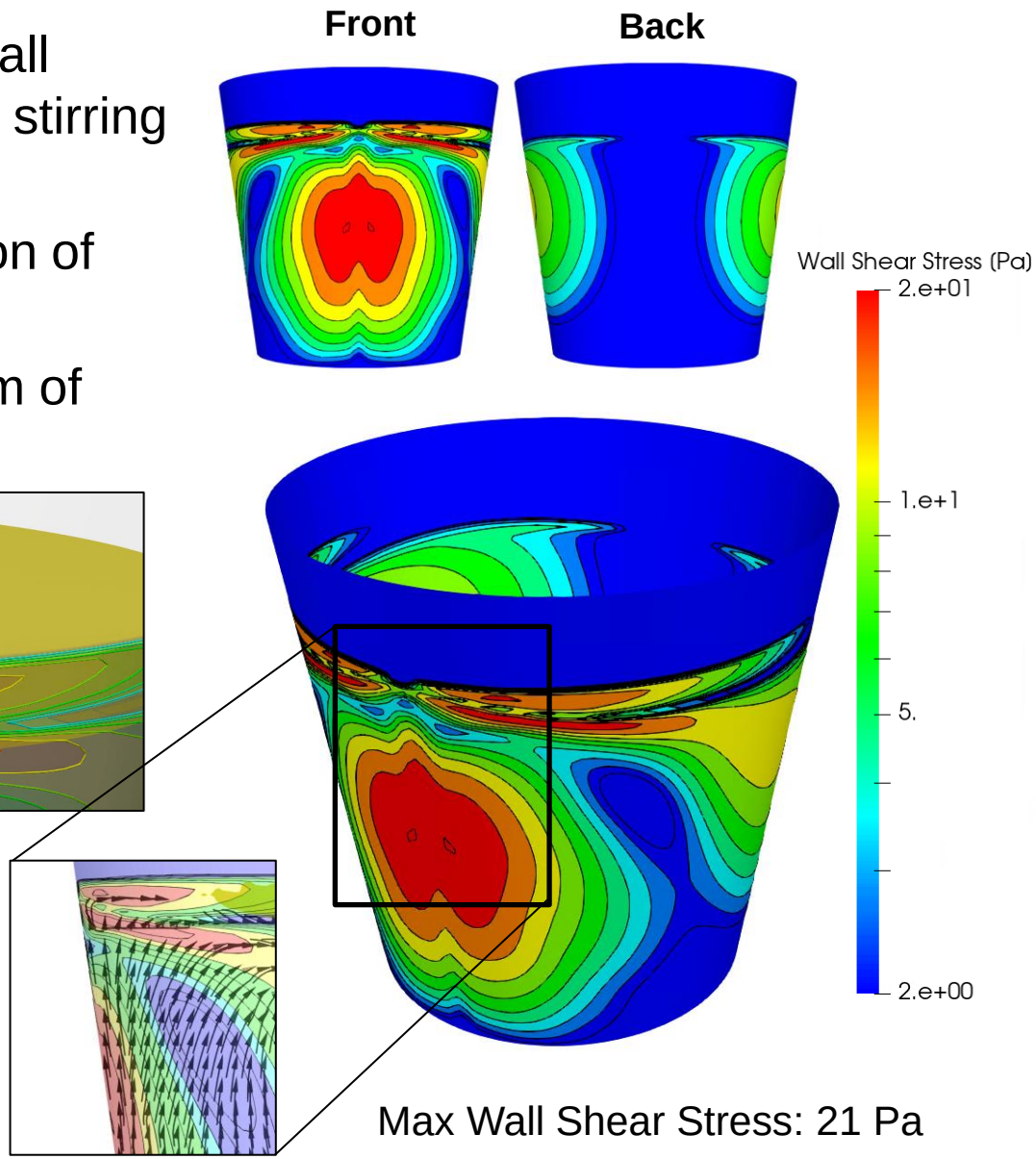
Sand, U., Yang, H., Eriksson, J.-E., & Fdhila, R. B. (2009). Control of Gas Bubbles and Slag Layer in a Ladle Furnace by Electromagnetic Stirring. *Iron & Steel Technology*, *July 2009*.

EMS Wall Shear Stress

- Ladle walls show very large wall shear stress at wall nearest to stirring unit ("front").
- Bottom shows slight distribution of shear stress
- Strong shear at top and bottom of slag layer near open eye



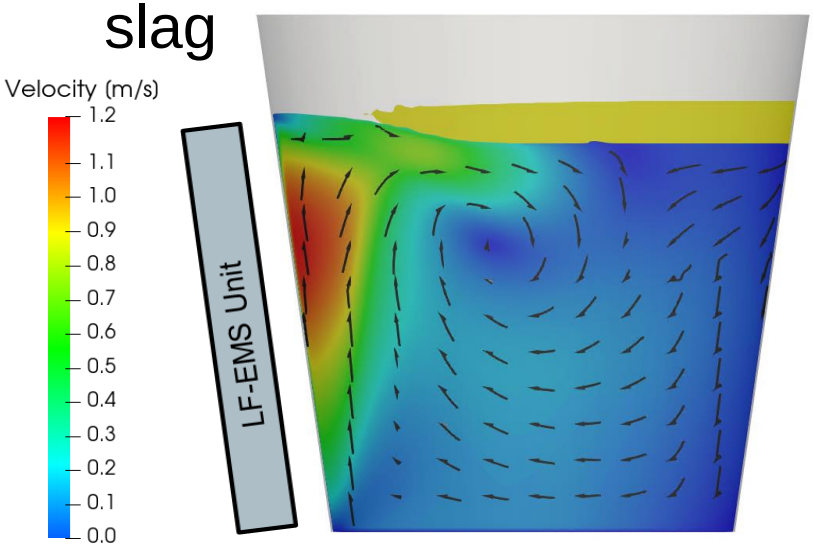
Above: Contours of wall shear stress with slag layer shown

