COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

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

Project Technical Committee (PTC):

- Joshua Anderson (AK Steel)
- Paul Wu (AK Steel)
- Hoyong Hwang (ArcelorMittal)
- Judy Li (ArcelorMittal)
- Rui Liu (ArcelorMittal)
- April Pitts-Baggett (Nucor)
- Abhishek Bhansali (Nucor)
- Eugene Pretorius (Nucor)
- Helmut Oltmann (Nucor)
- Vivek Thapliyal (Nucor)
- Chase Ault (SDI)
- Sunday Abraham (SSAB)
- Alyssa Briere (Stelco)
- Richard Zhang (Stelco)
- Jeffrey Becker (USS)

CIVS Team (current):

- Xipeng Guo
- Joshua Vandenoever
- Wenjie Liu
- Nicholas Walla
- Armin Silaen
- Chenn Zhou
- Senior design group
  - Qiqing Zhang
  - Haochen Cao

Presentation at CIVS on November 15, 2018

"Where Ideas Become Reality"

Presentation Outline

- Introduction
  - Project Motivation & Objectives
  - Ladle Sub-Projects
  - Research Outcomes
  - Project Timeline - 2018
- Methodology and CFD Models
- Results
  - Inclusion removal model
  - EMS model
- Potential Benefits
- Summary
- Future work

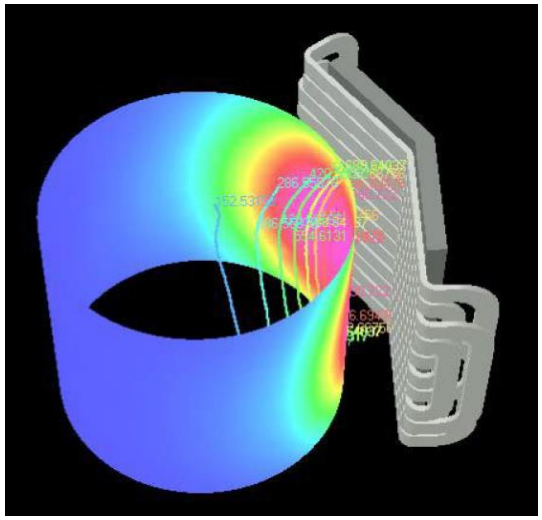
Project Motivation

Current Issues

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

Potential Impacts

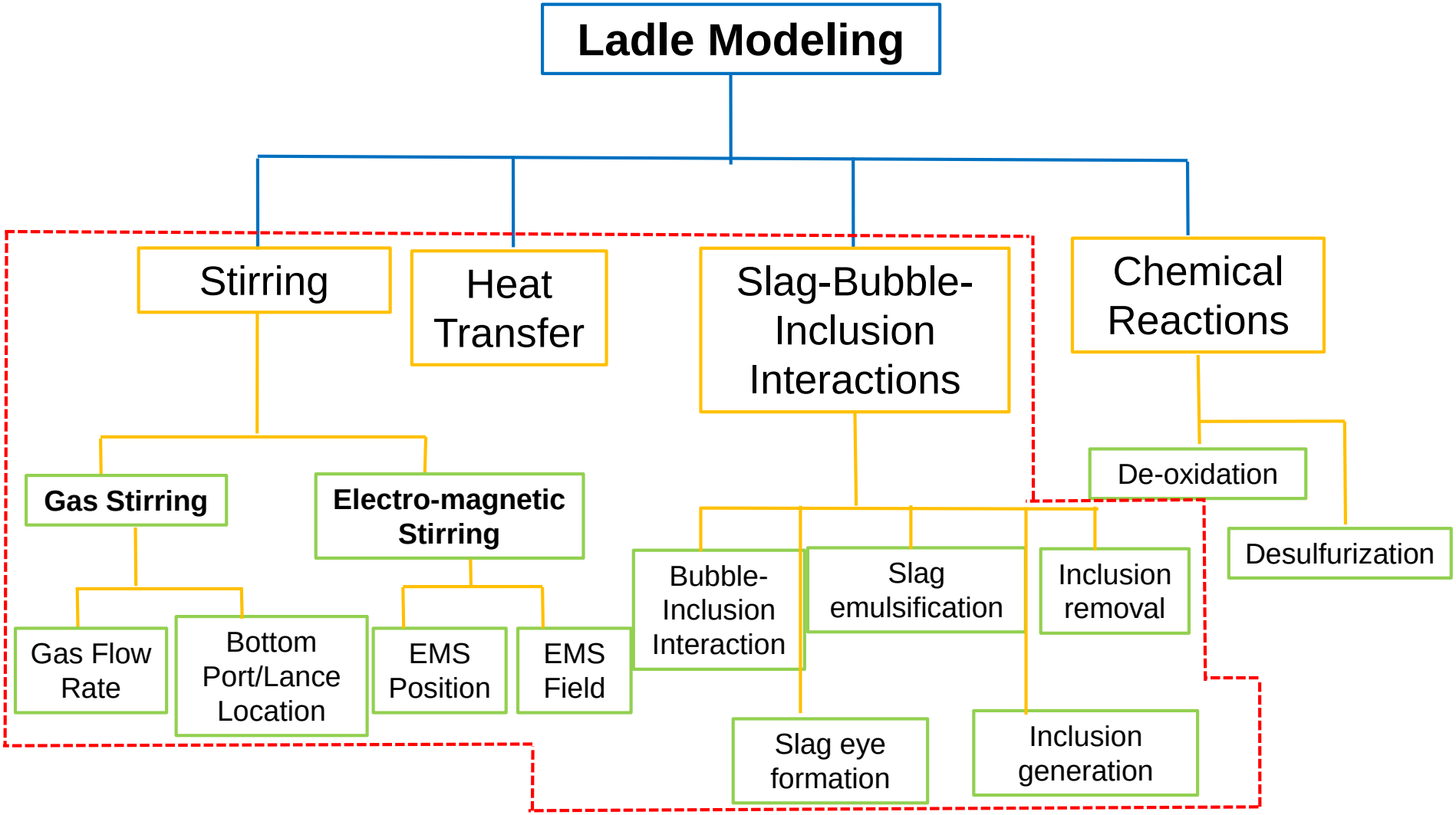
- Process design of optimized flow condition and physical properties
- Steel cleanliness improvement and final defects reduction



Project Objectives

- **Years 1 & 2:**
  - Develop a model for fluid flow and mixing in a steel ladle
  - Study effect of gas flow rates and ladle designs on mixing efficiency
  - Develop correlation between geometry parameters and mixing time
  - Develop correlation between fluid flow and slag physical properties
- **Year 3:**
  - Develop a comprehensive multiphase reacting CFD model of a steel ladle using two stirring conditions
    - Gas stirring condition
    - Electromagnetic stirring (EMS) condition
  - Study inclusion transport and evolution
    - Consider bubble interaction with inclusion, floatation removal mechanism
- **Long Term:**
  - Develop a model of inclusion generation through chemical reaction
  - Implement inclusion model in electromagnetic stirring condition

CFD Model Roadmap



Ladle Sub-Projects

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

Outcomes – Model Advancement

- CFD models of gas-stirred ladle developed based on Nucor Steel Decatur ladle
- CFD model of Isothermal gas-stirred flow models:
  - Bubble coalescence and breakup were developed
  - CFD predictions validated against experimental work percentage error within 11% and industrial measurements percentage error within 8%
- **CFD model of inclusion growth and removal models:**
  - **Three mechanisms of inclusion growth and six mechanisms of inclusion removal were added into the model**
  - **Bubble coalescence and breakup model was combined in order to calculate inclusion-bubble interaction**
- **EMS Ladle**
  - **Import magnetic field, multiphase EMS simulation**

Project Outcomes (Year 1 & 2)

- **Sub-Project 1 : Isothermal Gas-stirring Ladle Model (completed)**
  - Argon flow rate ↑
    - Slag eye size ↑, wall shear stress ↑, mixing time ↓
    - Bubble breakup frequency ↑, bubble coalescence frequency ↓
    - Slag thickness ↓, slag density ↑
  - All bubbles reach equilibrium diameters as time elapse
  - Plug distance ratio ↑
    - Mixing efficiency ↑
    - Mixing efficiency is better at separation angle of 60°
  - Aspect ratio ↑
    - Mixing efficiency ↑
- **Sub-Project 2 : Heat Transfer Model (completed)**
  - Effect of initial wall temperature – temperature stratification decrease faster with higher wall initial temperature

Project Outcomes (Year 3)

- **Sub-Project 3 – Gas-Stirred Isothermal Inclusion Growth and Removal (in progress)**
  - Model Advancement
    - Three mechanisms of inclusion growth
    - Six mechanisms of inclusion removal
    - Validate flow with industry measurements, and inclusion removal model with literature results.
  - Research findings
    - For 90 separation angle ladle, argon flow rate ↑, dead zone area ↓, wall shear stress ↑, slag eye ↑.
- **Sub-Project 4 – EMS Isothermal Inclusion Growth and Removal (in progress)**
  - Model Advancement
    - Develop external magnetic field
    - Develop single phase EMS model and validate magnetic field with literature results
    - Develop a working multiphase EMS model with included slag layer.

Timeline for 2018

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sub-Project 3-1 Gas-Stirred Isothermal Inclusion Removal	Literature research												
	Develop geometry												
	Develop base removal model												
	Model validation												
	Parametric study												
Sub-Project 3-2 Inclusion Interaction Mechanisms	Literature research												
	Inclusion-inclusion interaction(Inclusion growth)												
	Inclusion- bubbles interaction												
	Improve inclusion removal												
Sub-Project 4 EMS Isothermal Inclusion Removal	Develop magnetic field												
	Single-phase EMS												
	Multiphase EMS												
	EMS with inclusion												

State of the Art

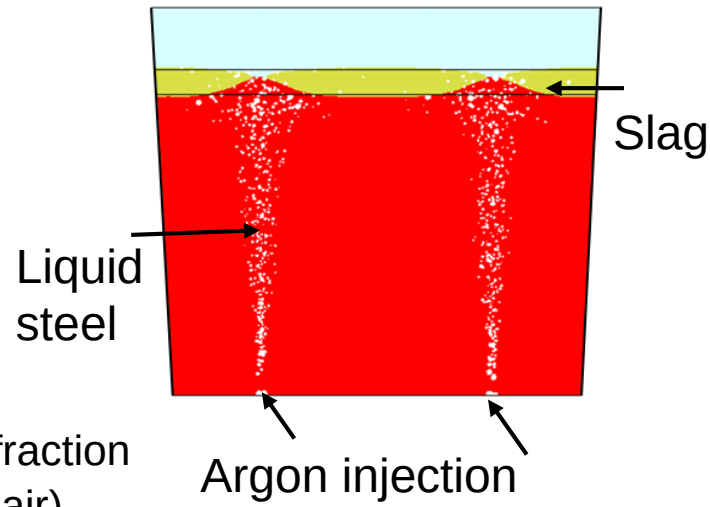
- Gas-stirred ladle - flow field, slag eye or effect of ladle design on the mixing efficiency [1-3].
- Comparison of induction stirring (EMS) with gas stirred ladle and combined gas/EMS [4].
- Inclusion behavior modeled by 4 main methods.
  - Static numerical models of nucleation, growth and removal of inclusions [5-7]. **No consideration of inclusion transport.**
  - CFD-based trajectory method [8-10]. **No consideration of inclusion collision and agglomeration.**
  - CFD-based characteristic inclusion parameters [11-13]. **Inclusion distribution is simplified with exponential function with inclusion radius.**
  - CFD-PBM coupled model [14-16]. Inclusion divided into multiple groups size. **Assumptions of flat free surface without slag and constant bubble size. Predefined initial inclusion distribution.**

GAS-STIRRED LADLE MODEL

Methodology & CFD Models

Gas-stirring ladle model

- Fluid zones (slag, melt, inclusion and air)
  - Multiphase flow: **Eulerian-Eulerian**
  - Turbulent model: Realizable k-epsilon
- Argon injection
  - Discrete phase model (DPM)



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

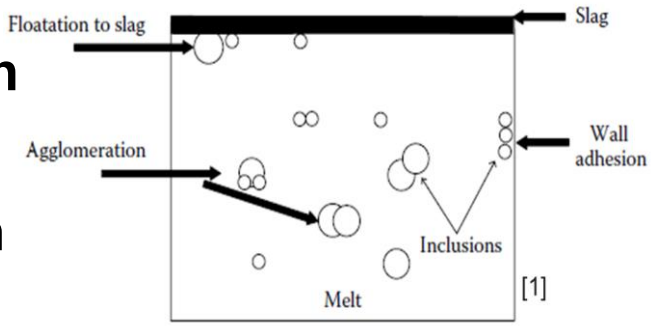
Inclusion removal and growth model

- Inclusion transport
  - Population balance model (PBM) – continuum method
- **Inclusion removal and growth**
  - **Removal from bubble, slag and wall**

Inclusion Growth & Removal Model

- Mechanisms for inclusion growth and removal

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



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

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

Inclusion Growth Model

- Overall inclusion growth rate

$$\beta_{ij} = \beta_{ij}^{TS} + \beta_{ij}^{TR} + \beta_{ij}^{S}$$

  - β_{ij}^{TR} = Turbulence random collision
  - β_{ij}^{TS} = Turbulence shear collision
  - β_{ij}^{S} = Stokes buoyancy collision

- Inclusion growth due to turbulence random collision (Lou et al., 2013)
  - For $d_1 = \min(d_i, d_j) \leq \eta \leq \max(d_i, d_j) = d_2$

$$\beta_{ij}^{\mathrm{TR}} = \frac{\pi}{2}(d_i + d_j)^2 \left(d_2^{2/3} + \eta^{2/3}\right)^{1/2} \varepsilon^{1/3} \left(\frac{d_1}{\eta}\right)^3$$

  - For $d_1 > \eta$

$$\beta_{ij}^{\mathrm{TR}} = \frac{\pi}{2}(d_i + d_j)^2 \left(d_2^{2/3} + d_1^{2/3}\right)^{1/2} \varepsilon^{1/3}$$

  - For $d_2 < \eta$

$$\beta_{ij}^{\mathrm{TR}} = \frac{\pi}{2}(d_i + d_j)^2 \sqrt{2}(\varepsilon\eta)^{1/3} \left(\frac{d_1 d_2}{\eta^2}\right)^3$$

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

η: Kolmogorov microscale (size of smallest eddies in turbulence, m)

ε: Turbulent dissipation rate(m^2/s^3)

ν: kinematic viscosity(m^2/s)

- W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." Metallurgical and Materials Transactions B 44.3 (2013): 762-782.

