COMPUTATIONAL STUDIES AND OPTIMIZATION OF PROCESSES IN A STEEL LADLE

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- Senior design teams

November 10, 2021

"Where Ideas Become Reality"

CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

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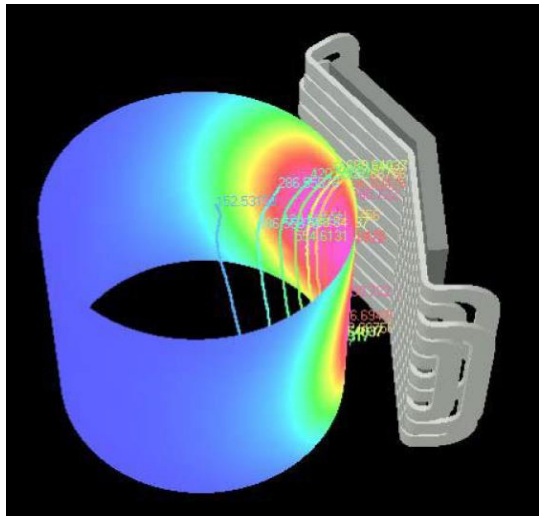
Presentation Outline

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

Motivation

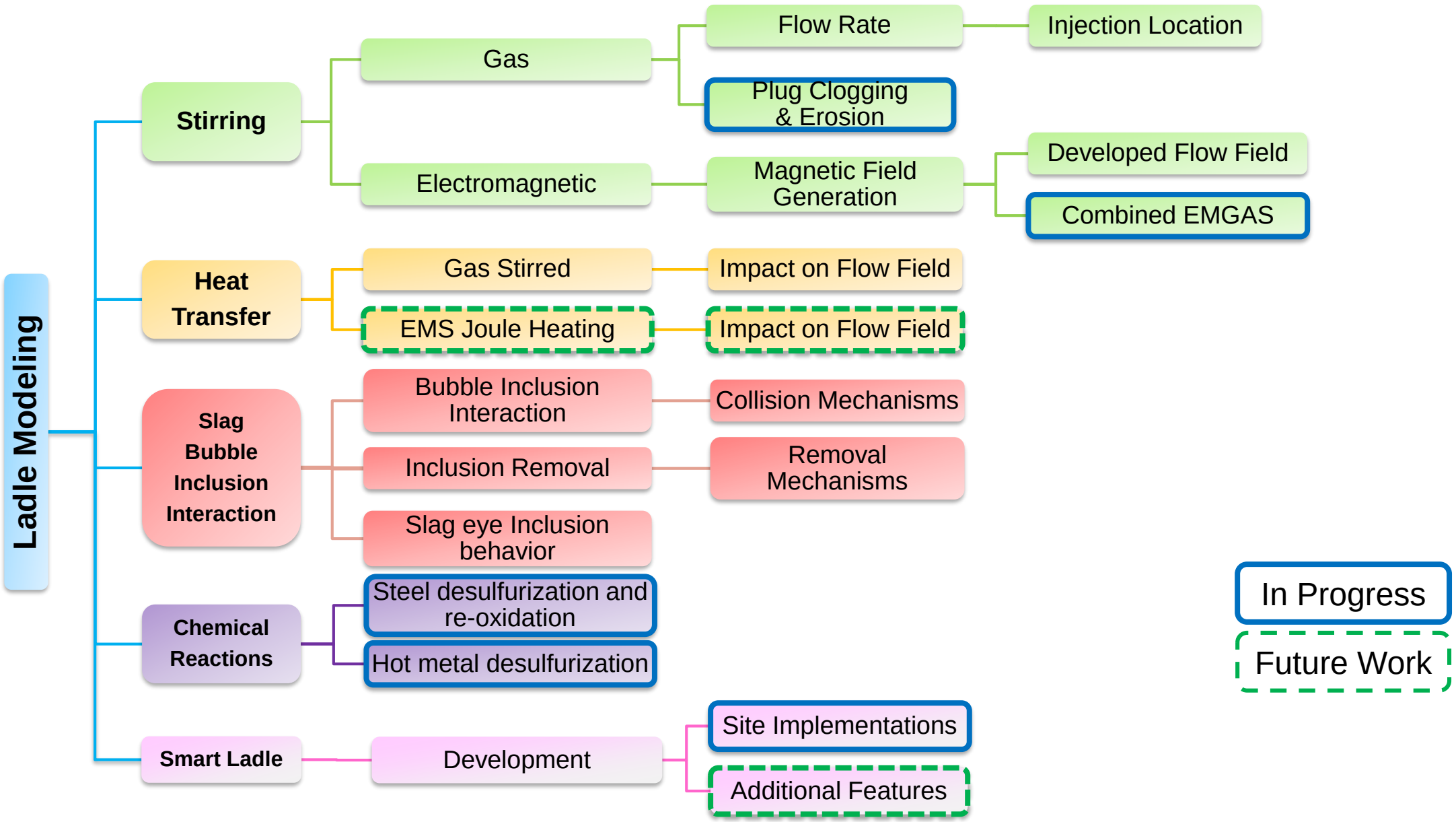
- Current Issues
  - Complex transport phenomena
  - Incomplete understanding the dynamics of multiphase flow and inclusions
  - Need for correlations between LMF operation and ladle history with desired casting temperature
- Potential Impacts
  - Optimized flow condition and physical properties
  - Improved steel cleanliness and final defects
  - Better operator control over steel temperatures and product quality



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



Ladle Application Roadmap

Project 11: Cleveland-Cliffs Mansfield Stirring Ladle

Associated Models:
- *Gas Stirring Models*

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

Project 12: Shipping Temperature and Superheat Control

Associated Models:
- *Smart Ladle*

Site Companies:
- *Site A: Steel Dynamics, Inc. (01/2021 – 05/2021)*
- *Site B: Nucor Steel (10/2021 – 02/2022)*
- *Site C: Tata Steel (11/2021 – 04/2021)*
- *…*

Project 14: Hot Metal Desulfurization

Associated Models :
- *Gas and EMS Stirring Models*

Companies interested:
- ***Cleveland-Cliffs (Site company)***
- *ArcelorMittal Global R&D*

01/2021 – 10/2021

GOALI - inclusion formation and removal *09/2021 – 09/2024*

01/2022 – 05/2022

06/2021 – 12/2021

01/2022 – 08/2022

06/2022 – 12/2022

01/2021 – 04/2022

Gerdau Stirring Side Project

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

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

Hot Metal Desulfurization Side Project

Completed: October 2021

Associated Models:
- *Hot Metal Desulfurization*

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)***
- *Cleveland-Cliffs*
- *ArcelorMittal Global R&D*
- *Charter Steel*
- *Evraz*
- *SSAB Americas*