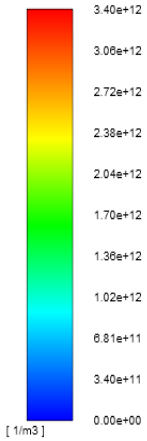


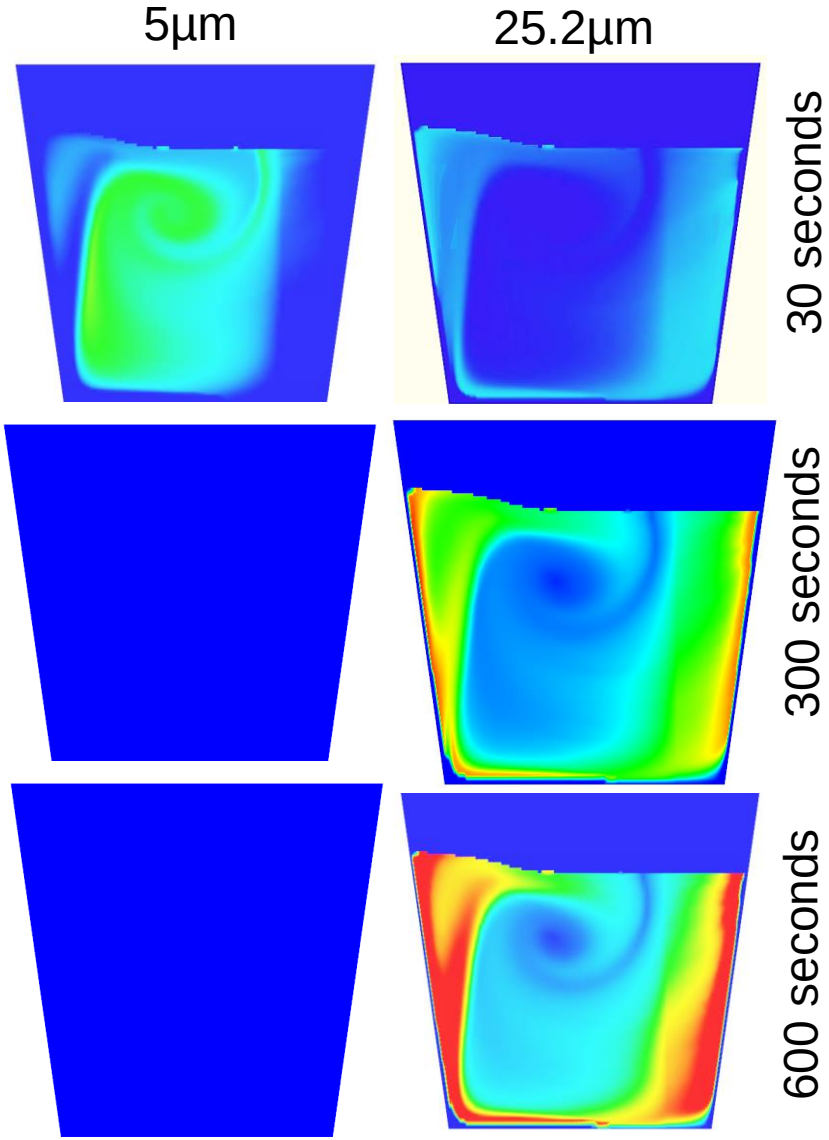
Max Wall Shear Stress: 21 Pa

EMS Inclusion Removal

- Slag "eye" cuts some of the inclusion removal effect
- Creates a "downstream" area with reduced inclusion removal
- Inclusion growth occurring in slower near-wall areas then being pushed towards the slag







Contours of inclusion number density [n/m3]

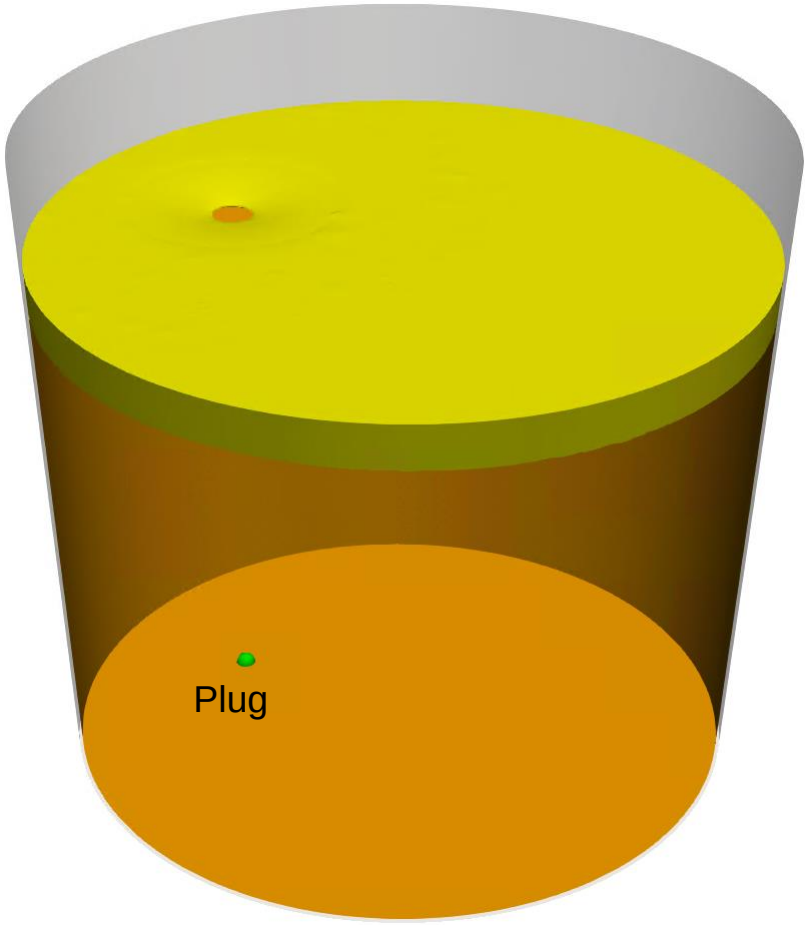
Project 6:
Plug Clogging Study

Objective: Investigate solutions for plug clogging operations

Start: February 2020

Plug Clogging Study

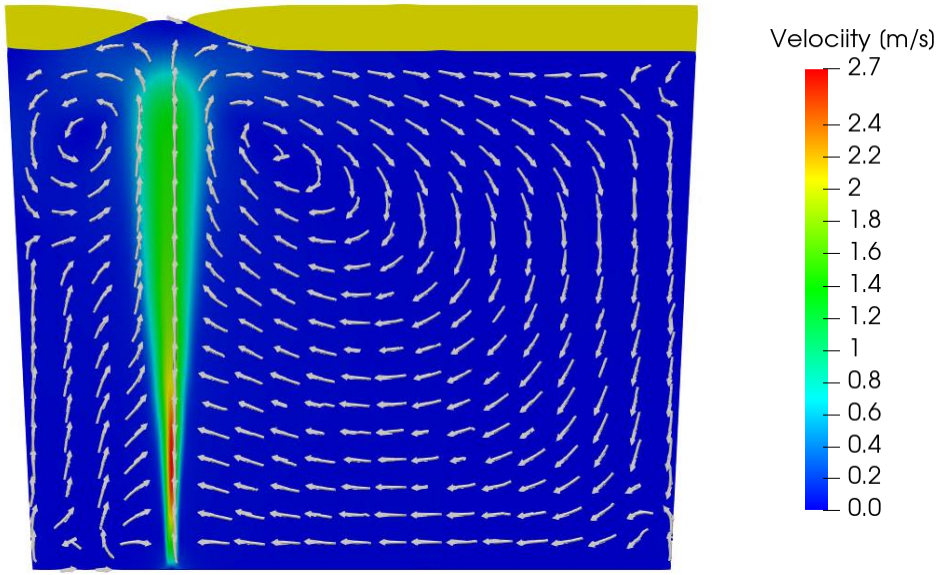
- Issue:
  - What to do when a plug is clogged?
- Potential solutions:
  - Maintain same gas flow rate through other plug
  - Inject more gas through other plug
- Approach:
  - Simulate generic ladle with one plug off (5 SCFM)
  - Examine flow field and inclusion removal
  - Compare with two-plug equivalent