Inclusion Growth Model

- Inclusion growth rate due to turbulence shear collision ($d_i, d_j < \eta$)

$$\beta_{ij}^{\mathrm{TS}} = 1.294 \varsigma_{\mathrm{eff}}^{\mathrm{p-p}} (\varepsilon/\nu)^{0.5} (r_i + r_j)^3$$

$\varsigma_{\mathrm{eff}}^{\mathrm{p-p}}$: capture efficiency;

- Inclusion growth due to stokes buoyancy collision

$$\beta_{ij}^{\mathrm{S}} = \frac{2g\pi(\rho_{\mathrm{l}} - \rho_{\mathrm{inc}})}{9\mu_{\mathrm{l}}} (r_i + r_j)^3 |r_i - r_j| E_{\mathrm{s}}^{\mathrm{p-p}}$$

E_s^{p-p}: <u>buoyancy collision efficiency (collision probability)</u>

- W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." Metallurgical and Materials Transactions B 44.3 (2013): 762-782.

Inclusion Removal by Wall & Slag

- **Overall inclusion removal rate**

$$S_i = S_i^{wall} + S_i^{F} + S_i^{BF} + S_i^{TR} + S_i^{TS} + S_i^{wake}$$

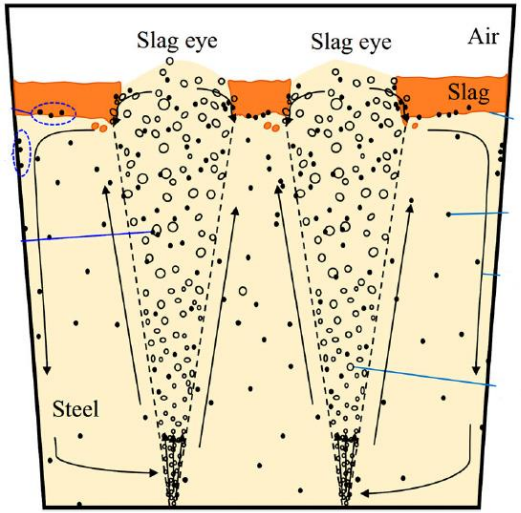
- S_i^{wall}: Inclusion attach to wall
- S_i^{F}: Inclusion floatation
- S_i^{BF}: Turbulence buoyancy collision
- S_i^{TR}: Turbulence random collision
- S_i^{TS}: Turbulence shear collision
- S_i^{wake}: Bubble wake capture collision

- Inclusion removal due to wall adhesion through diffusion process

$$S_i^W = \frac{0.0062\varepsilon^{\frac{3}{4}}}{v^{\frac{5}{4}}} \frac{A_s}{V_{cell}} r_i^2 n(V_i, t)$$

- Inclusion removal at slag/steel interface due to inclusion Stoke flotation (Kwon et al., 2008)

$$S_i^S = \frac{dn}{dt} = \frac{n_i \cdot u_{st}}{h}$$



Cao et. al (2018)

- You-Jong. Kwon, J. Zhang, and L. Hae-Geon. "A CFD-based Nucleation-growth-removal Model for Inclusion Behavior in a Gas-agitated Ladle during Molten Steel Deoxidation." *ISIJ International* 48.7(2008):891-900.
- Cao, Qing, and L. Nastac. "Numerical modelling of the transport and removal of inclusions in an industrial gas-stirred ladle.".

Inclusion Removal by Bubbles

- Bubble-inclusion buoyancy collision (Lou et al., 2013)
  - Buoyancy collision due to difference rising velocity between bubble and inclusion (kg/m^3/s):

$$S_i^{\mathrm{BF}} = \frac{\pi}{4}\left(d_i^2 + d_{\mathrm{g}}^2\right)\left(u_{\mathrm{g}} - u_{\mathrm{p}}\right) E_{\mathrm{s}}^{\mathrm{g-p}} \frac{6\alpha_{\mathrm{g}}}{\pi d_{\mathrm{g}}^3} n(V_i)$$

E_s^{g-p}: <u>buoyancy collision efficiency</u>

- Bubble inclusion turbulent random collision
  - Inclusion dragged by velocity fluctuations when inclusion size larger than the Kolmogorov microscale in bubble plume area.
  - 1. For d_i>η

$$S_i^{TR} = C\frac{\pi}{4}\left(d_i + d_g\right)^2 (\varepsilon d_i)^{1/3} \frac{6\alpha_g}{\pi d_g^3} n(V_i)$$

  - 2. For $d_i \leq$ η

$$S_i^{TR} = C\frac{\pi}{4}\left(d_i + d_g\right)^2 (\varepsilon \eta)^{1/3} \left(\frac{d_i}{\eta}\right)^3 \frac{6\alpha_g}{\pi d_g^3} n(V_i)$$

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

η: Kolmogorov microscale (size of smallest eddies in turbulence, m)

ε: Turbulent dissipation rate(m^2/s^2)

- W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." Metallurgical and Materials Transactions B 44.3 (2013): 762-782.

Inclusion Removal by Bubbles

- **Bubble-inclusion turbulence shear collision**
  - Shear collision due to shear rate in turbulent eddies especially for the small bubble diameter.

$$S_i^{\mathrm{TS}} = 1.294\varsigma_{\mathrm{shear}}^{\mathrm{p-g}}(\varepsilon/\nu)^{0.5}(R_i + R_j)^3 \frac{6\alpha_{\mathrm{g}}}{\pi d_{\mathrm{g}}^3} n(V_i)$$

$\varsigma_{\mathrm{shear}}^{\mathrm{p-g}}$ capture efficiency

- **Inclusion removal due to bubble wake capture**
  - Inclusion near the interface of steel and slag trapped in the bubble wake.

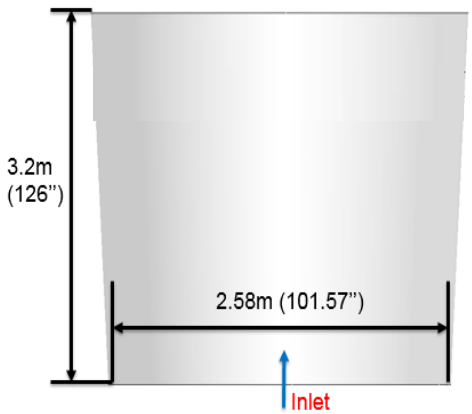
$$S_i^{\mathrm{Wake}} = \lambda\alpha_{\mathrm{g}}(u_{\mathrm{g}} - u_{\mathrm{l}}) \frac{A_{\mathrm{s}}}{V_{\mathrm{cell}}} n(V_i)$$

- W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." Metallurgical and Materials Transactions B 44.3 (2013): 762-782.

Inclusion Model Validation

- Inclusion growth and inclusion removal model was validated with Lou et al. CFD work;
  - CFD-PBM coupled method
  - Multiphase (steel & inclusion), assumed isothermal condition and flat surface
  - Flow rate: 200NL/min (7.45 SCFM) & 100NL/min (3.725 SCFM)
  - Constant bubble size: 4mm
  - Time step size: 0.25s

Lou et al., 2013



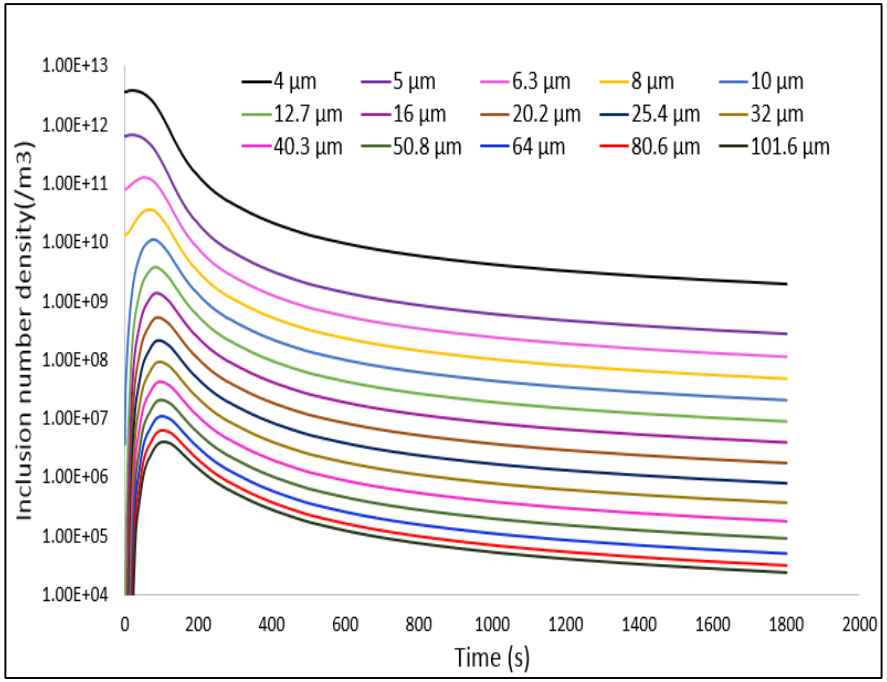
Parameters	Lou, et al. 2013
Diameter of ladle	2.58 m
Height of ladle	3.2 m
Number of plugs	1
Inclusion size	4~200 μm
Group of inclusion	18

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

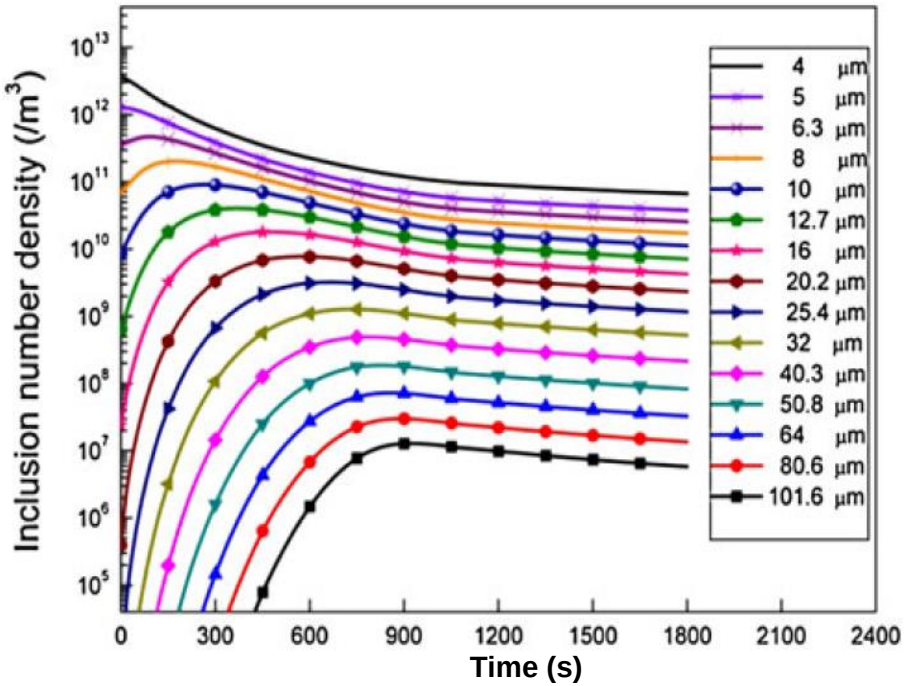
Inclusion Removal Validation

- Inclusion growth and removal efficiency are assumed to 100% in simulation
- CFD predicted removal rate based on mass for 200 NL/min is 91.17%, comparing to paper is 68.16%

  - SMSVC Validation (100 NL/min)



  - Lou et al., 2013 (100 NL/min)



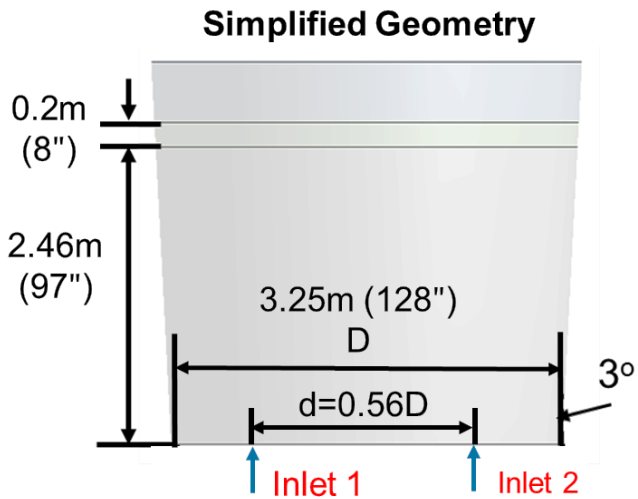
- Overall trends of inclusion number density change are similar.