Project 15: Minimization of Ladle Erosion and Wear

Associated Models:
- *Gas and EMS Stirring Models*

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

Major Outcomes – Models & Applications

Projects (2016 – 2021): Completed: 5, 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
- **Project #5:** Inclusion Removal Enhancement & Validation – Nucor Generic Ladle
  - Validated against measurement data (avg 12.1% number density difference)
  - **1.3%** final inclusion removal rate increase as ladle separation angle from 90° to 180°

Major Outcomes – Models & Applications

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

- **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
  - **Desulfurization model is validated well against plant measurement from literature (5.8% final sulfur mass fraction difference)**
- **Project #9:** Smart Ladle
  - Developed a trained deep learning algorithm using industry data
  - Prediction of tundish midpoint temperature and slope
  - **The Mean Average Error for the current model is 1.4°F with a standard deviation of 2°F**
  - **Smart Ladle Web Tool created and made available on SMSVC member's page**
- **Project #10:** Hot metal desulfurization
  - **Developed Mg and Cao desulfurization model**

Major Accomplishments since April 2021

- Inclusion Removal Enhancement & Validation
  - Trend from optimized inclusion model is validated well with Nucor ladle measurements
- Desulfurization and Re-oxidation in Refining Ladle
  - Desulfurization model is developed and validated well with plant measurements from literature
- Smart Ladle
  - The accuracy of the predictions increased, the Mean Average Error for the current model is 1.4°F with a standard deviation of 2°F
  - Simplified web tool made available on SMSVC website

2021 Objectives

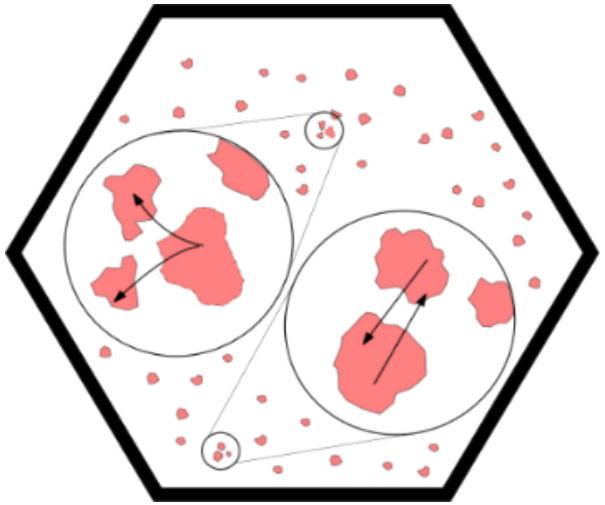
- Investigate Inclusion Removal in Gas-stirred & EMS Ladle
  - Validate inclusion removal results with industrial measurement data
  - Apply inclusion model to EMS & EM-gas ladle
- Investigate Chemical Reactions in Steel Ladle Refining
  - Develop desulfurization model and validate it with industrial measurements
- Smart Ladle
  - On-site implementation and testing of Smart Ladle
  - Expansion to other sites/companies
  - Simplified Web tool

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 Hot metal desulfurization	Literature Search												
	Model development and validation												
Project 11 Application of Cleveland Cliffs Gas Stirring Ladle	Geometry development												
	Simulation of flow field												
Project 12 Shipping Temperature and Superheat Control	Data collection												
	Model development and implement												
Project 13 Stirring Time Optimization for Homogenization and Inclusion Floatation	Literature Search												
	Model application												



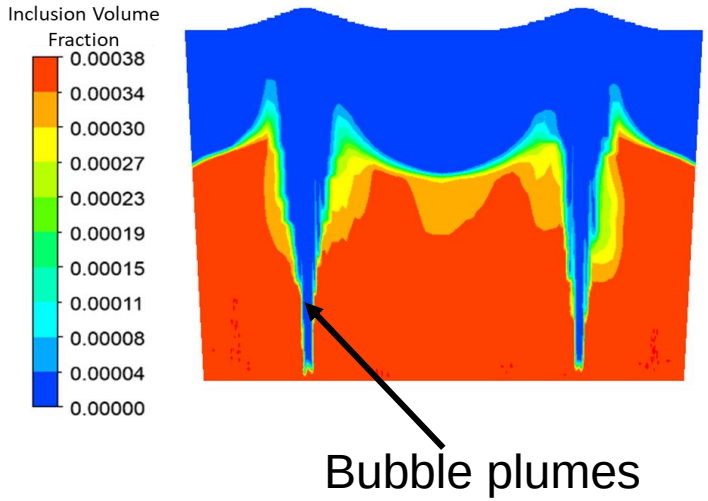
Project 5:
Isothermal Inclusion Removal Enhancement and Validation