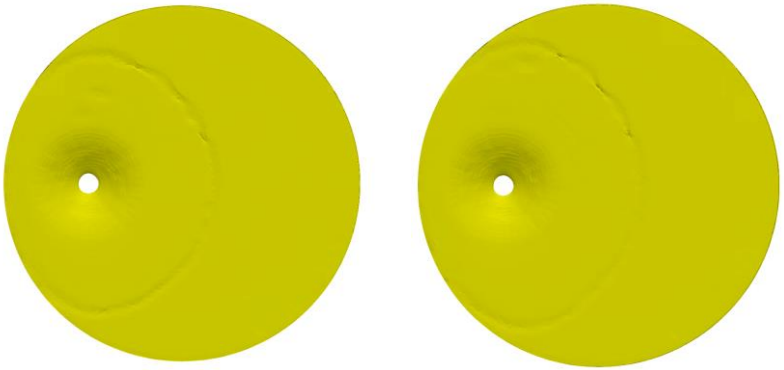


"Clogged" case with working plug shown in green

Single Plug Flow Field

- Flow field shows highest velocity above plug, as expected
- Rest of ladle has very low velocity
- Small slag eye forms above plug
  - Roughly 0.2m diameter
  - Consistent with simulations of two plug 5/5 SCFM case

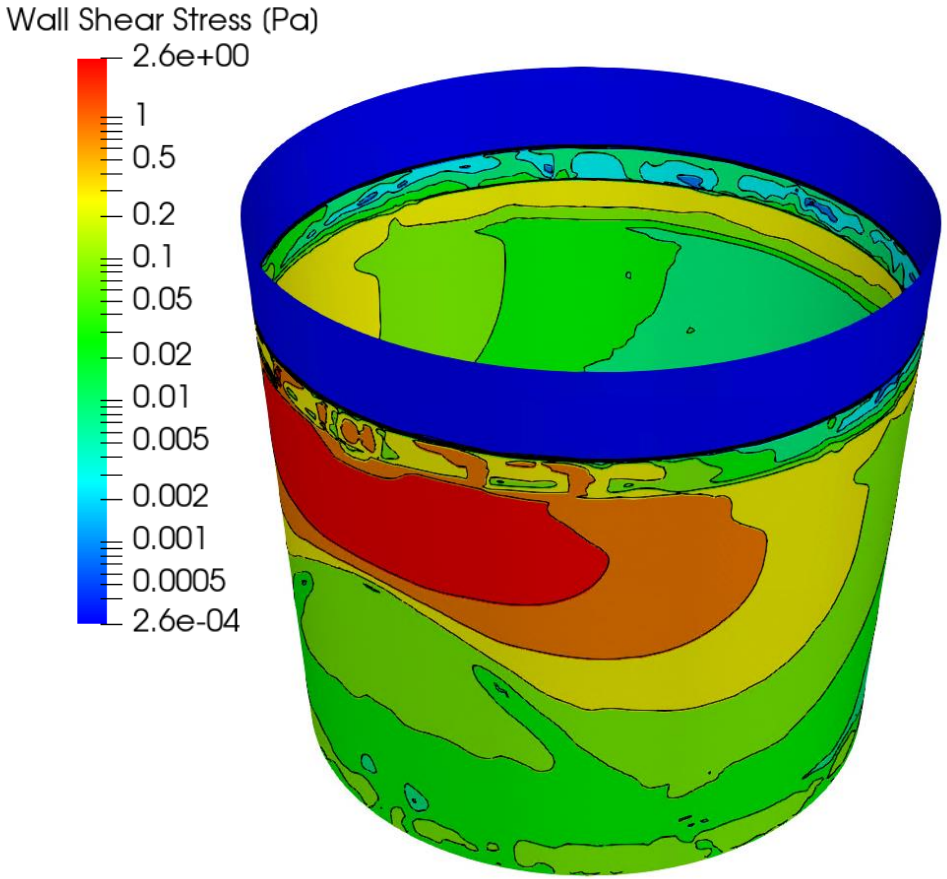




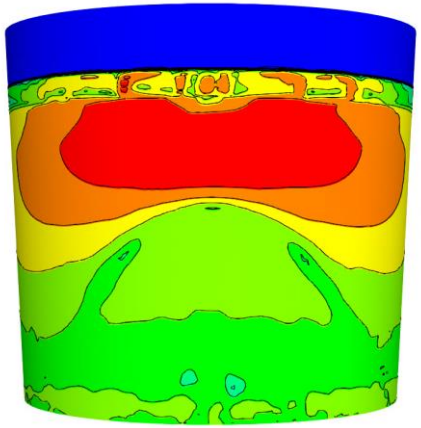
Top: Contours and vectors of steel velocity at 90 seconds
Below: Slag eye at 55 sec (left) and 75 sec (right)

Plug Clogging Wall Shear Stress

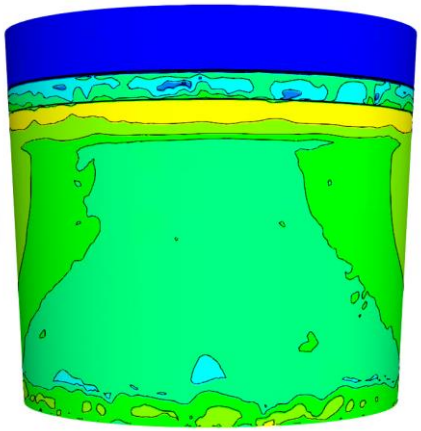
- Highest wall shear stress found at top of steel region nearest to plume