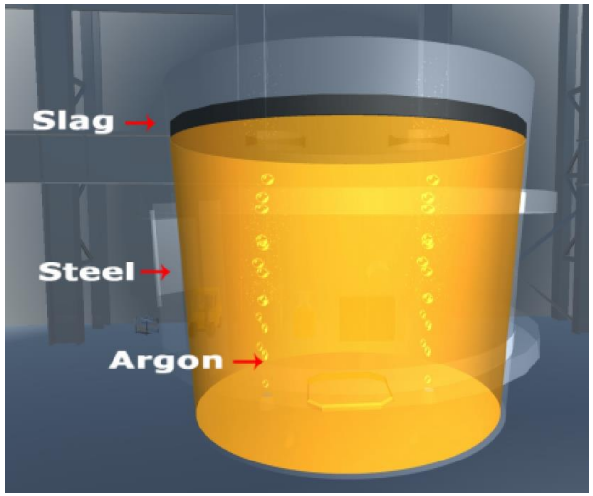
PARAMATRIC STUDY OF FLOW RATE

Generic Ladle Geometry

- Generic ladle model simulation results can be applied to all different ladles

Parameters	Simplified Geometry
Melt depth (m)	2.46
Slag depth (m)	0.2
Wall taper angle	3°
Plug distance ratio $\left(\frac{\text{Distance between plugs}}{\text{Floor diameter}}\right)$	0.56
Aspect ratio $\left(\frac{\text{Melt height}}{\text{Diameter @ slag} - \text{metal interface}}\right)$	0.7
Separation angle	180°



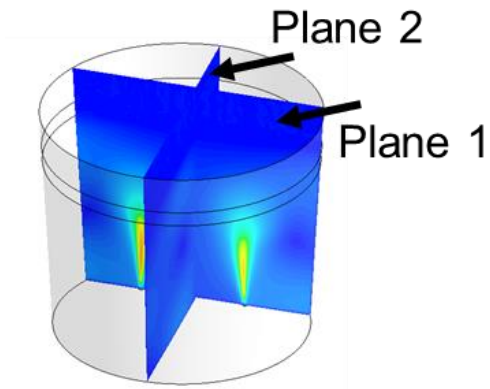


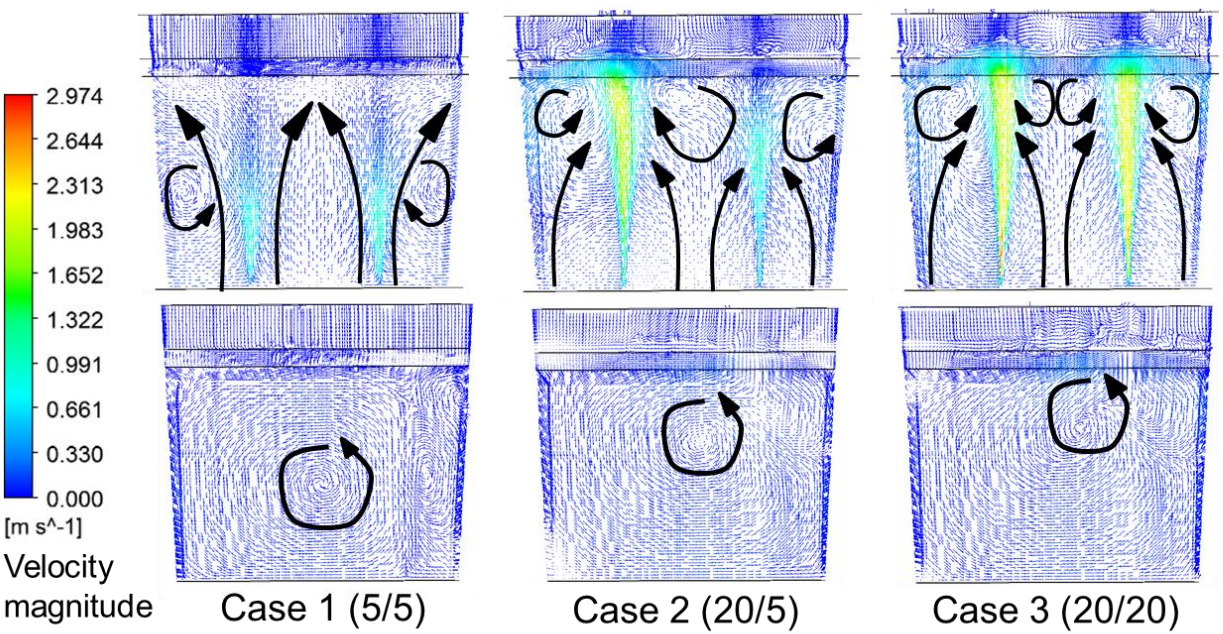
Flow Rate Evaluation

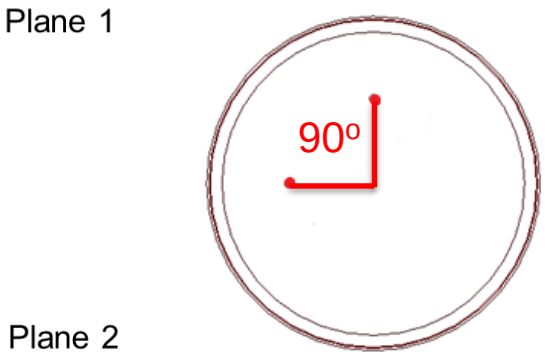
- Objectives: Identify impact of flow rate on flow field at 90° separation angle:
  - Wall shear stress, slag eye formation, dead zone

Argon Flow Rate

	Plug 1	Plug 2
Case 1	5 SCFM	5 SCFM
Case 2	5 SCFM	20 SCFM
Case 3	20 SCFM	20 SCFM

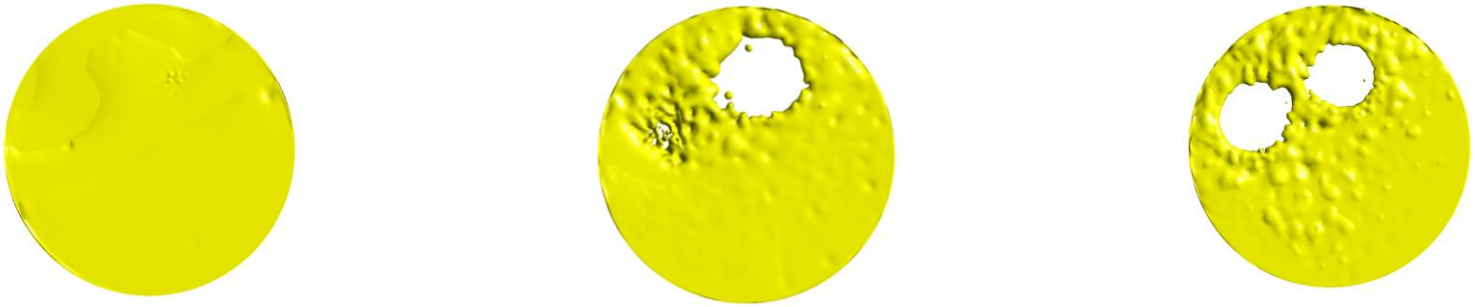






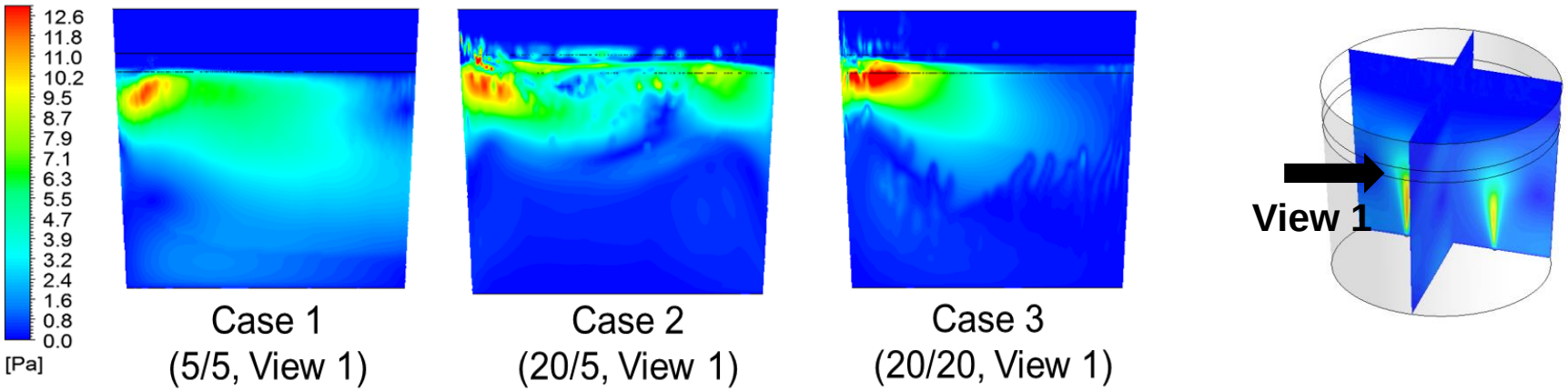
Flow Rate Evaluation

- Analysis of slag eye



  - Slag eye shown up as gas flow rate increased
  - Because of the high flow rate 20 SCFM plug, 5 SCFM plug has very small slag eye

- Analysis of wall shear stress

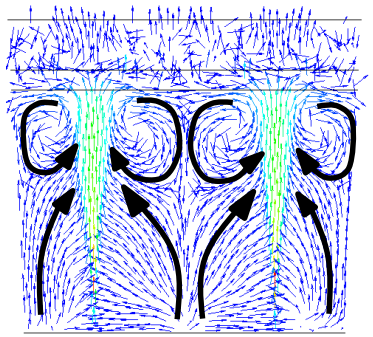


  - Wall shear stress increases as the flow rate of argon gas increases

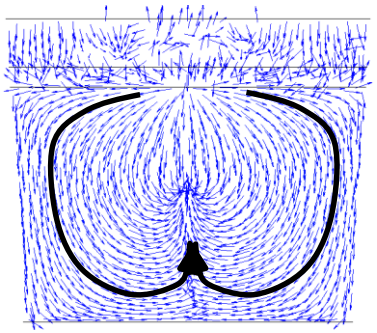
INCLUSION GROWTH AND REMOVAL MODEL

Baseline Flow Simulation

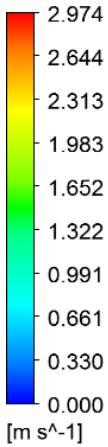
- Flow simulation is used previously validated model
- For inclusion removal process gentle stirring is needed
  - Argon flow rate: **5SCFM**/plug

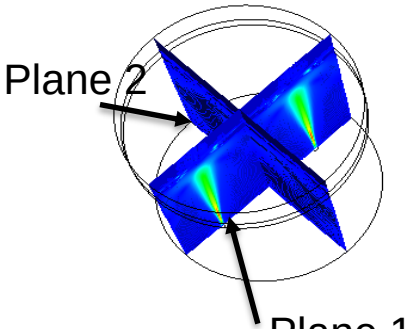


Plane 1

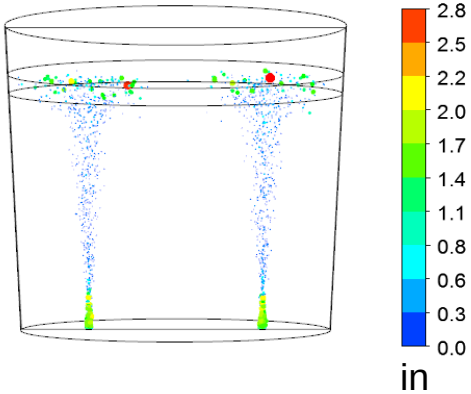


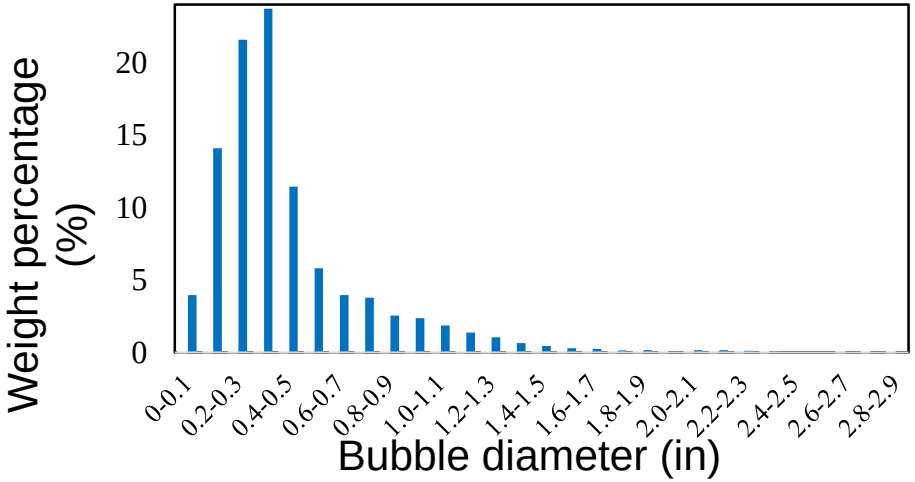
Plane 2





- Argon bubble distribution





Nucor Ladle Conditions

- Inclusion number density: n ≈ 4.23×10^{12} /m^3 (Geng et al., 2010)