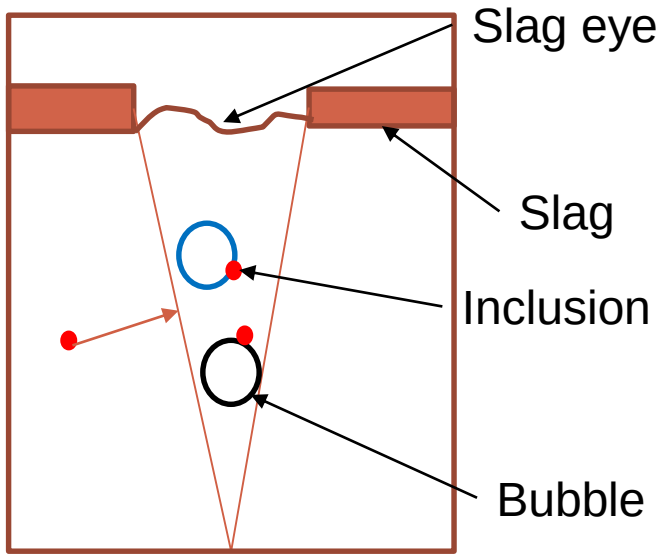
Site: Nucor Decatur

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





CFD 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

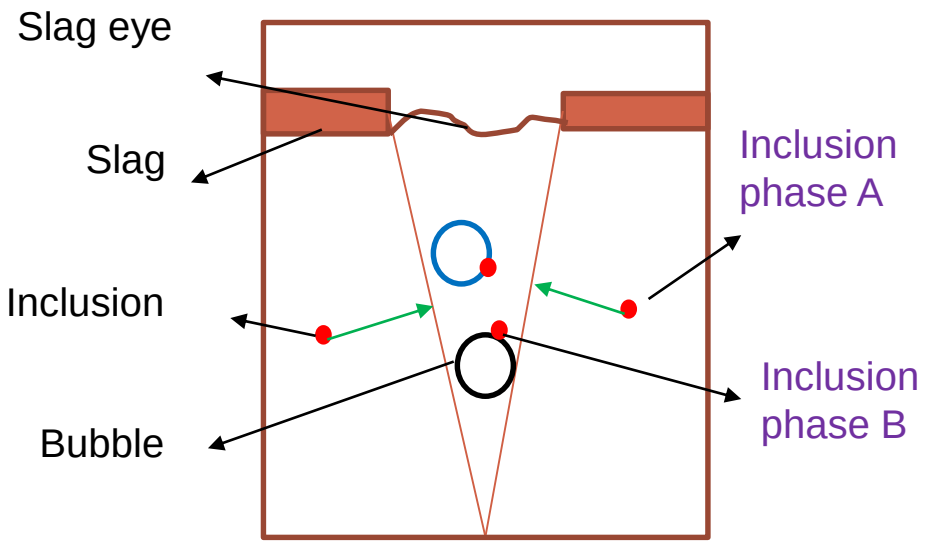
2. Flow field simulation (Find velocity of gas phase)

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

Velocity, turbulence, pressure, etc.

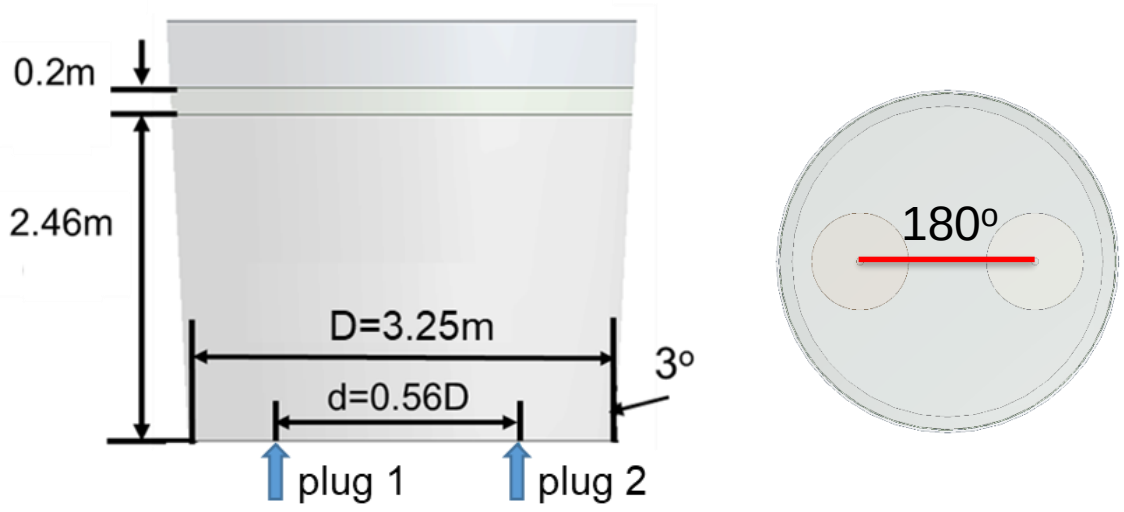
3. Inclusion removal and aggregation model

- 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

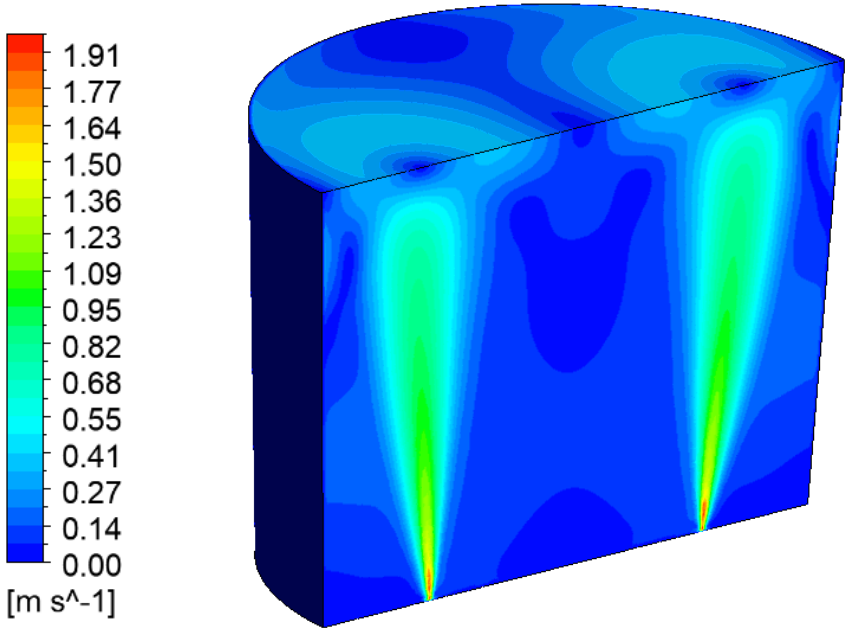


Validation of CFD Model

- Only steel layers is modeled (because no slag eye appear)
- Two plugs at bottom
- Plug separation angle of 180 degrees
- Velocity distribution of steel domain is shown below



