CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

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COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

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Presentation at CIVS on April 11, 2019

"Where Ideas Become Reality"

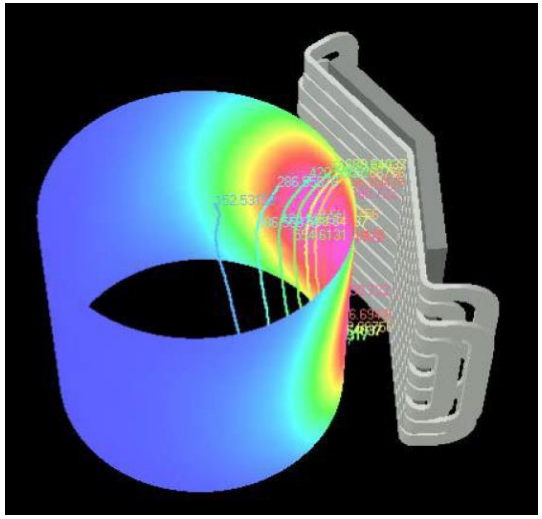
Presentation Outline

- Introduction
  - Project Motivation & Objectives
  - Ladle Subprojects
  - Research Outcomes
  - Project Timeline - 2019
- 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



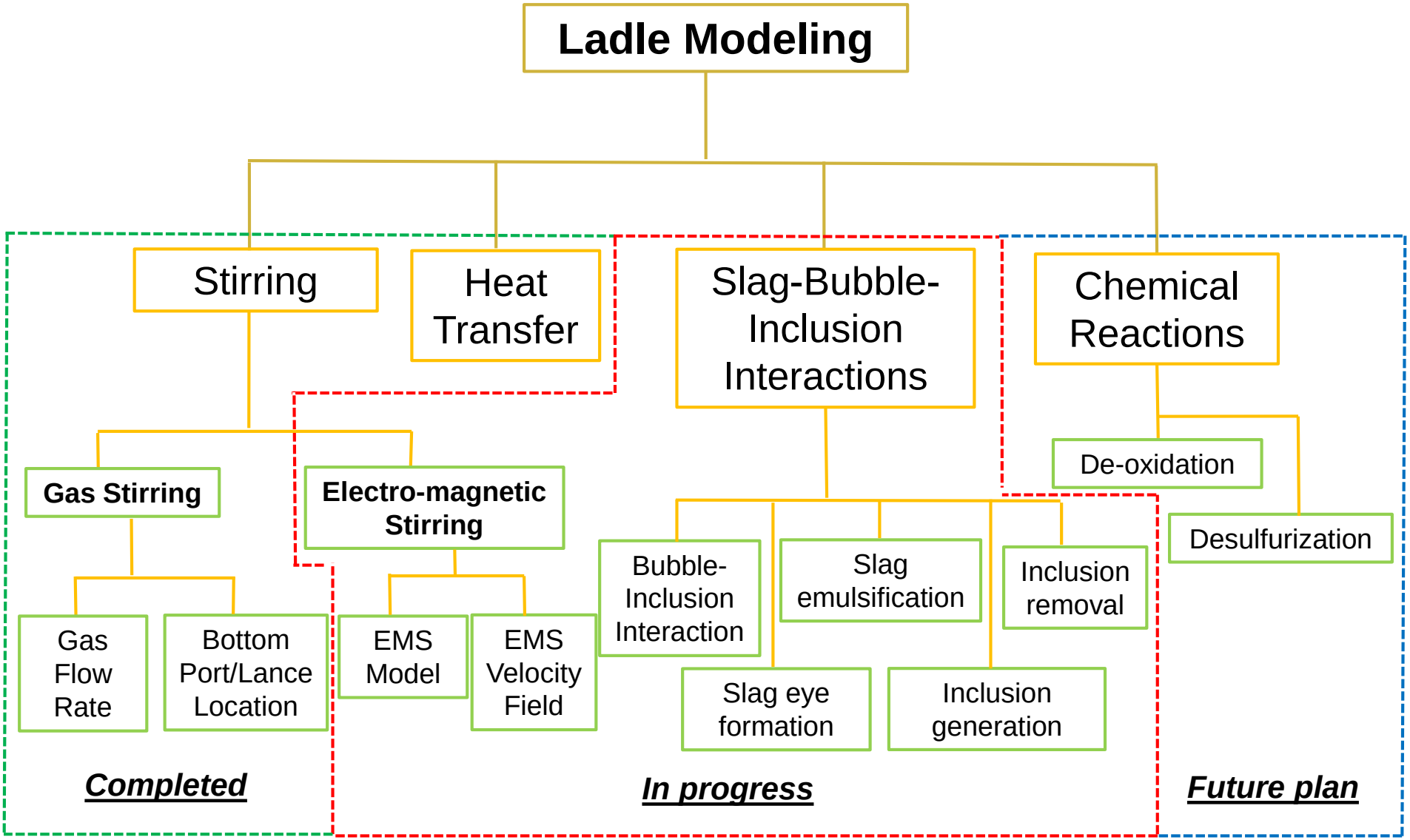
Project Objectives (5+ Years)