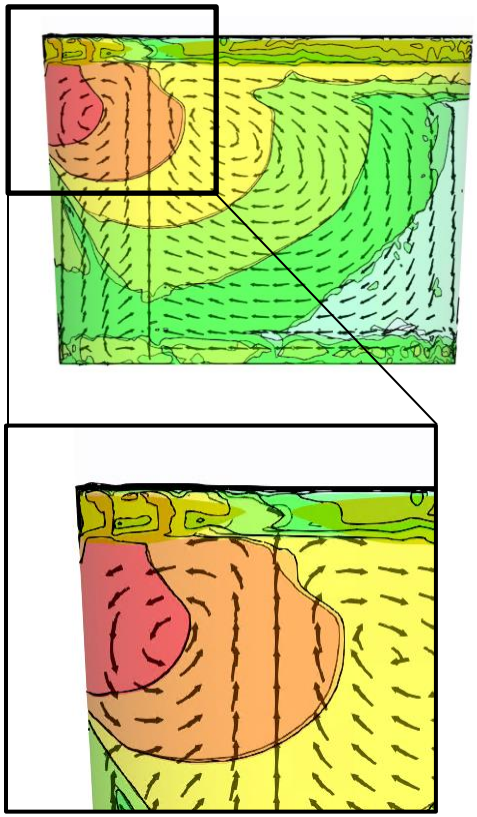


Front



Back

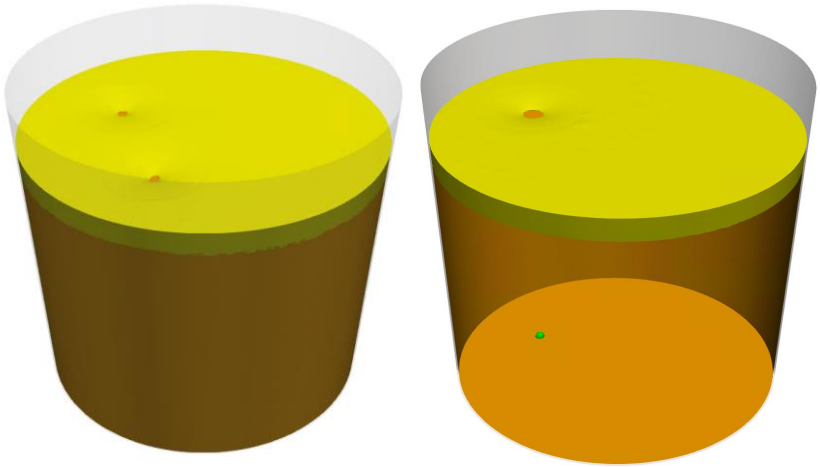




Comparison with Two Plug Flow

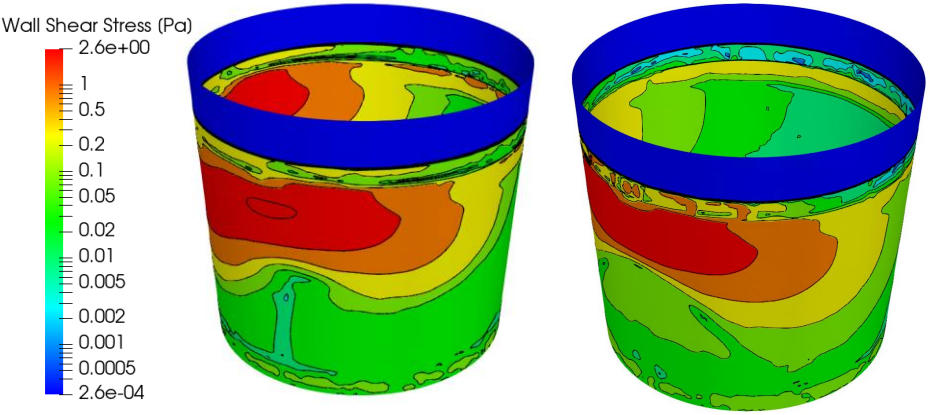
- Slag eye slightly larger in one plug case
  - 0.2m vs. 0.17m
- Turbulence confined to smaller area
- Wall shear stress shows has similar values, but is in smaller region

Two Plug Case One Plug Case



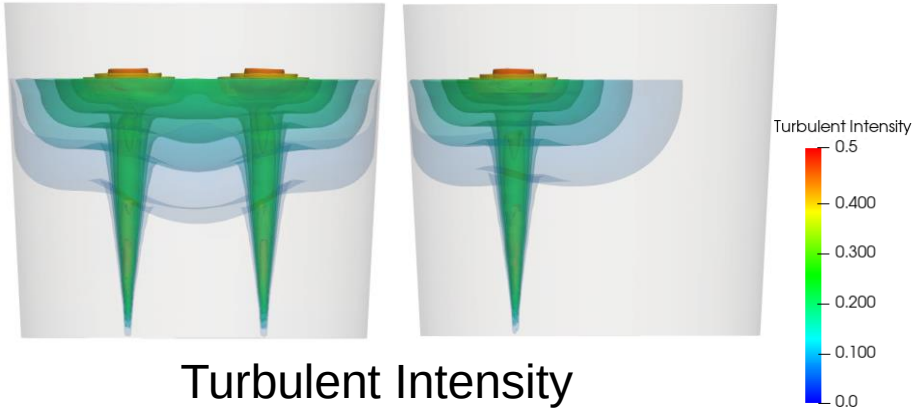
Slag Eye Formation

Two Plug Case One Plug Case



Wall Shear Stress

Two Plug Case One Plug Case



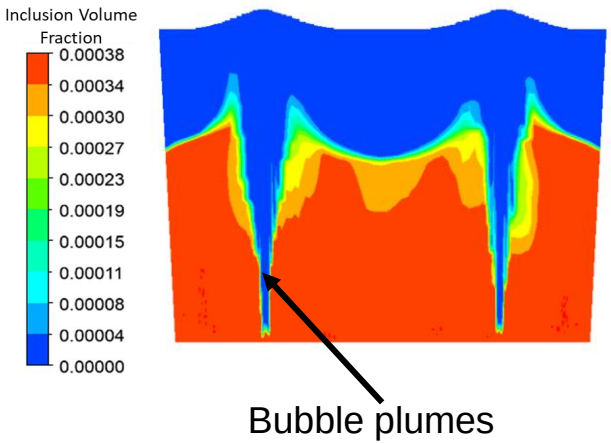
Turbulent Intensity

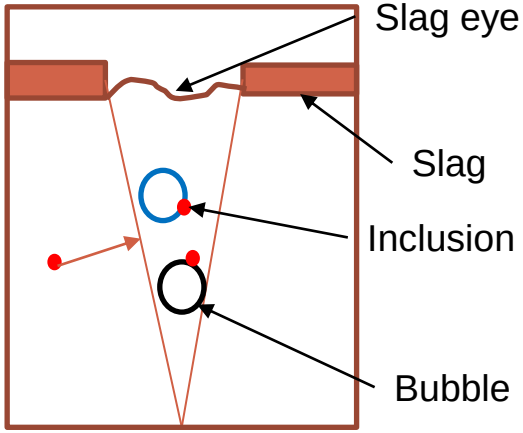
Project 5:
Inclusion Removal Model Enhancement and Validation

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

Inclusion Removal Modeling

- Objective:
  - Refine inclusion model to include inclusion release at slag eye and improve overall removal rate accuracy
  - Validate model with industry sampling
- Current model:
  - Assumes inclusions are removed by bubbles immediately
  - Overpredicts inclusion removal
- Approach:
  - Enable bubbles to transport inclusions upwards
  - Remove inclusions when bubble reaches slag interface, release if bubble reaches slag eye