Schematic of ladle geometry



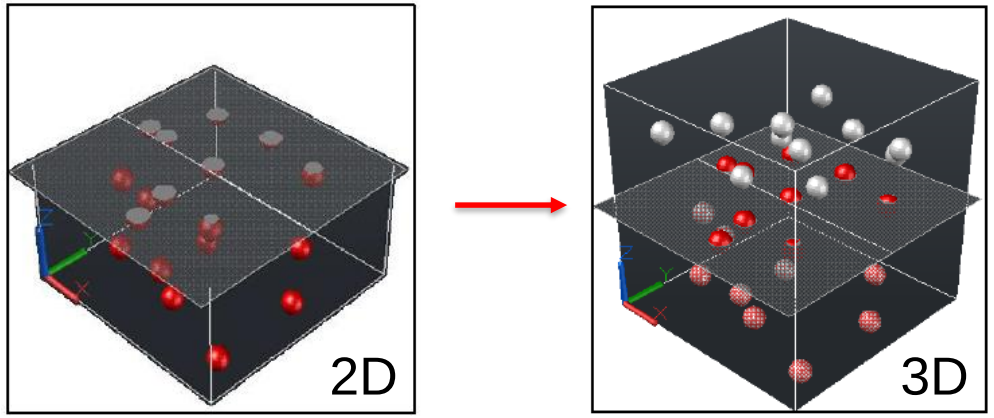
Velocity distribution of steel domain

Converting Sample Data for Validation

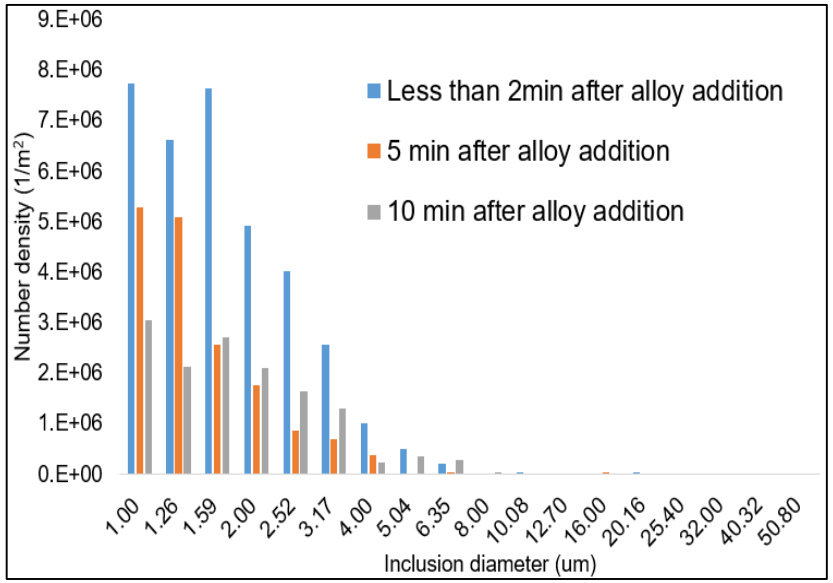
- Measured data: 2D surface density distribution
- Schwartz-Saltykov method: 2D cross section density to 3D distribution

$$N_V = \frac{N_A}{PD_{max}}$$

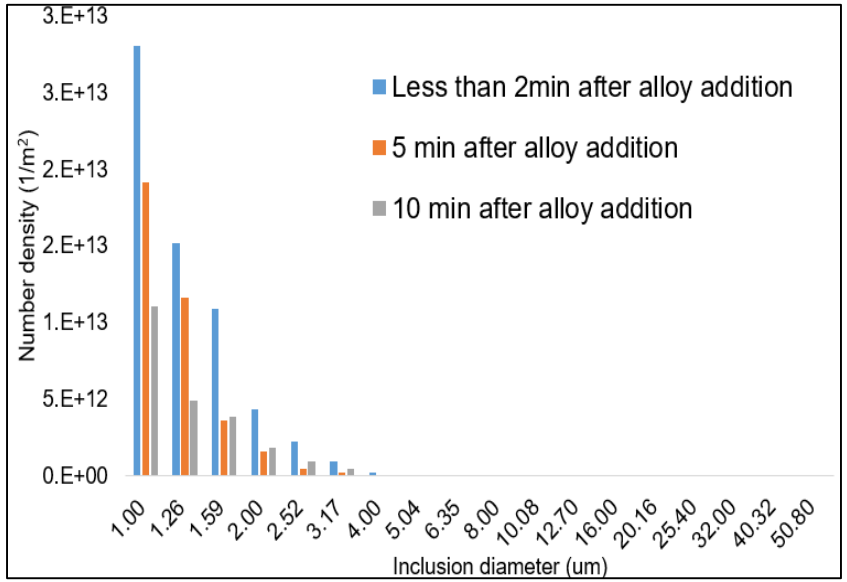
$$P(d_1 < d < d_2) = \frac{\sqrt{D_{max}^2 - d_1^2} + \sqrt{D_{max}^2 - d_2^2}}{D_{max}}$$



- Note:
  - N_V, N_A: number density in volume or surface
  - P: Probability of finding N_A
  - D_{max}: maximum diameter in surface
  - d_1, d_2: lower or upper limit of inclusion group