	Size (μm)	Volume fraction (t=0s)
Bin 10	5.0	75%
Bin 9	6.3	20%
Bin 8	7.9	4%
Bin 7	10.0	1%
Bin 6	13.3	0%
Bin 5	16.6	0%
Bin 4	20.0	0%
Bin 3	25.2	0%
Bin 2	30.7	0%
Bin 1	40.0	0%
Bin 0	50.0	0%

$$n(d_i)_{t=0} = 2 \times 10^{14} e^{-1.0 d_i \times 10^6}$$

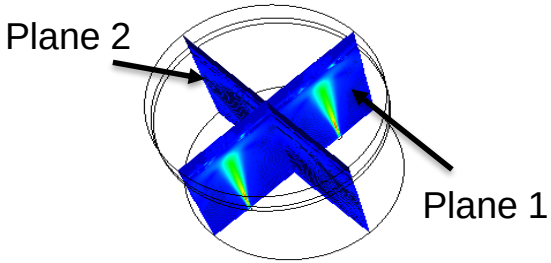
- Material properties:
  - Density of inclusion → $\rho_i = 3900$ kg/m^3
  - Density of liquid steel → $\rho_s = 6975$ kg/m^3

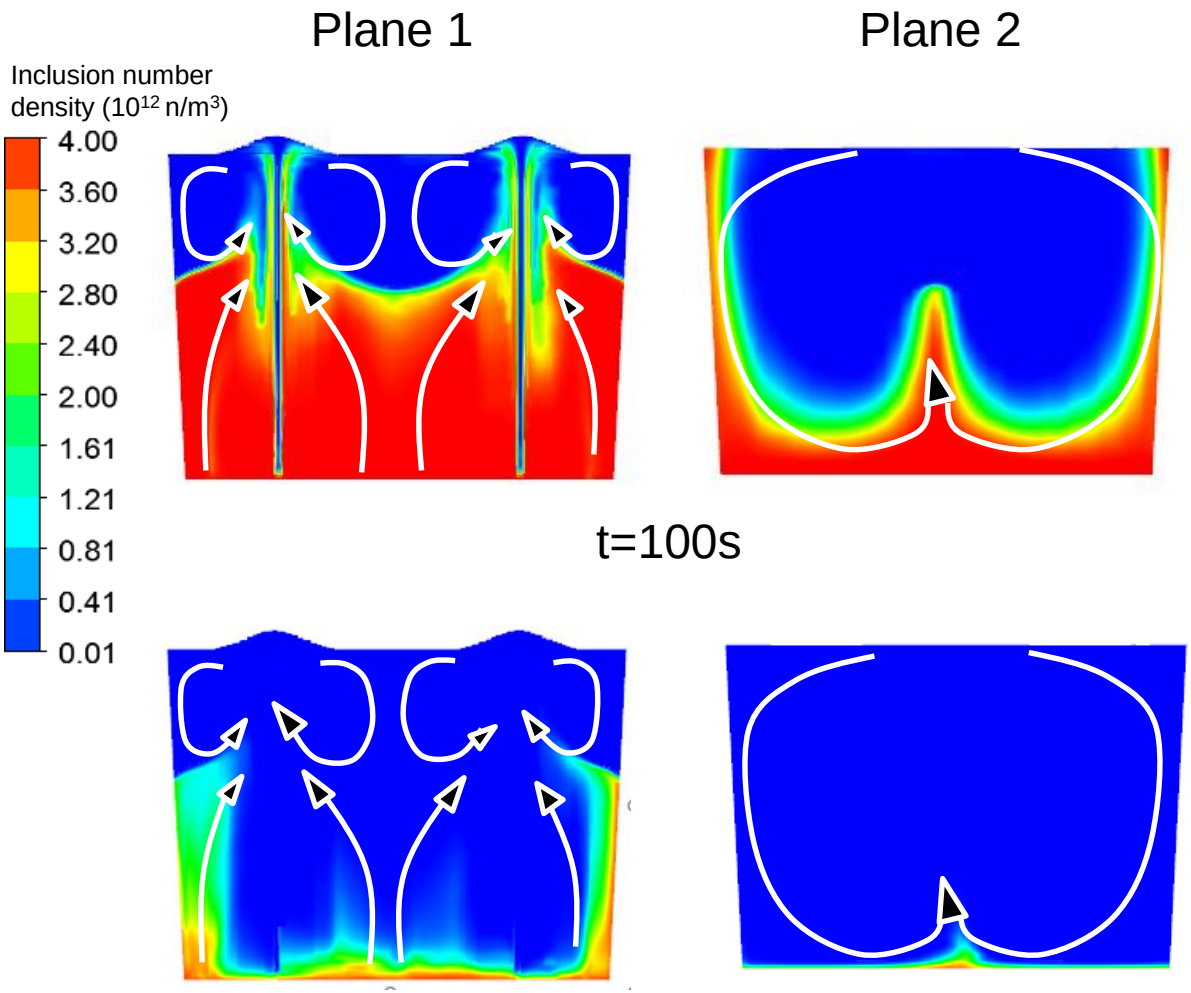
- D. Q. Geng, H. Lei, and J. C. He. "Numerical simulation for collision and growth of inclusions in ladles stirred with different porous plug configurations." *ISIJ international* 50.11 (2010): 1597-1605.

Results of Inclusion Removal

- Flow field drives inclusions towards plumes and ladle center
- Steel near the ladle top is cleaner after passing through high-removal rate regions

- Note:
  - No slag eye
  - De-attachment = 0
  - No transportation
  - Buoyancy collision efficiency = 100%

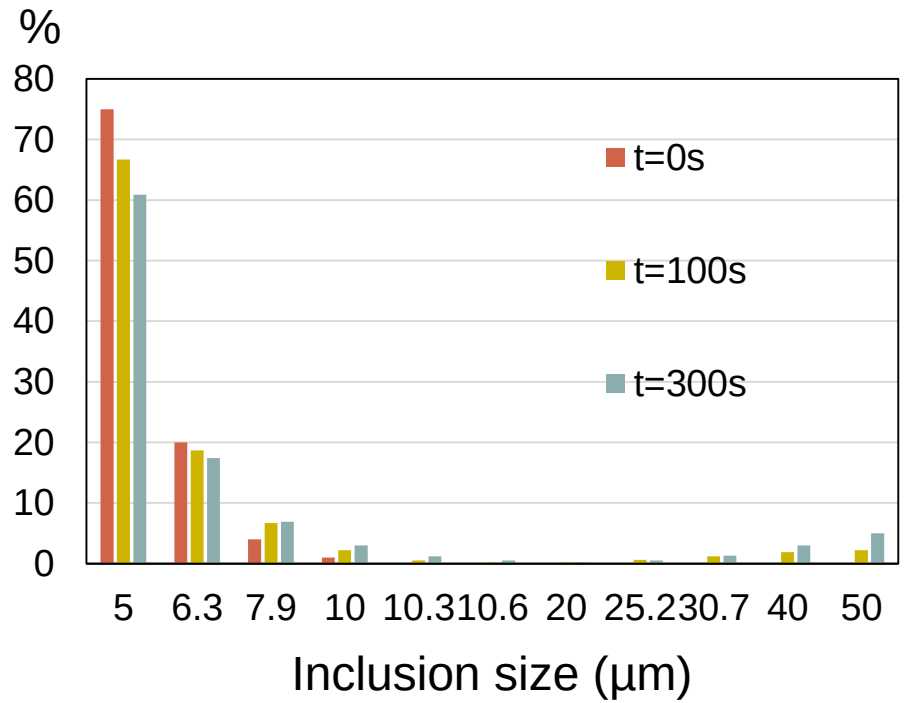




Inclusion Removal Simulation

- Inclusion volume fraction distribution

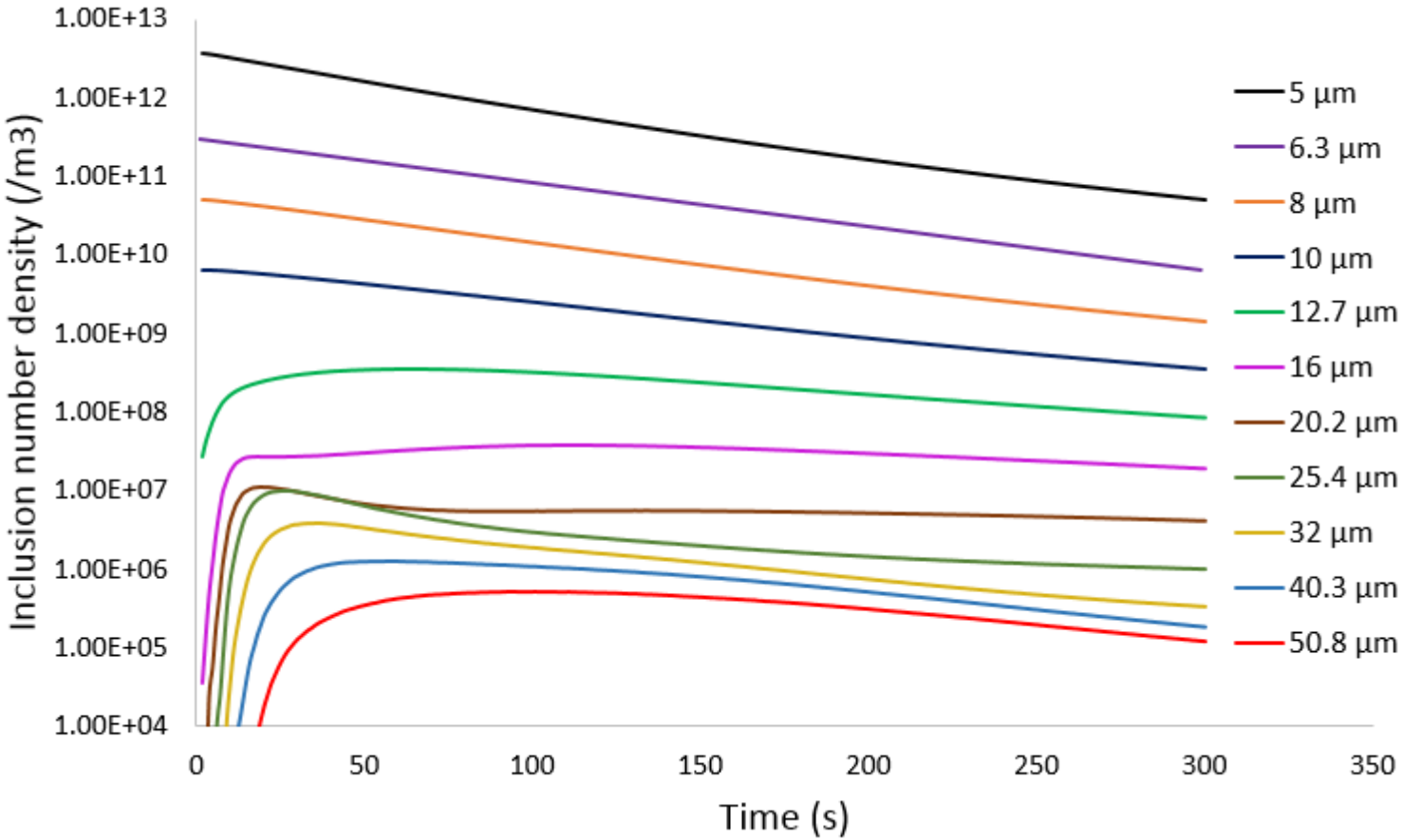
n	Size (μm)	Bin Volume fraction%		
		t=0s	t=100s	t=300s
Bin 10	5.0	75	66.7	60.9
Bin 9	6.3	20	18.7	17.4
Bin 8	7.9	4	6.7	6.9
Bin 7	10.0	1	2.2	3.0
Bin 6	10.3	0	0.5	1.2
Bin 5	10.6	0	0.2	0.5
Bin 4	20.0	0	0.2	0.2
Bin 3	25.2	0	0.6	0.5
Bin 2	30.7	0	1.2	1.3
Bin 1	40.0	0	1.9	3.0
Bin 0	50.0	0	2.2	5.0



- As time goes by, larger inclusion sizes appear, and volume fractions continues to grow
- The small inclusions still make up the majority of the population

Inclusion Removal Rate

- Inclusion growth and removal due to 9 mechanisms (3 growth, 6 removal) after 300 seconds



- At 300 (s) the overall inclusion removal rate—based on mass—is 97.1%

EMS LADLE MODEL

Electromagnetic Stirring (EMS)

- Utilizing LF-EMS in a ladle has the following benefits:
  - No physical contact needed with material
  - Unbroken slag layer (no slag eye formation)
- Physical phenomena: Magnetohydrodynamics (MHD)
  - MHD is the combination of electromagnetics and fluid dynamics
  - Requires a magnetic field and a conductive fluid

Ladle with LF-EMS

- Sand, U., Bel Fdhila, R., Yang, H., Eriksson, J. (2008). *Control of gas bubbles and slag layer in a ladle furnace by electromagnetic stirring*. Presented at the AISTech-The Iron; Steel Technology Conference and Exposition.