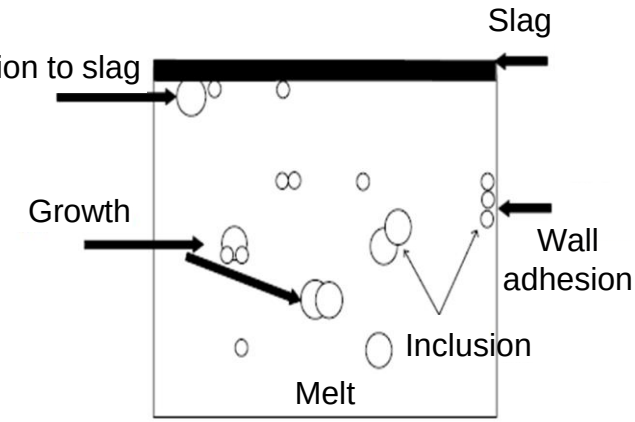




Inclusion Growth and Removal Model

Inclusion removal behavior

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



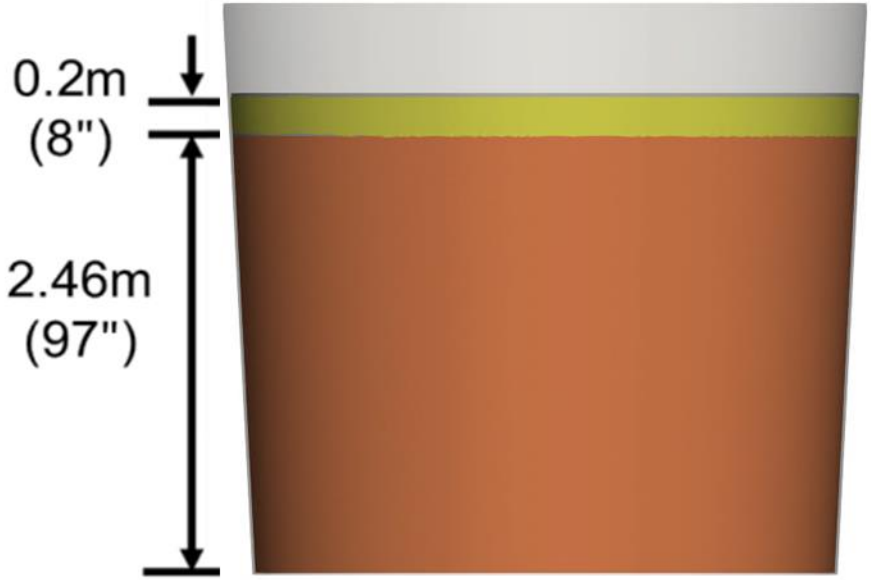
Inclusion removal
- Slag
  - Inclusions flow motion and flotation.
- Wall
  - Inclusion attachment to refractory
- Bubble
  - Buoyancy collision
  - Turbulent random collision
  - Turbulent shear collision
  - Bubble wake capture

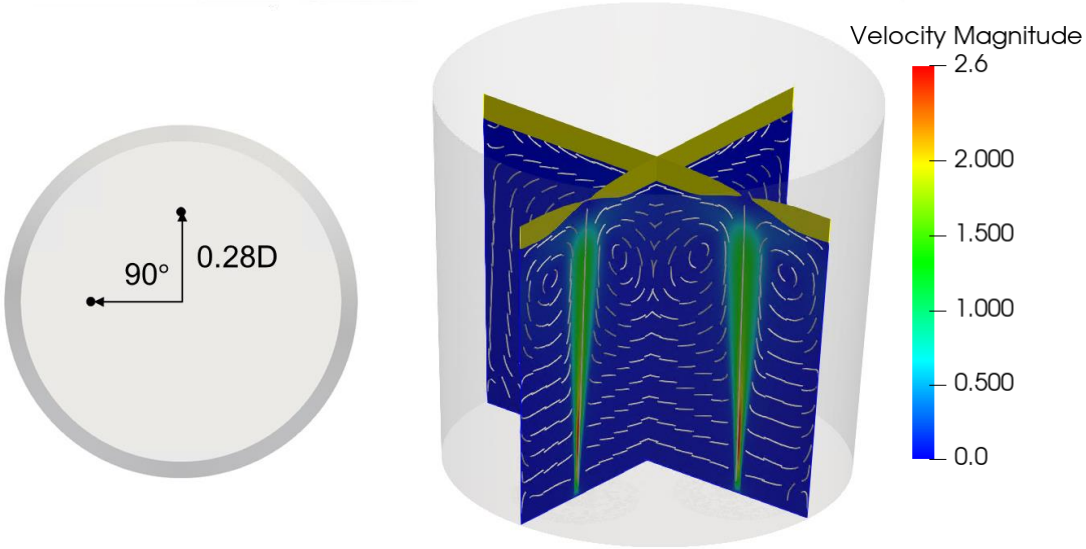
  } Inclusion transport to slag

- 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.".

Two Plug 90-deg Case

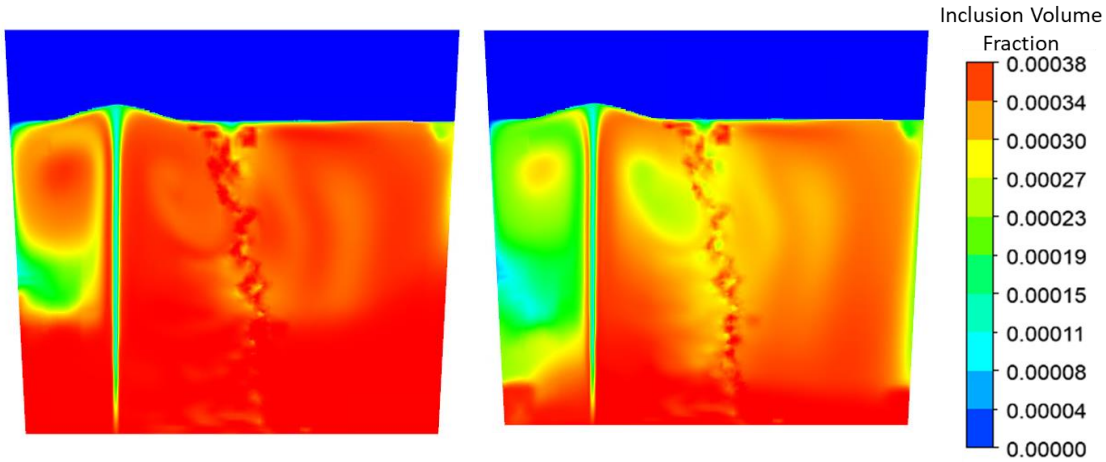
- Simplified Nucor ladle
  - 2.46m melt depth (97”)
  - 0.2m slag depth (8”)
  - Wall taper: 3°
- Two inlet plugs
  - 90° separation angle
  - 0.28D from center
- Inclusion modeling tested using 5-5 SCFM case