2D Number density distribution

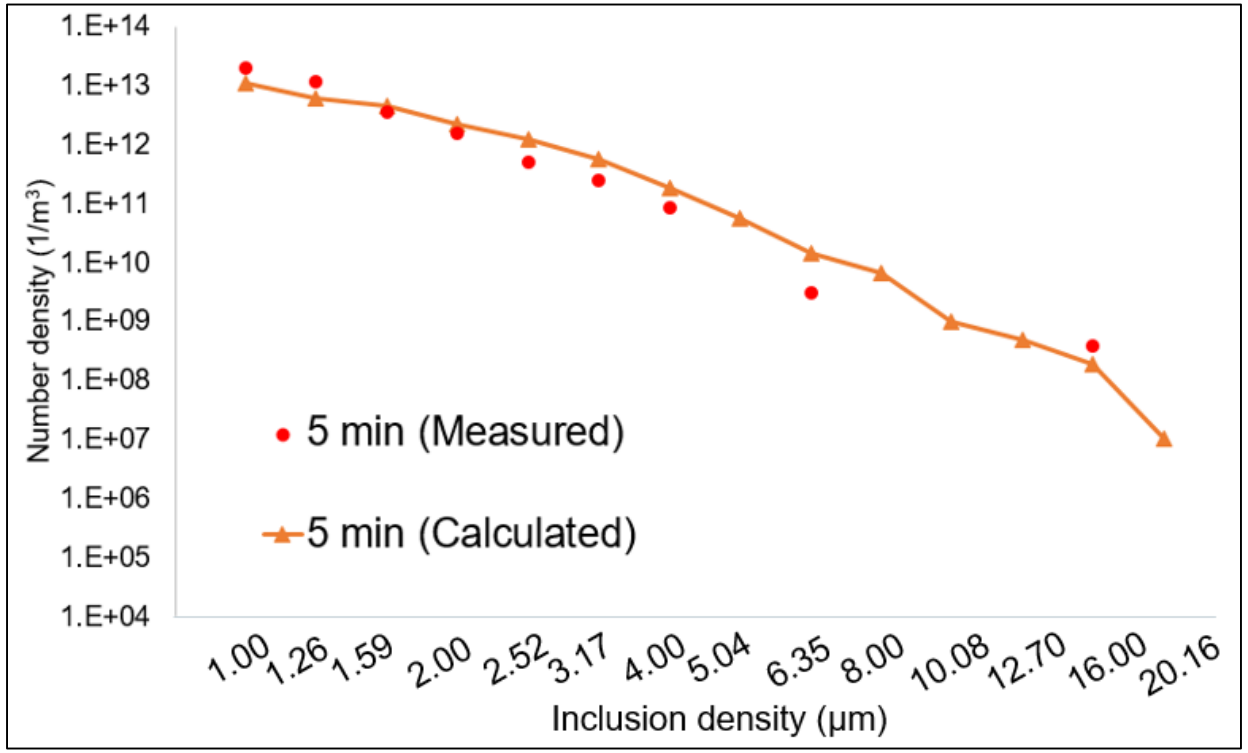


3D Number density distribution

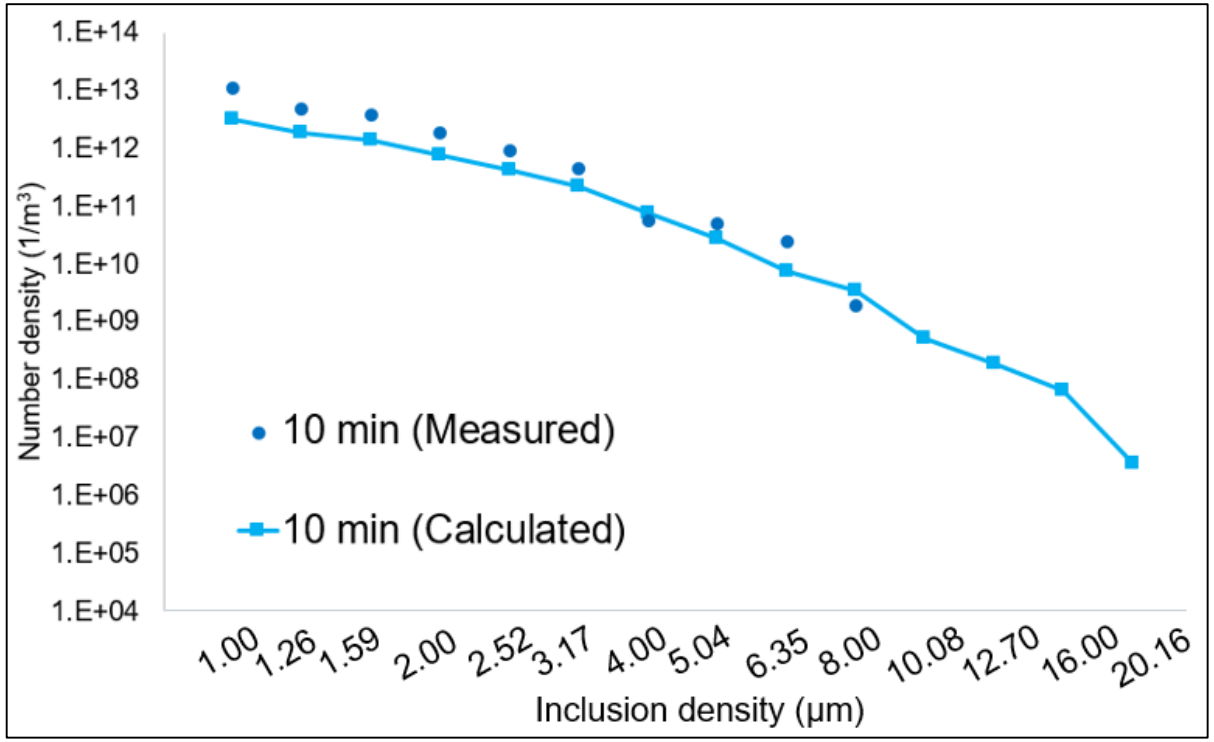
- Adaba, O., et al. "Three-dimensional study of inclusion morphology and size distribution in Mn-Si killed steel." *AISTech, Philadelphia, USA* (2018).

Validation: Number Density Distribution

- Good agreement between CFD with measured data



Measured and CFD comparison at 5 min after alloy addition



Measured and CFD comparison at 10 min after alloy addition

Model Applications

Simulation Capability

- Inclusion removal rate in different scenarios
  - Plug arrangement
  - Argon flow rate
  - Initial inclusion number density

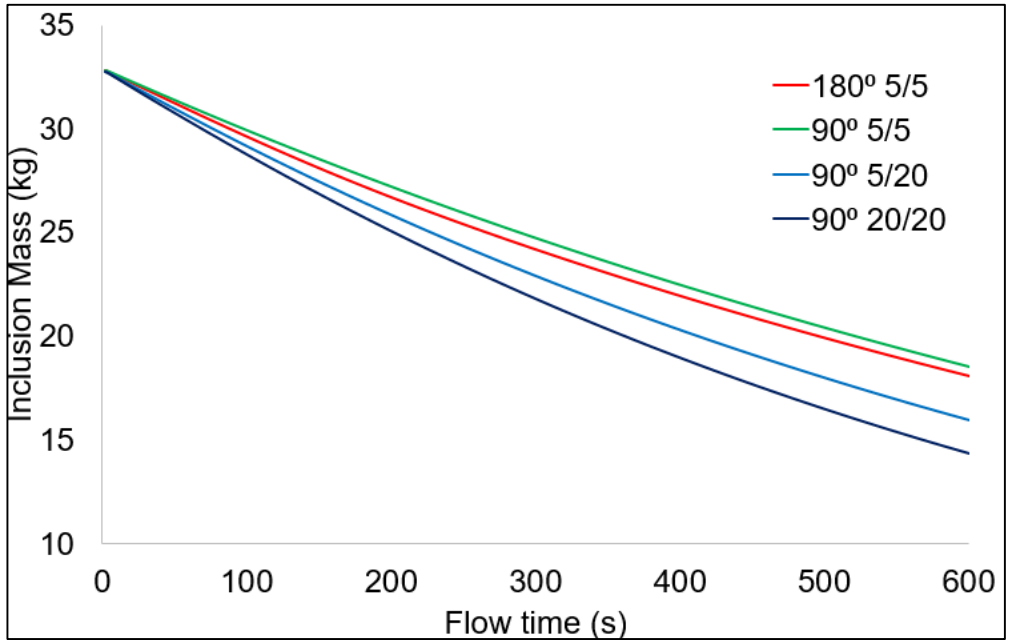
Industry Implementation

- Control Inclusions
  - Compare inclusion amount after a fixed stirring duration
- Optimize Stirring Time
  - Compare operations for quicker inclusion removal
- Reduce Costs
  - Input rates needed to reach targets

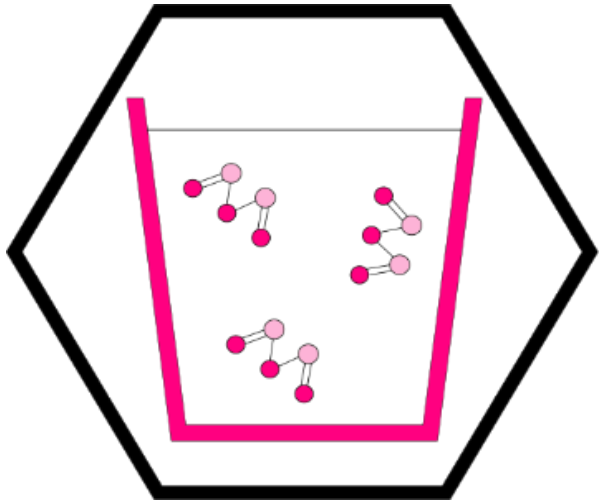
Application Example: Plug Separation Angle and Flow Rate