Magnetic Field Simulation

- The magnetic field was modeled in ANSYS Electronics Desktop
  - Produced through current carrying wire
  - FEA to solve the magnetic field
  - The solver is frequency domain based
- The magnetic field used for EMS is a traveling magnetic field (TMF) (Fireteanu et al., 2015)
  - This is created by successive current carrying wires that are out of phase
  - Phase shift is dependent on number of coils

- V. Fireteanu, E Rousset, E Chauvin, N Chouard. Simultaneous Induction Heating and Electromagnetic Stirring of a Molten Glass Bath. 8th International Conference on Electromagnetic Processing of Materials, Oct 2015, Cannes, France. EPM2015. <hal-01335037>

Fluent MHD Simulation

- The magnetic field data is imported into Fluent and applied to the fluid domain
- The conductive fluid (molten steel) is influenced by the external magnetic field, $\vec{B}_o$, through the Lorentz Force

$$\vec{F}_{Lorentz} = \sigma\left(\vec{v} \times \vec{B}\right)$$

- An induced magnetic field, $\vec{b}$, is created by the motion of the molten steel. This makes a combined magnetic field of

$$\vec{B} = \vec{B}_o + \vec{b}$$

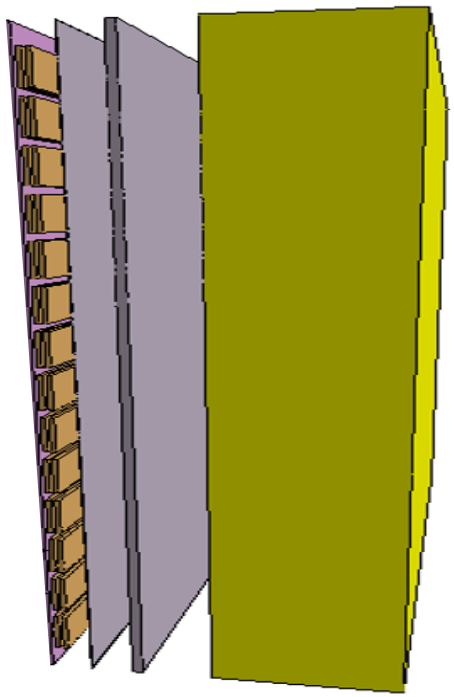
- The magnetic induction is governed by

$$\frac{\partial \vec{B}}{\partial t} + (\vec{v} \cdot \nabla)\vec{B} = \frac{1}{\mu\sigma}\nabla^2 \vec{B} + \left(\vec{B} \cdot \nabla\right)\vec{v}$$

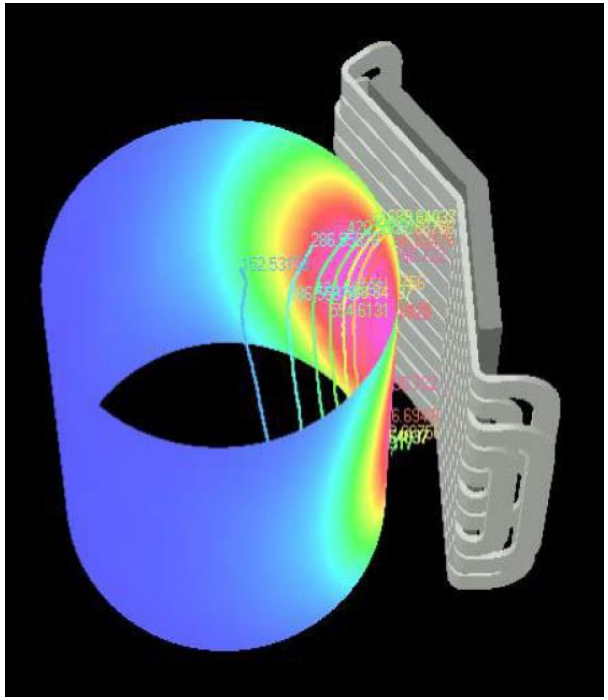
SIMULATION OF COIL SYSTEM

Coil System Depictions

- Coil design features rarely described in literature
  - Industry Information
  - Literature Information



Expanded View of Coils

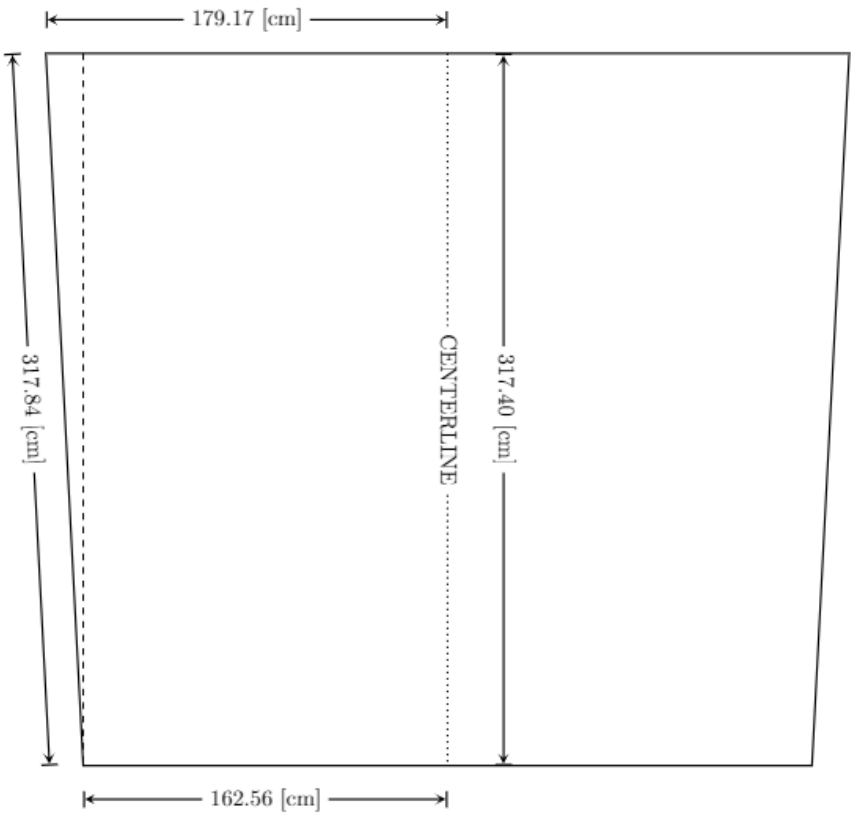


Ladle & Coils (Teng et al., 2017)

- Lidong Teng. (2017). Effect of EMS on Inclusion Removal in Ladle Furnace for Specialty Steel Production. AISTech 2017 Proceedings, ABB Metallurgy Products, Industrial Automation, ABB AB, Terminalvägen 24, Västerås, SE-721 59 Sweden.

Ladle Dimensions

- Ladle used in simulation
  - Height = 3.17 $[m]$
  - Inner Diameter = 3.25 $[m]$
  - Initial Slag Height = 0.2 $[m]$
- Ladle used in literature
  - Height = 2.80 $[m]$
  - Inner Diameter = 2.85 $[m]$
  - Initial Slag Height = 0.1 $[m]$



SMSVC Ladle Dimensions

- Sand, U., Bel Fdhila, R., Yang, H., Eriksson, J. (2008). *Control of gas bubbles and slag layer in a ladle furnace by electromagnetic stirring*. Presented at the AISTech-The Iron; Steel Technology Conference and Exposition.

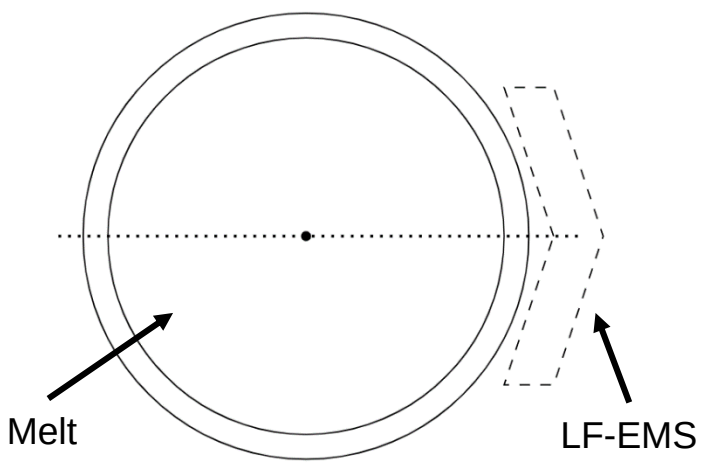
Operating Conditions

- Industry information
  - Frequency
    - 1.5 $[Hz]$
  - Number of coils
    - 14
  - Magnetic field range
    - 0.0002 – 0.9 $[T]$
  - Magnetic contours
  - Force contours
- Literature information (Sand et al., 2008)
  - Electric current amplitude
    - 1350 $[A]$
  - General stirring pattern
    - Figure on slide 33
  - Velocity range
    - 0.2 – 2 $[m/s]$
  - Flow field development
    - ~ 25 $[s]$

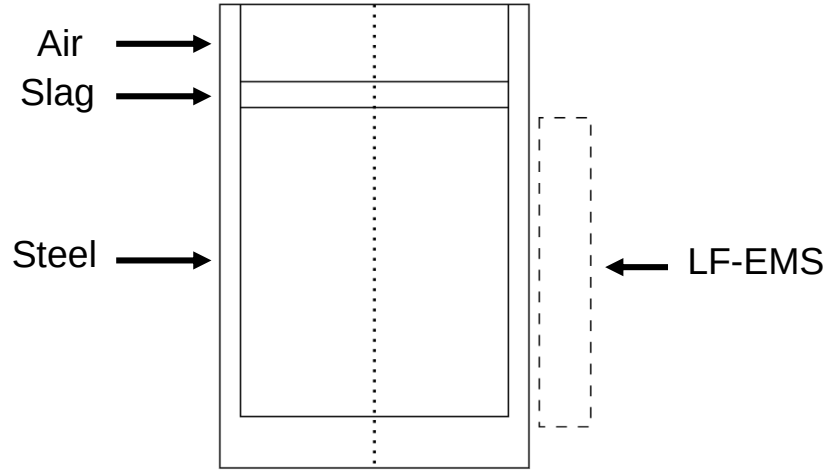
- Sand, U., Bel Fdhila, R., Yang, H., Eriksson, J. (2008). *Control of gas bubbles and slag layer in a ladle furnace by electromagnetic stirring*. Presented at the AISTech-The Iron; Steel Technology Conference and Exposition.