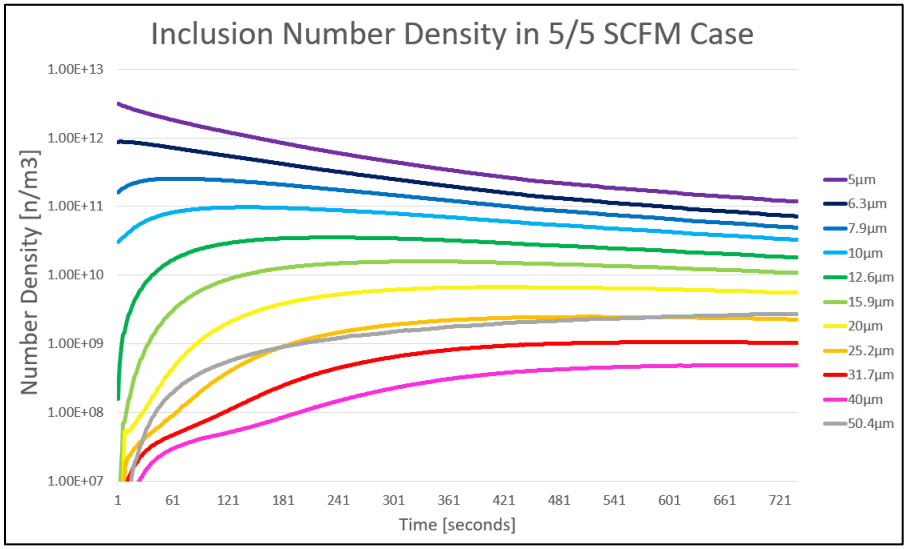


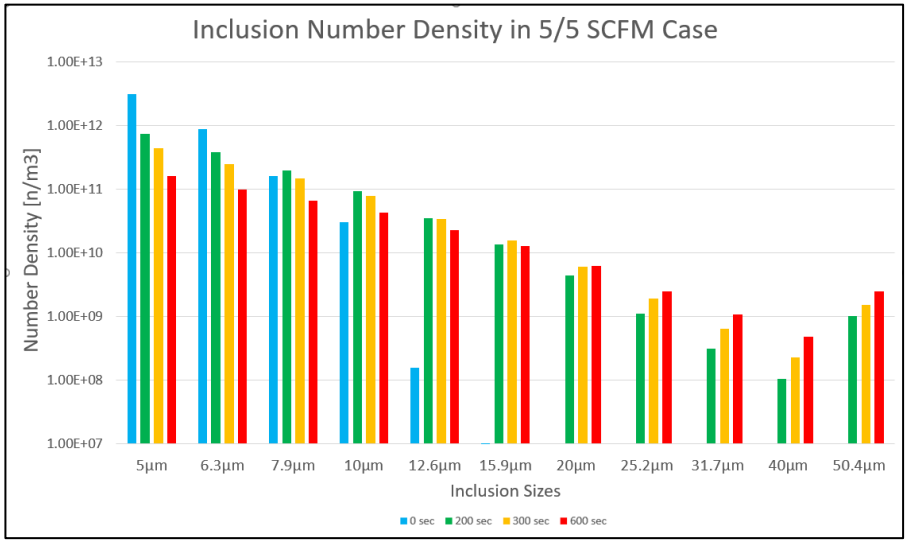
Inclusion Distributions

- Inclusion removal model shows strongest effect in bubble-influenced areas
- Inclusion growth rate overcomes removal rate
- 50.4um inclusions continue to grow at 720 seconds