- Site: Nucor 180° and 90° ladles
- Application roadmap Project 13
- Recommended separation angle: 180°
  - removal rate increase 1.3% from 90° to 180°
- Recommended flow rate: 20/20 SCFM
  - removal rate increase 6.5% as flow rate increase from 10 SCFM to 25 SCFM (total flow rate)
  - removal rate increase 4.7% as flow rate increase from 25 SCFM to 40 SCFM (total flow rate)

Case	180° 5/5 SCFM	90° 5/5 SCFM	90° 5/20 SCFM	90° 20/20 SCFM
Removal rate (600s)	45.2%	43.9%	51.7%	56.4%



Mass of inclusion change over time in four cases



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

Desulfurization and Re-oxidation

- **Motivation**
  - Sulfur and alloying oxides in steel lead to surface defects and fatigue cracks, impairing the steel strength and resistance
  - The content of sulfur and alloying oxides can be controlled by chemical reactions between steel and slag
- **Objective**
  - To develop a model for the desulfurization and re-oxidation process
  - To validate the model with industry sampling
  - To apply the model to the practical ladles and optimize the operating conditions to control sulfur content as well as alloying oxides
- **Potential Impact**
  - Improved product quality and castability

CFD Methodology

Multiphase Flow Field

- **Steel/slag/argon multiphase**
  - Steel velocity and turbulence
  - Slag eye size and position

liquid flow field

- **Species transport model**
  - Local element content distribution in steel

velocity
turbulence
interface area

species mass fraction

species source term

Reaction Model

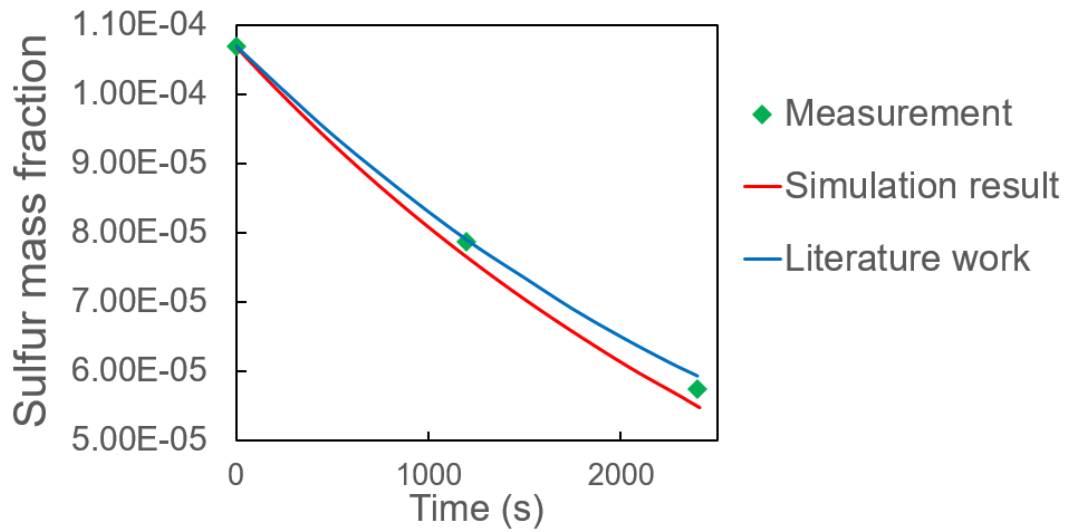
- **Reaction rate calculation**
  - Calculation of parameters based on multiphase flow field by user-defined function
  - Source terms of the element at the slag-steel interface

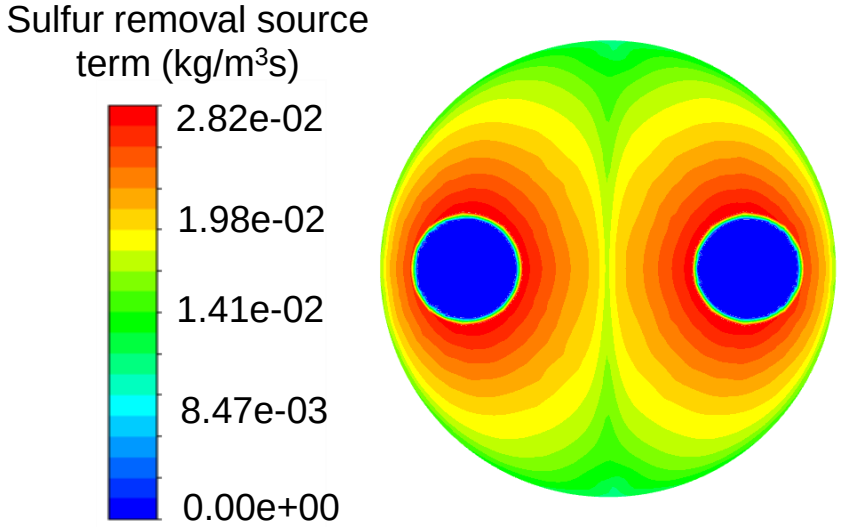
Desulfurization Validation

- Model validation by an 80-ton ladle [1] investigation
  - Initial compositions and conditions

Species in Steel (%)					Species in Slag (%)						
[Al]	[Si]	[Mn]	[C]	[S]	(Al_2O_3)	(SiO_2)	(CaO)	(MnO)	(S)	(FeO)	(MgO)
0.058	0.18	0.66	0.35	0.0107	21.32	5.84	57.79	0.24	0.07	0.95	6.02

  - Error of final sulfur mass fraction: 5.95% between simulation result and trial





[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.