Coil System Positioning

- Positioning of coil based on literature

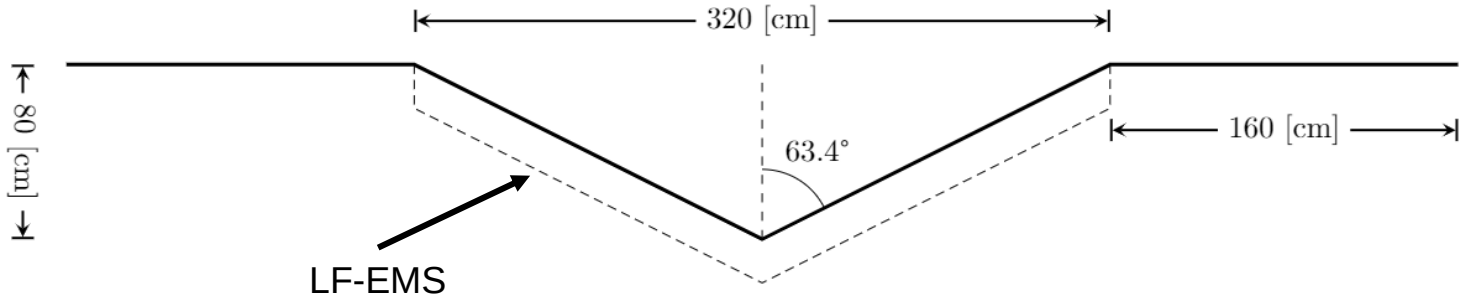


Top View



Side View

- SMSVC corner coil span dimensions

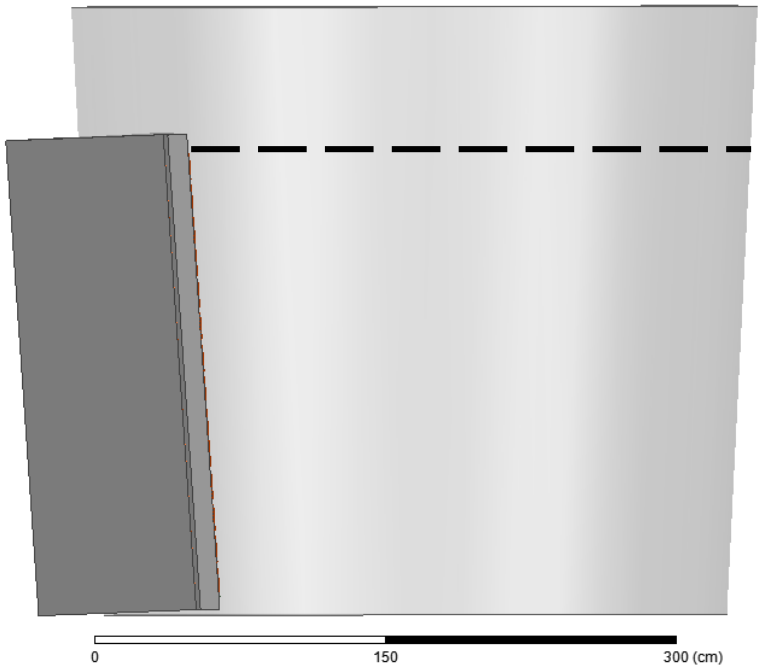


Top View

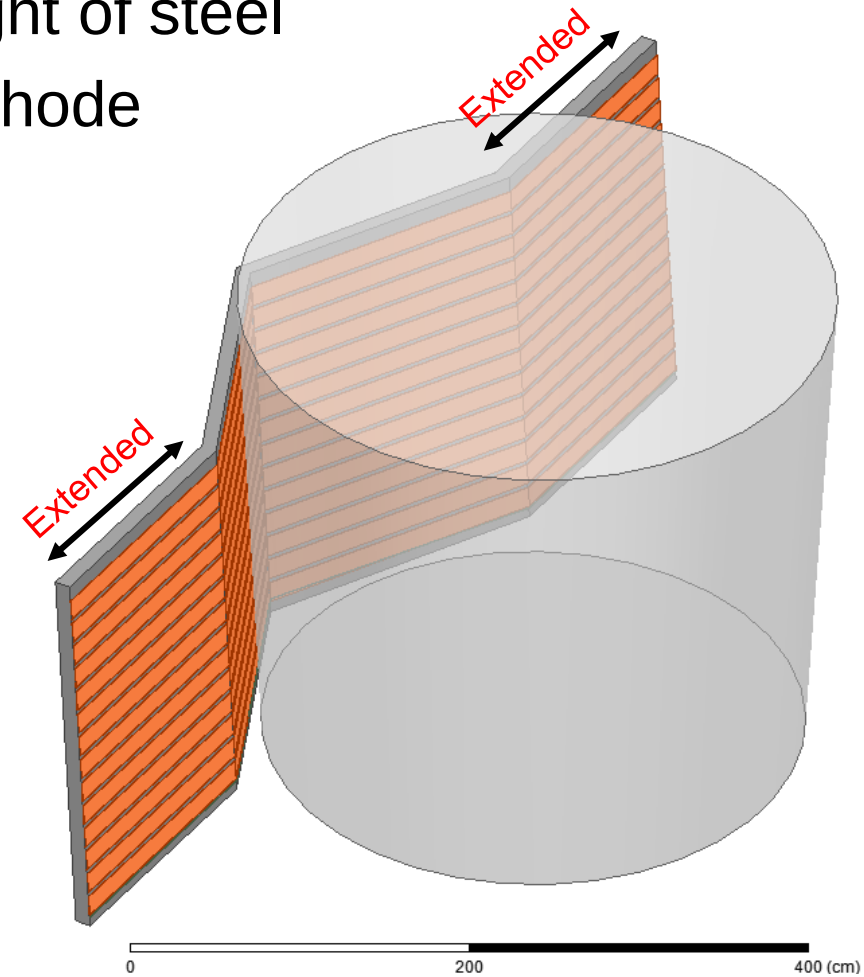
- Sand, U., Bel Fdhila, R., Yang, H., Eriksson, J. (2008). *Control of gas bubbles and slag layer in a ladle furnace by electromagnetic stirring*. Presented at the AISTech-The Iron; Steel Technology Conference and Exposition.

Geometry of Coil System

- SMSVC coil design
  - Coil height matches height of steel
  - Extended anode and cathode



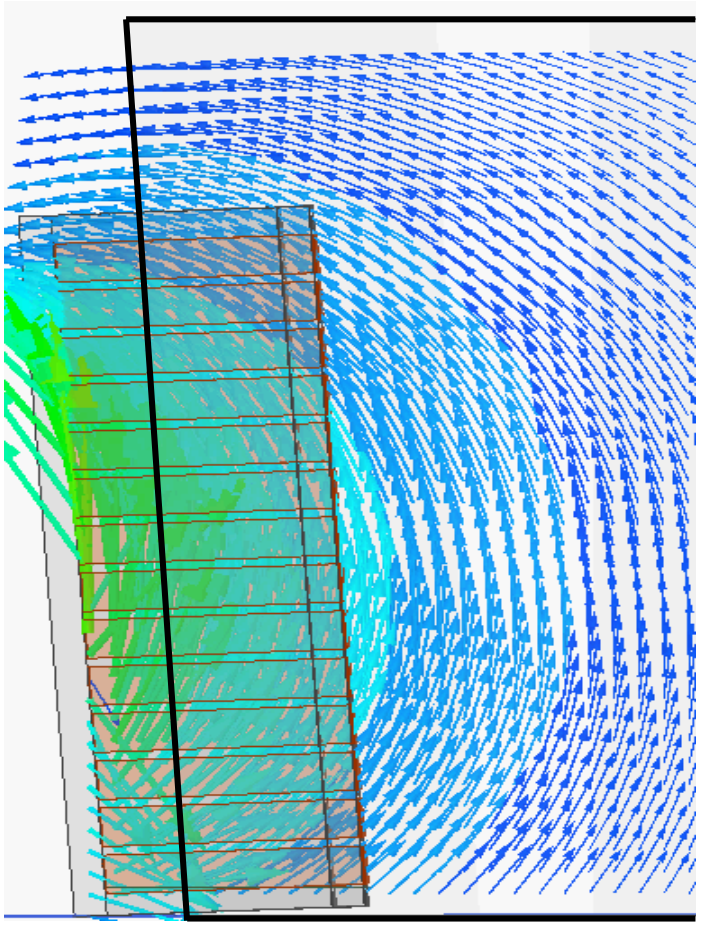
Coil & Ladle Side View



Isometric View

Coil Simulation Conditions

- Properties of coil system
  - Frequency
    - 1.5 $[Hz]$
  - Electric Current
    - I = 1500cos($2\pi \times 1.5t + \phi$) $[A]$
  - Number of Coils: N = 14
    - Windings per Coil: 50
  - Phase Shift per Coil
    - $\phi_n = \frac{180°}{N}$, (Fireteanu, et al. 2015)
    - 12.85, [0°, 180°]
  - Magnetic Field Range
    - 0.0007 – 0.3 $[T]$

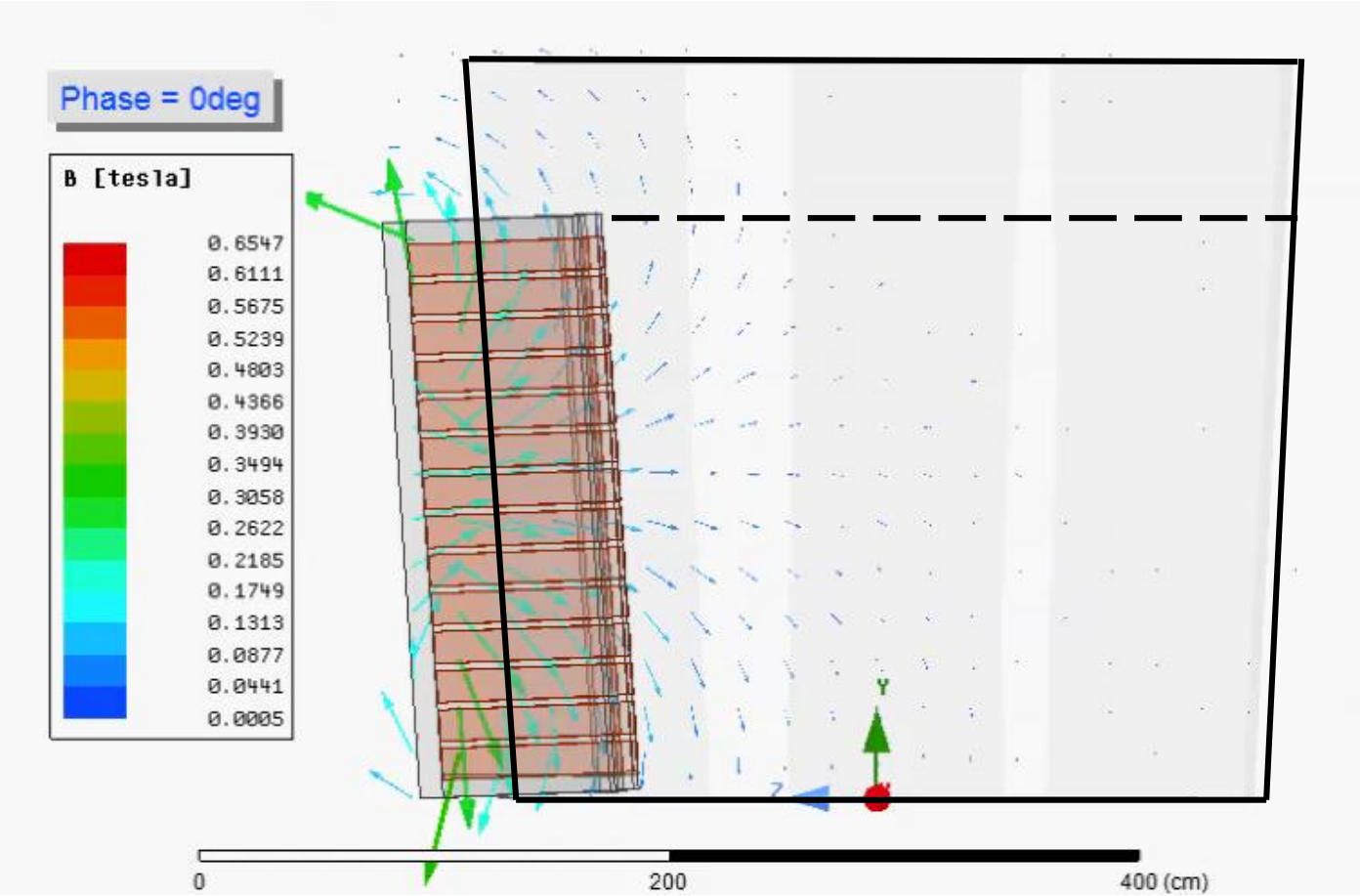


Coils, Ladle Side,
& Magnetic Field

- V. Fireteanu, E Rousset, E Chauvin, N Chouard. Simultaneous Induction Heating and Electromagnetic Stirring of a Molten Glass Bath. 8th International Conference on Electromagnetic Processing of Materials, Oct 2015, Cannes, France. EPM2015. <hal-01335037>

Magnetic Field Vector Plots

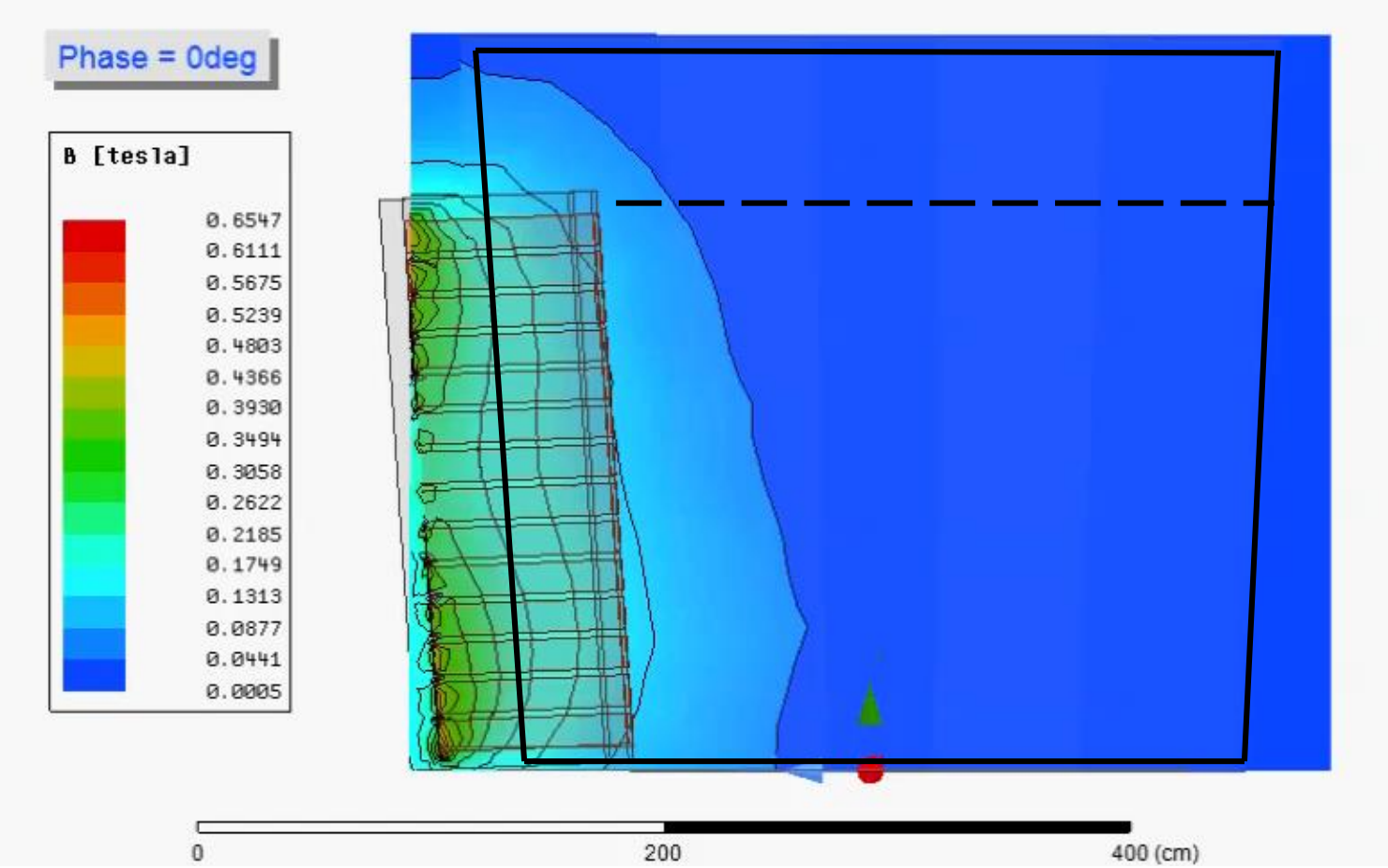
- Magnetic field strength range: [0.005, 0.400] [T]