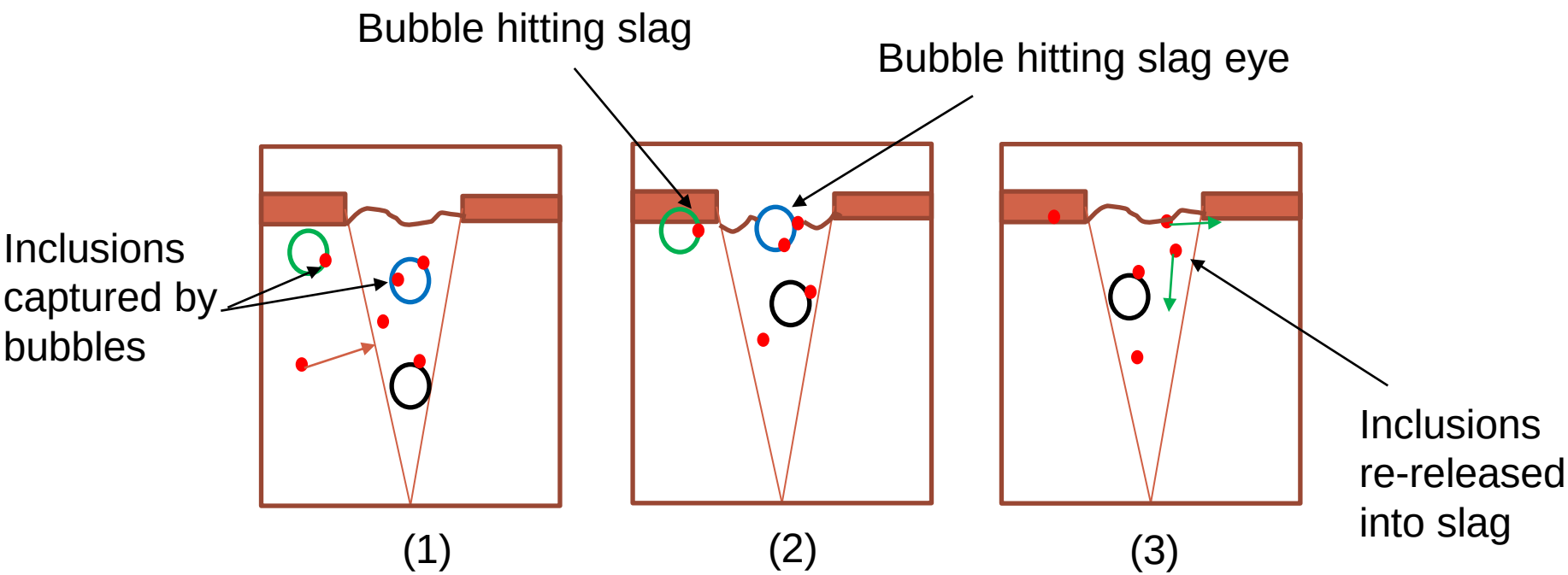
100 s 300 s





Slag Eye Inclusion Re-Release

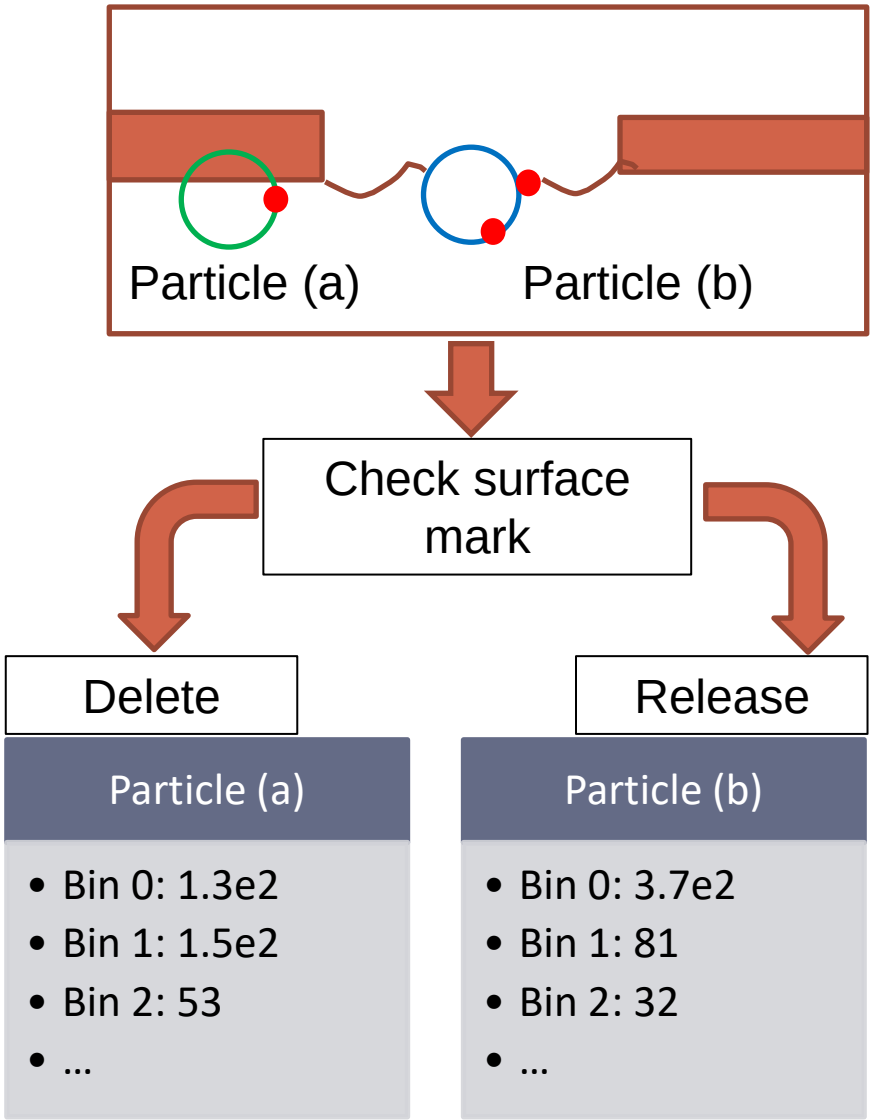
- Approach:
  - Track number of inclusions absorbed by each bubble
  - Release inclusions to steel if bubble reaches slag eye



Inclusion Re-Release Approach

1. Inclusion UDF calculates source (sink) term for inclusions
2. Number of inclusions removed (each bin) added to particle memory based on particle ID
3. When particle hits surface:
   a) Is slag? -> Delete particle and inclusions
   b) Is eye? -> Delete particle, create source term for inclusions
      i. Number from each bin

- Process loops across all particles in cell at end of iteration
- Delete/release triggered on DPM escape



Project 9:
Desulfurization and Reoxidation in Ladle

Objective: Develop desulfurization and reoxidation model in ladle

Start: March 2020

Desulf. and Reoxidation Overview

- Goal:
  - Develop model for desulfurization and reoxidation in ladle
- Approach:
  - Model desulfurization in generic Nucor ladle using approach found in literate
    - Reactions at slag-metal interface
    - Species Al, Si, Mn, Fe and S in metal and slag
  - Add reoxidation model
- Progress:
  - Adding desulf. through User-Defined-Functions (UDF) scripts using work by Lou and Zhu (2014) as reference

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.

AIST Digital Transformation Grant
Project 9:
Smart Ladle

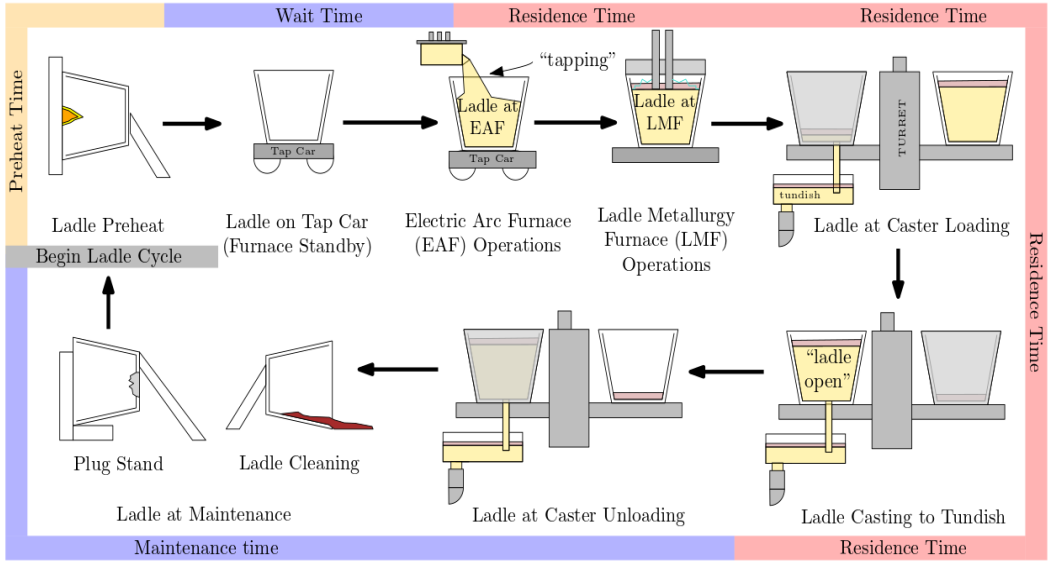
Start: September 2019
Site: Steel Dynamics, Inc – Butler, IN
Industrial Mentor: Yury Krotov
Other Supporters: SMSVC Members

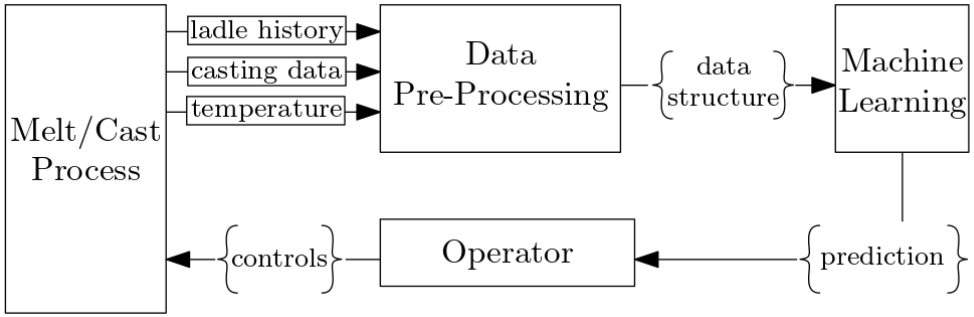
Objectives

- Create an adaptable AI engine for ladle operation
  - Fundamentally relate how input variables affect steel casting temp.
- Correlate casting temperature with known input variable conditions,
- Improve operational responses for casting temperature control
- Student engagement in digital technologies and deep learning
- Student awareness of steel industry careers