Potential Application

Simulation Objective

- The sulfur mass fraction in different scenarios
  - Plug arrangement
  - Argon flow rate
  - Initial compositions of steel and slag
  - Slag thickness

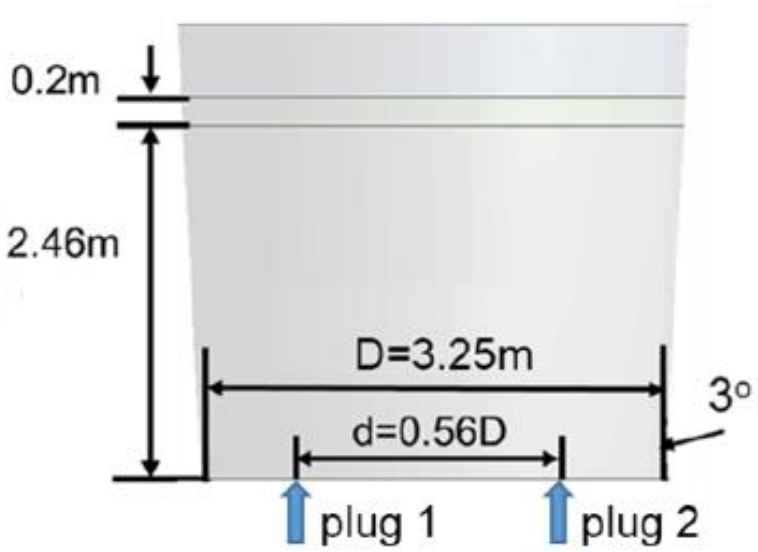
Potential Application

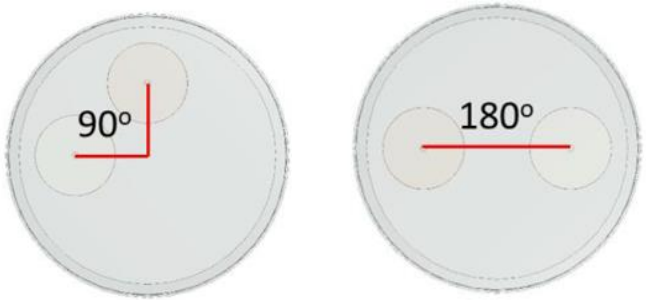
- Sulfur control
  - Sulfur content prediction
- Ladle design optimization
  - Layout improvement for lower sulfur content
- Cost reduction
  - Treatment time estimation

Application: Nucor Generic Ladle

- Model application in a Nucor generic ladle
  - Ladle geometry
    - Two plugs at bottom with different separation angle:
      - 90° & 180°
  - Scenarios for study:
    - 90° 5/5 SCFM 180° 5/5 SCFM

      90° 5/20 SCFM 90° 20/20 SCFM
  - The initial compositions of steel and slag are the same used in validation study [1]





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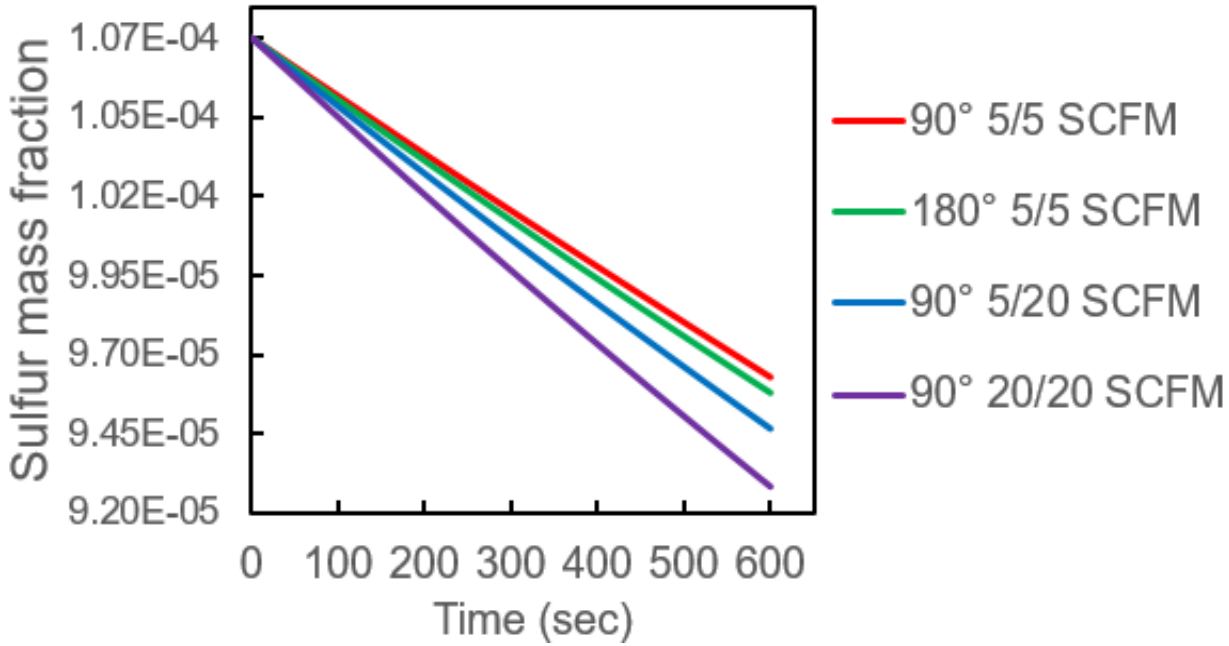
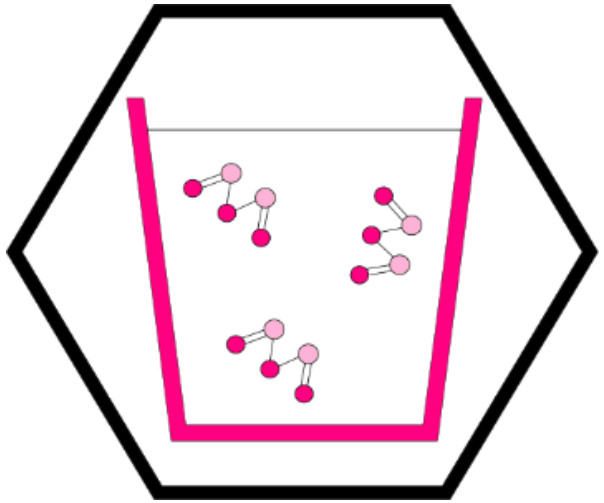
Sulfur Content and Desulfurization Rate

- Sulfur concentration reduction with time in each scenario
- Recommended configuration: 90°20/20 SCFM
- Different desulfurization rates under different settings
  - Better sulfur removal behavior
- Desulfurization enhancement by ladle design optimization



	Desulf. rate	Improvement rate
90° 5/5 SCFM	1.66 PPM/sec	
180° 5/5 SCFM	1.74 PPM/sec	+ 6.63%
90° 5/20 SCFM	1.92 PPM/sec	+ 15.66%
90° 20/20 SCFM	2.20 PPM/sec	+ 32.53%