Animation of Magnetic Field Vectors

Magnetic Field Contour Plots

- Magnetic field strength range: [0.005, 0.400] [T]



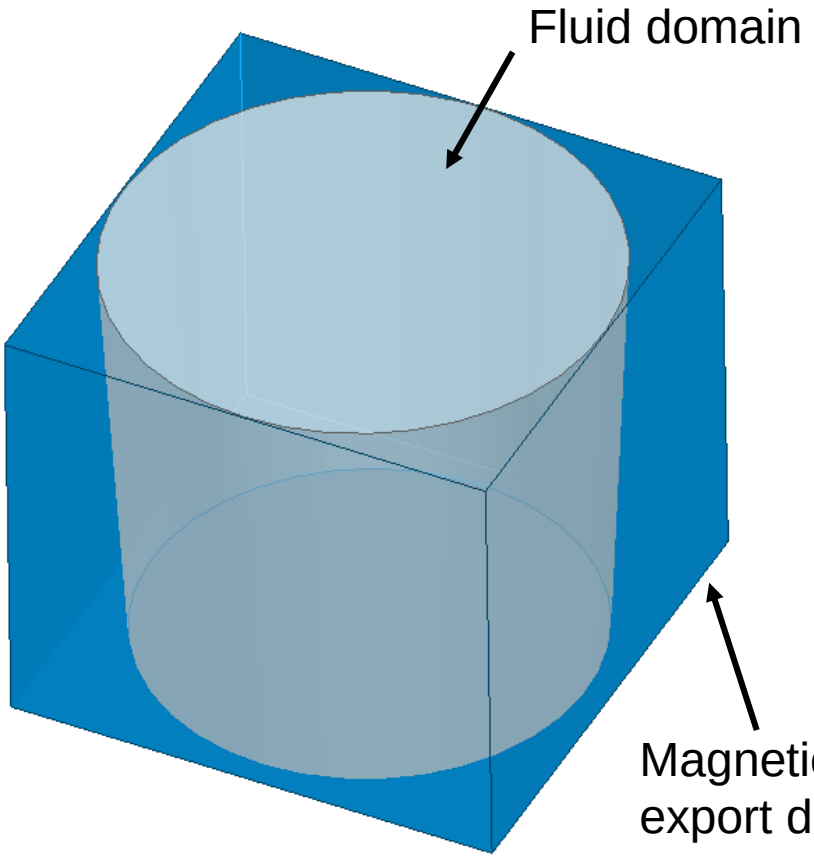
Animation of Magnetic Field Vectors

MHD MULTIPHASE LADLE SIMULATION

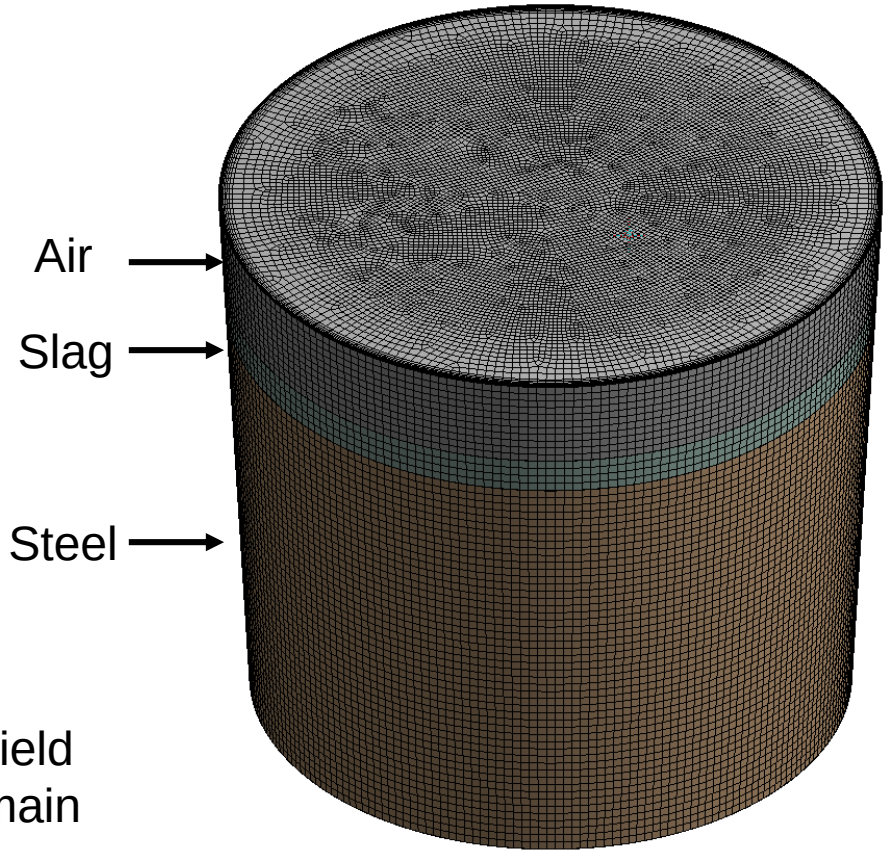
CFD Multiphase MHD Model

- Fluent Simulation Setup
  - Transient 3D Model
    - Current time-step: $0.01\ [s]$
      - In bulk: $\Delta t = \frac{\Delta x}{v_{max}} = \frac{50\times10^{-3}}{2} = 0.025\ [s] \Rightarrow \Delta t = 0.01\ [s]$
      - Near wall: $\Delta t = \frac{\Delta x}{v_{max}} = \frac{2\times10^{-3}}{2} = 0.001\ [s]$
  - Multiphase (no gas injection)
    - VOF (Implicit) Model
    - k-ϵ Turbulent Model, Realizable, & Standard Wall Functions
  - Isothermal (neglecting Joule Heating)
  - Magnetic Induction MHD Model
    - Up to 250 iterations per time step required for convergence

Magnetic Field & Fluid Domain



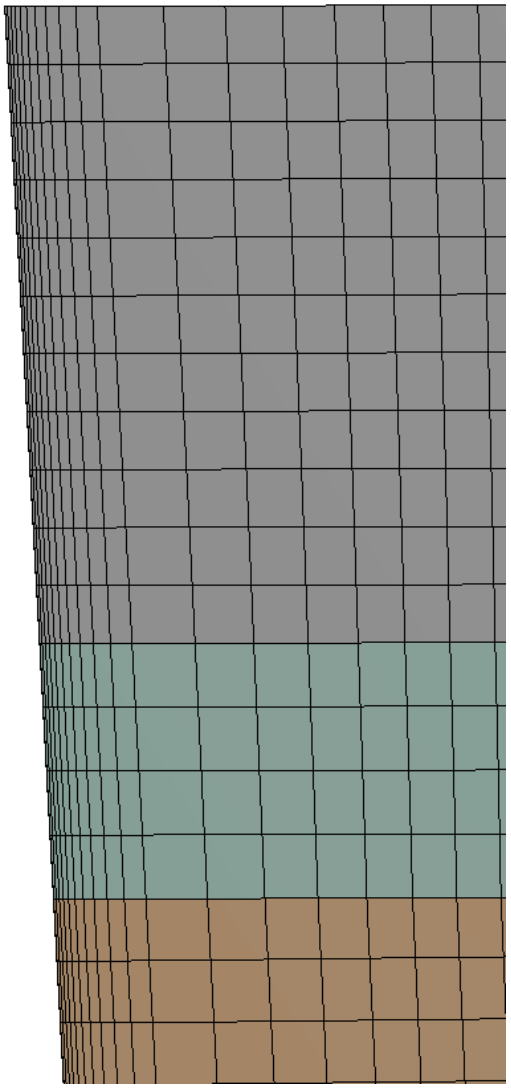
Maxwell 3D Domain



Fluent Domain

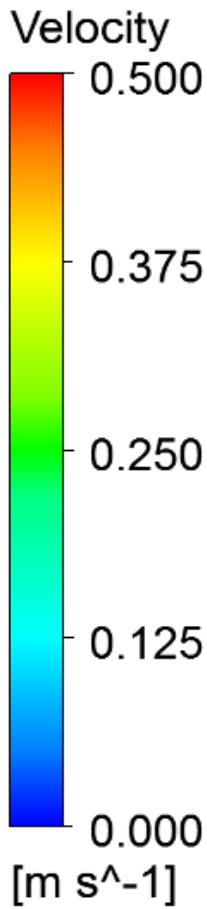
Computational Mesh

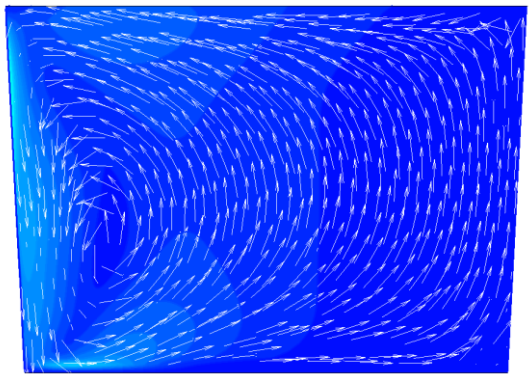
- Structured Mesh
  - Element Size: $50\ [mm]$
  - Inflation:
    - Type: First layer thickness
    - First layer height: $2.0\ [mm]$
    - Max layers: 10
    - Growth rate: 1.27
  - Structured
  - Nodes: 867,996
  - Elements: 847,340



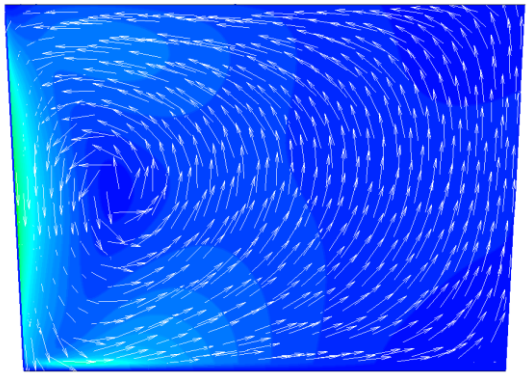
Interior Mesh Slice

Vortex Development – Vector Plots

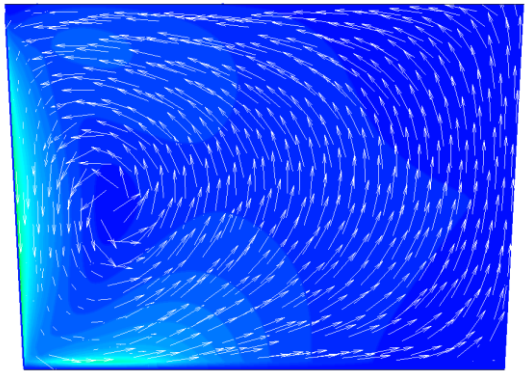




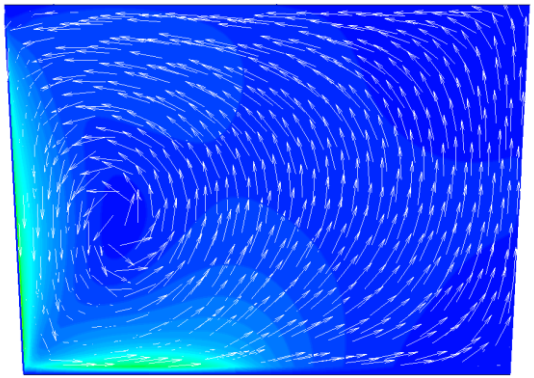
$t = 1\ [s]$
$\hookrightarrow v_{avg} = 0.0040\ [m/s]$



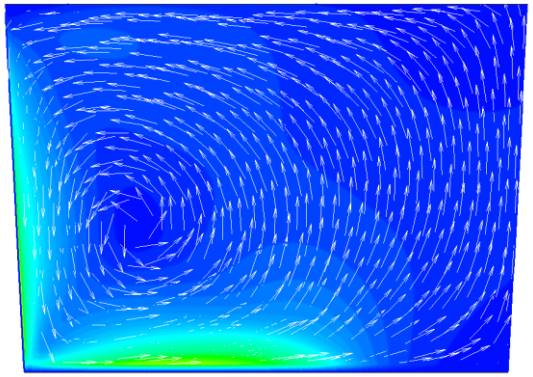
$t = 5\ [s]$
$\hookrightarrow v_{avg} = 0.0134\ [m/s]$