Methodology

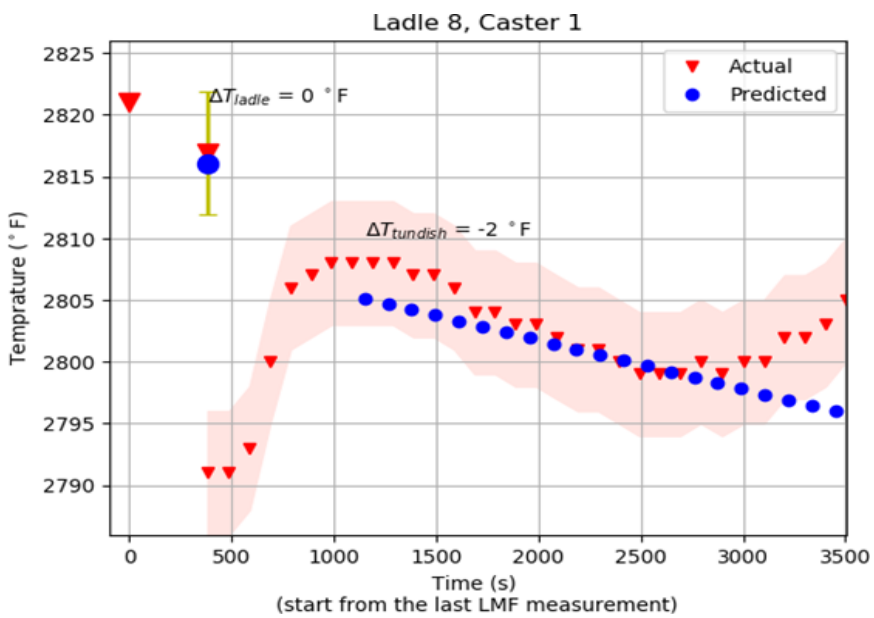
- Data taken from ladle and casting processes
- Ladle and tundish "history" data structure created
  - Time with steel, time empty, preheat time, heats in campaign
  - Heats in sequence, temperature data, throughput
- Deep learning model creates correlations

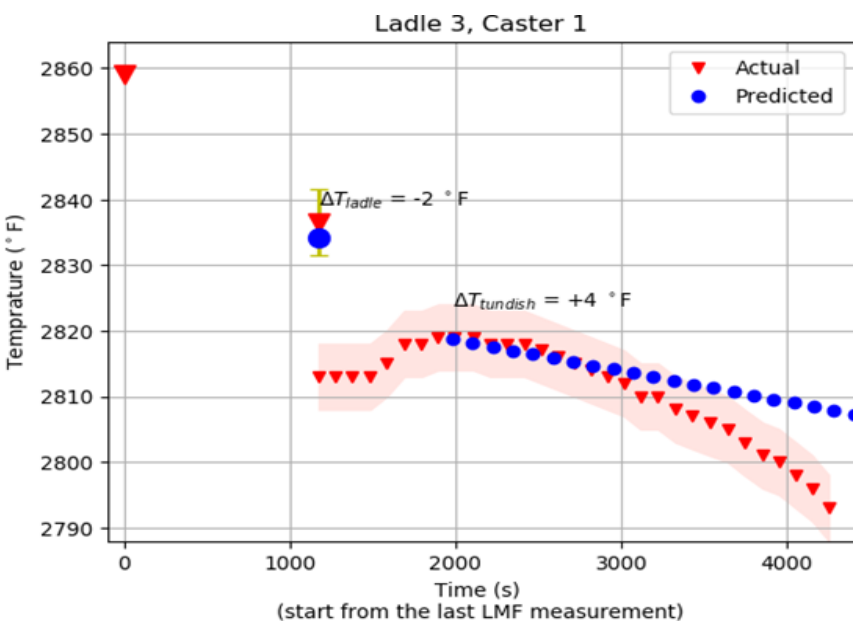




Smart Ladle Results

- Model trained using data from SDI Butler, IN facility
- Predicts three targets:
  - Temperature drop in ladle from last LMF temperature sample to ladle open at tundish
  - Midpoint tundish temperature
  - Tundish temperature slope of linear region





Implementation

- Model currently being tested at SDI Butler facility
- Read-only configuration
  - Take raw data from SQL database
  - Algorithm runs on-demand
    - Python script to call sandboxed code
    - Code runs machine learning algorithm to generate output data
    - Provides predictions to HMI software

Summary

Summary

- **Project 4: EMS Isothermal Ladle**
  - New approach uses imported Lorentz force data
  - Highest wall shear stress near stirring unit location
  - Slag opening forms at same area
- **Project 5: Inclusion Removal Enhancement & Validation**
  - Baseline inclusion removal established
  - Addition of slag-eye effect in progress
- **Project 6: Plug Clogging Study**
  - Flow field and wall shear stress data consistent with industry observation
- **Project 8: Desulfurization and Reoxidation**
  - Development of desulfurization model underway
- **Project 9: Smart Ladle**
  - Deep learning algorithm trained using industry ladle and casting data
  - Machine learning tool created to predict tundish temperature using trained model
  - Implementation in progress

Model Applications

- Refining Process Improvements:
  - Stirring time
  - Wall shear stress reduction
  - Gas flow rates
  - Ladle heat loss, refractory life
  - Inclusion removal effectiveness
- Evaluation of ladle design:
  - Ladle shape
    - Height, diameter, wall taper angle
  - Plug parameters
    - Plug number, separation angle, distance
- Smart Ladle
  - Optimize ladle operations

Future Work

- **Project 5: Inclusion Removal Enhancement & Validation**
  - Evaluate inclusion removal for various stirring conditions
  - Validation of model using Nucor data
- **Project 6: Plug Clogging Study**
  - Comparison of refining behavior to non-plugged case
  - Adjust inputs to offset lost efficiency
  - Erosion rates of refractory wall
- **Project 7: Combined Gas/EMS Ladle Study**
  - Simulate EMS and gas injection in AM ladle
- **Project 8: Desulfurization and Reoxidation**
  - Develop and validate desulfurization and reoxidation models
  - Apply models to generic Nucor ladle
- **Project 9: Smart Ladle**
  - Develop and validate desulfurization and reoxidation models

Comments from Industry Collaborator

Thank You
Questions and Comments