Project 10:
Hot Metal Desulfurization
Start: October 2021

Hot Model Desulfurization

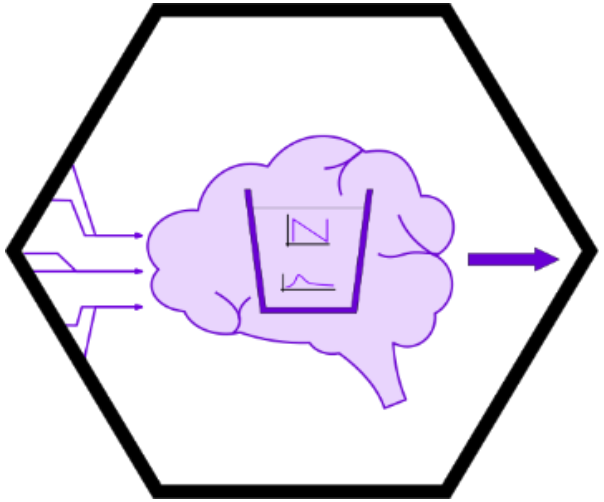
- **Motivation**
  - Hot metal desulfurization serves as the main unit process for removing sulfur in blast-furnace-based steelmaking
  - The model can be used to predict sulfur removal rate in the hot metal
- **Objective**
  - To develop an comprehensive 3D CFD model to predict the sulfur removal rate in the ladle
- **Potential Impacts**
  - Improvement in the efficiency of desulphurization by
    - Decrease in reagent consumption
    - Increase in productivity.

Desulfurization Mechanism

- Desulfurization reagents: Mg(s), CaO(s), or both
- Due to the high temperature of hot metal, Magnesium powder will vaporize quickly. ~80% of vaporized Mg will dissolve into iron
- Desulfurization also happens at slag-steel interface
- In general, desulfurization process is as follows

Reaction number	Chemical formulas	Reaction site
Reaction 1	S + Mg(l) = MgS(s)	MgS particle
Reaction 2	S + Mg(g) = MgS(s)	Gas bubble
Reaction 3	S+ CaO = CaS + O	CaO particle
Reaction 4	-	Slag-Iron interface

- A side project is finished on the topic with a SMSVC member company



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

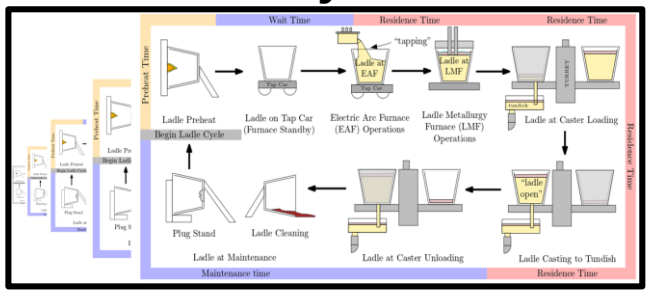
Smart Ladle

- **Issue:**
  - Operators must predict future temperature requirements using limited information
- **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

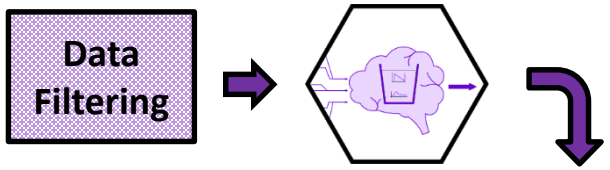
Smart Ladle Usage

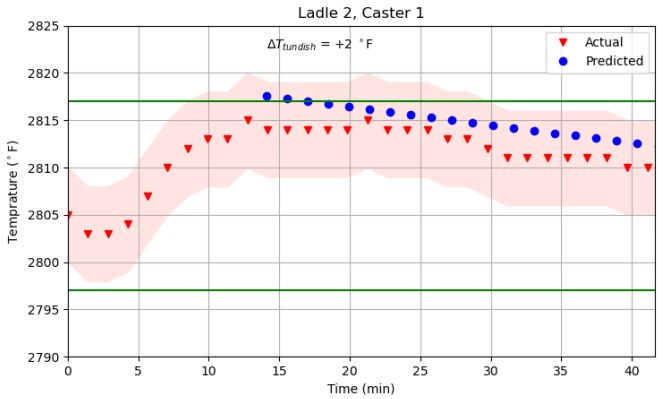
- Smart Ladle executed on ladle at LMF (or pre-cast)
- Trained using industry data
  - Varies per-site, e.g. SDI is 25 inputs
  - Steel contact time, number of heats on ladle, temperature measurement, etc.
- Model makes three predictions:
  - Time until ladle will be half-empty at caster
    - using time-to-open, ladle tonnage, and avg. casting speed
  - Tundish midpoint temperature
  - Temperature slope at midpoint
- Inputs and results stored to database for query and display

Ladle Process & History Data



Smart Ladle





Smart Ladle Results

- LightGBM algorithm improvements since April
  - Test dataset shows an average error below 1.5°F (45% improvement since April), with a standard deviation of 2.20°F (37% improvement since April)
  - Slope average error of 0.108°F/min

Midpoint Temperature (°F)		Midpoint Slope (°F/min)		Temperature Outliers (°F)	
MAE	**RMSE**	**MAE**	**RMSE**	**Lowest**	**Highest**
1.42	2.20	0.108	0.138	-10.07	14.24

Smart Ladle Web Tool

- Simplified version of the Smart Ladle embedded in the SMSVC website
- Features
  - Web user interface
    - Accessed in member-only section of SMSVC website
  - Simplified model
    - Trained using reduced dataset and inputs
  - Manually input features
    - Six inputs entered by users (no database connections)
  - Encrypted traffic

Using the Smart Ladle Web Tool

Smart Ladle Current Focus

- Current model is based on data from one site
  - Model to be developed for other sites/companies
  - Coordination with Nucor and Tata Steel has begun
- New features and methodologies
  - Tundish temperature prediction vs. superheat suggestion
  - Additional inputs for processes (ladle size, etc.)
- Improvements to web version

Smart Ladle Implementation

- Smart Ladle can be adapted to any facility
- How to Proceed:
  - Data table formats for Smart Ladle input/output
    - Dedicated Smart Ladle table or read from full database?
  - Interface requirements
    - Standalone interface? Integrate into own HMI?
  - Provide data samples to build and train the model
    - 6+ months of relevant data
  - CIVS packages software to test and deploy
    - Executable, internal server, etc.

Summary

Summary

- **Project 5: Inclusion Removal Enhancement & Validation**
  - Inclusion removal model validated with industry data
- **Project 8: Desulfurization and Re-oxidation**
  - Desulfurization model validated with literature
  - Model used to compare ladle configurations
- **Project 9: Smart Ladle**
  - Accuracy further improved
  - Smart Ladle Web Tool deployed to SMSVC website

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 Re-oxidation**
  - Validation of re-oxidation with measurements
- **Project 9: Smart Ladle**
  - Improve web tool
  - Implementation at other plants
- **Project 10: Hot Metal Desulfurization**
  - Validation of model with industry data
  - Application under different stirring conditions

Comments from Industry Collaborator

Thank You
Questions and Comments

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