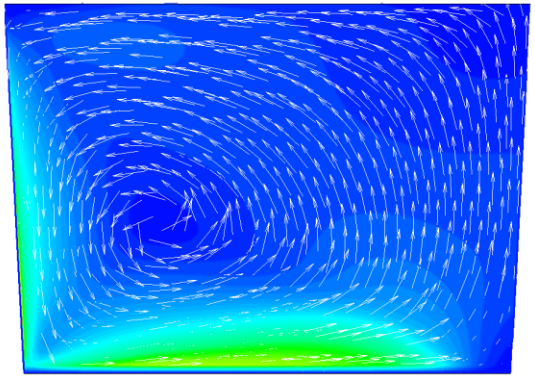
$t = 10\ [s]$
$\hookrightarrow v_{avg} = 0.0223\ [m/s]$



$t = 15\ [s]$
$\hookrightarrow v_{avg} = 0.0312\ [m/s]$

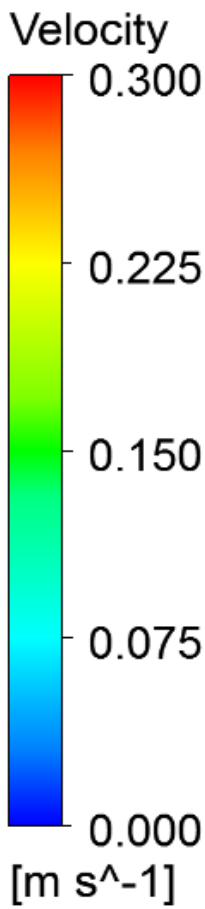


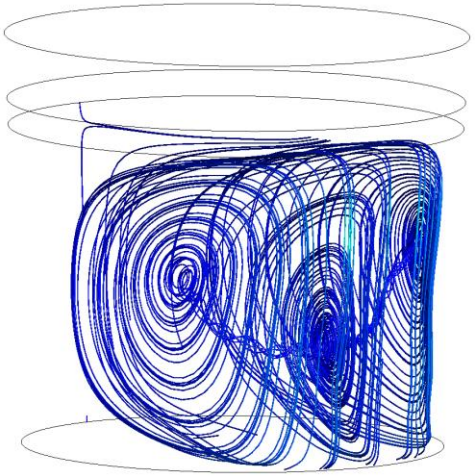
$t = 20[s]$
$\hookrightarrow v_{avg} = 0.0405\ [m/s]$



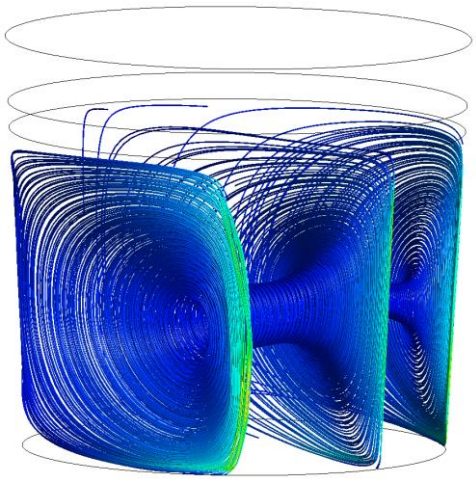
$t = 25\ [s]$
$\hookrightarrow v_{avg} = 0.0498\ [m/s]$

Vortex Development – Streamlines

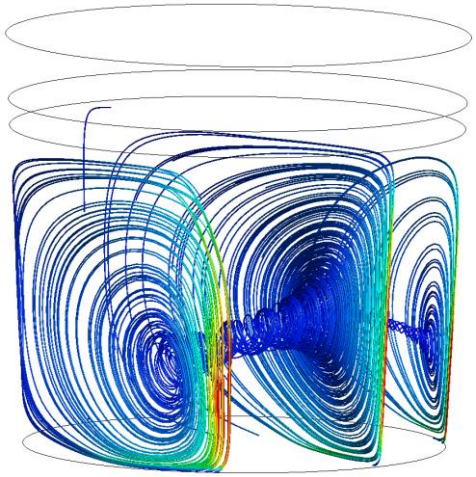




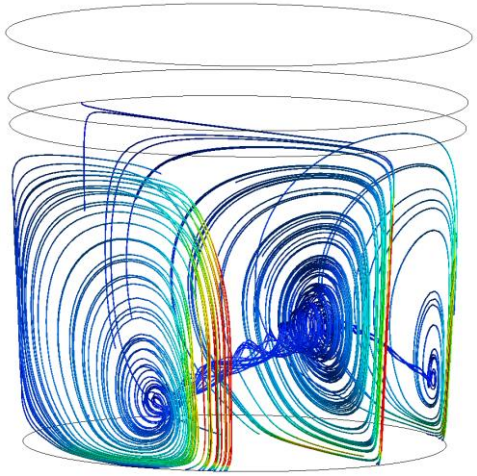
$t = 1\ [s]$
$\hookrightarrow v_{avg} = 0.0040\ [m/s]$



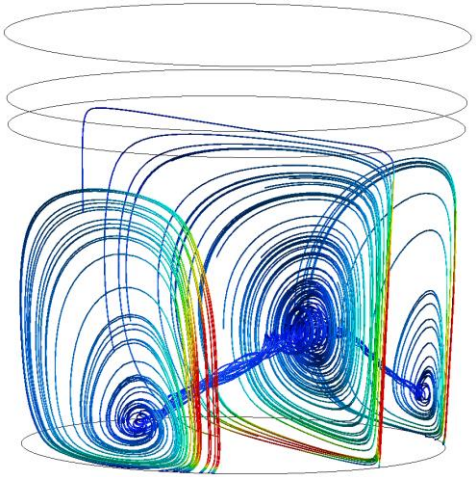
$t = 5\ [s]$
$\hookrightarrow v_{avg} = 0.0134\ [m/s]$



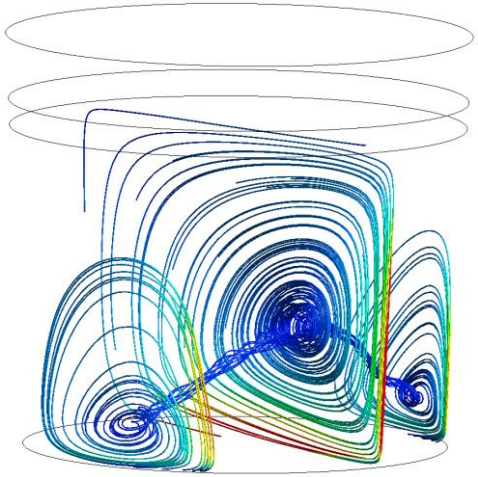
$t = 10\ [s]$
$\hookrightarrow v_{avg} = 0.0223\ [m/s]$



$t = 15\ [s]$
$\hookrightarrow v_{avg} = 0.0312\ [m/s]$



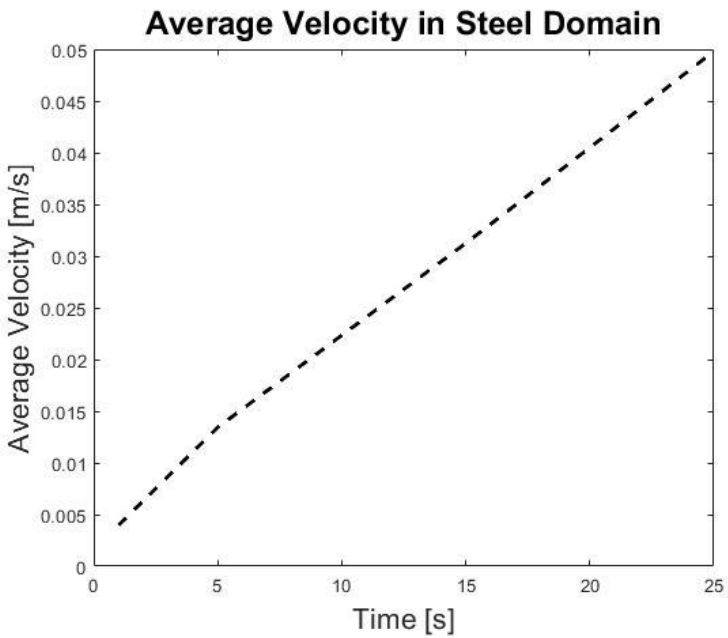
$t = 20[s]$
$\hookrightarrow v_{avg} = 0.0405\ [m/s]$



$t = 25\ [s]$
$\hookrightarrow v_{avg} = 0.0498\ [m/s]$

MHD Simulation Results

- General mixing trends correlate with literature
  - Single vortex obtained
- Velocity in steel melt falls within literature range
  - Lower average velocity at 25 [s] than literature result
    - Larger ladle
      - Longer stirring time expected
- The increase of velocity with time follows a linear trend
- Flow field still developing



Potential Implementation

- Gas-stirred Ladle:
  - Investigate effects of argon flow rate on slag eye size during inclusion removal process **(underway)**
  - Investigate mixing time of different ladle design (parameters of slag thickness, plug position and separation angle, aspect ratio)
  - Investigate the effect of ladle refectory life time on wall stress during ladle treatment.
- EMS Ladle:
  - Investigate the impact of a LF-EMS system on a steel ladle **(underway)**
    - Effect on the slag with magnetic field strength
    - Effectiveness of inclusion removal
  - Investigate the combination of gas and electromagnetic stirring
    - Impact of stirring on the slag
    - Effectiveness of inclusion removal

Project Potential Benefits

- Optimizing the steel cleaning process can result in:
  - Reduced cleaning cycle time
  - Improved steel quality
- Optimizing ladle mixing and cleaning improves entire ladle cycle
  - Energy savings
    - Reducing 5 minute mixing time by 1 minute can prevent up to 20% energy loss
  - Increased production
- "Cascading" impact:
  - Improved production of quality steel affects any industry that uses steel products

Future Work

- Gas-stirred Ladle
  - Improve the current inclusion removal model by adding buoyancy collision efficiency
  - Investigate the effect of different parameters on inclusion removal efficiency
  - Integrate chemical reactions into the current model
- EMS Ladle
  - Continue MHD model development
    - Mesh sensitivity study (near wall effects)
    - Fine-tune coil design
    - Examine EMS under varied ladle dimensions
  - Integrate inclusion modeling into EMS simulation
  - Combined Gas and EMS stirring

Comments from Industry Collaborator

Thank You
Questions and Comments

Reference

1. D. Mazumdar, P. Dhandapani, and R. Sarvanakumar. "Modeling and Optimization of Gas Stirred Ladle Systems." ISIJ International 57.2 (2017): 286-295.
2. S. W. P. Cloete , J. J. Eksteen, and S. M. Bradshaw. "A numerical modelling investigation into design variables influencing mixing efficiency in full scale gas stirred ladles." Minerals Engineering 46 (2013): 16-24.
3. L. Jonsson, and P. Jönsson. "Modeling of fluid flow conditions around the slag/metal interface in a gas-stirred ladle." ISIJ international 36.9 (1996): 1127-1134.
4. U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, “Numerical and Experimental Study on Fluid Dynamic Features of Combined Gas and Electromagnetic Stirring in Ladle Furnace.”
5. H. Lei, K. Nakajima, and J. C. He. "Mathematical model for nucleation, Ostwald ripening and growth of inclusion in molten steel." *ISIJ international* 50.12 (2010): 1735-1745.
6. H. Arai, K. Matsumoto, S. I. Shimasaki and S. Taniguchi. "Model experiment on inclusion removal by bubble flotation accompanied by particle coagulation in turbulent flow." *ISIJ international* 49.7 (2009): 965-974.
7. M. Söder, P. Jönsson, and L. Jonsson. "Inclusion Growth and Removal in Gas-Stirred Ladles." *steel research international* 75.2 (2004): 128-138.
8. Q. Cao, and L. Nastac. "Numerical modelling of the transport and removal of inclusions in an industrial gas-stirred ladle." *Ironmaking & Steelmaking* (2018): 1-8.
9. Q. Yuan, B. G. Thomas, and S. P. Vanka. "Study of transient flow and particle transport in continuous steel caster molds: Part II. Particle transport." *Metallurgical and Materials Transactions B* 35.4 (2004): 703-714.
10. Y. Miki, and B. G. Thomas. "Modeling of inclusion removal in a tundish." *Metallurgical and materials transactions B* 30.4 (1999): 639-654.
11. D. Q. Geng, H. Lei, and J. C. He. "Numerical simulation for collision and growth of inclusions in ladles stirred with different porous plug configurations." *ISIJ international* 50.11 (2010): 1597-1605.
12. M. Y. Zhu, S. G. Zheng, Z. Z. Huang and W. P. Gu. "Numerical Simulation of Nonmetallic Inclusions Behaviour in Gas-Stirred Ladles." *Steel research international* 76.10 (2005): 718-722.
13. H. Lei, L. Wang, Z. Wu and J. Fan. "Collision and coalescence of alumina particles in the vertical bending continuous caster." *ISIJ international* 42.7 (2002): 717-725.
14. W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." *Metallurgical and Materials Transactions B* 44.3 (2013): 762-782.
15. Y. J. Kwon, Z. Jian, and H. G. Lee. "A CFD-based nucleation-growth-removal model for inclusion behavior in a gas-agitated ladle during molten steel deoxidation." *ISIJ international* 48.7 (2008): 891-900.
16. L. T. Wang, Q. Y. Zhang, S. H. Peng and Z. B. Li. "Mathematical model for growth and removal of inclusion in a multi-tuyere ladle during gas-stirring." *ISIJ international* 45.3 (2005): 331-337.