- Develop a comprehensive multiphase reacting CFD model of a steel ladle using two stirring conditions
  - **Gas stirring condition**
  - **Electromagnetic stirring (EMS) condition**
- Study effect of gas flow rate and different ladle design on mixing efficiency
  - Develop a correlation between geometrical parameters and mixing time
- **Study inclusion transport and evolution**
  - **Develop a model of inclusion collision and removal from ladle**
  - **Consider bubble interaction with inclusion, floatation removal mechanism**
- Develop correlation between fluid flow and slag physical properties
- Verification from industrial process conditions with measurement

Project Objectives (2019)

- Develop a comprehensive multiphase reacting CFD model of a steel ladle using Electromagnetic stirring (EMS) condition
- Study and validate inclusion growth, transportation and removal model in a generic ladle
- Study inclusion slag interaction
- Study effect of flow rate and different ladle design on mixing efficiency
- Validate inclusion removal result with industrial measurement

CFD Model Roadmap



Projects

	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					

Project Outcomes Since 2016

- Advancement of models
  - CFD model of gas-stirred ladle developed based on Nucor Steel Decatur ladle
  - CFD model of Isothermal gas-stirred flow model:
    - Bubble coalescence and breakup were developed
    - CFD predictions validated against experimental work percentage error within 11% and industrial measurements percentage error within 8%
  - EMS model:
    - Import magnetic field
    - Multiphase EMS model development
    - Flow field developed
  - 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

Project Outcomes (Year 1 & 2)

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

Project Outcomes (Year 3 & 4)

- **Project 3: Gas-Stirred Isothermal Inclusion Growth and Removal (in progress)**
  - Three mechanisms of inclusion growth
  - Six mechanisms of inclusion removal
  - **Inclusion buoyancy collision efficiency added**
  - **Inclusion transport by bubble**

- **Project 4: EMS Isothermal Inclusion Growth and Removal (in progress)**
  - Develop a traveling magnetic field to be imported into EMS model
  - Develop a multiphase EMS model
  - **Obtain a flow field that agrees with literature and theory**

Timeline for 2019

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Project 3-3 Gas-Stirred Isothermal Inclusion Removal	Bubble Model Literature Research												
	Improve Current Bubble Model												
	Validate Modified Model												
Project 3-4 Improvement of Inclusion Removal Model	Add Buoyancy Collision Efficiency												
	Validate Improved Inclusion Removal Model												
	Modified Bubble Model Applied in Generic Model												
	Inclusion Removal Animation												

Timeline for 2019

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Project 4 Isothermal EMS Inclusion Removal	EMS Multiphase Model												
	Add of Inclusions to EMS Multiphase Model												
	Combined Gas-Stirring and EMS												
Project 5 Develop Slag-Inclusion Chemical Reaction Model	Literature Research												
	Basic Model Development												
	Validate Basic Model												
	Chemical Reaction Model Applied in Generic Model												

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.**

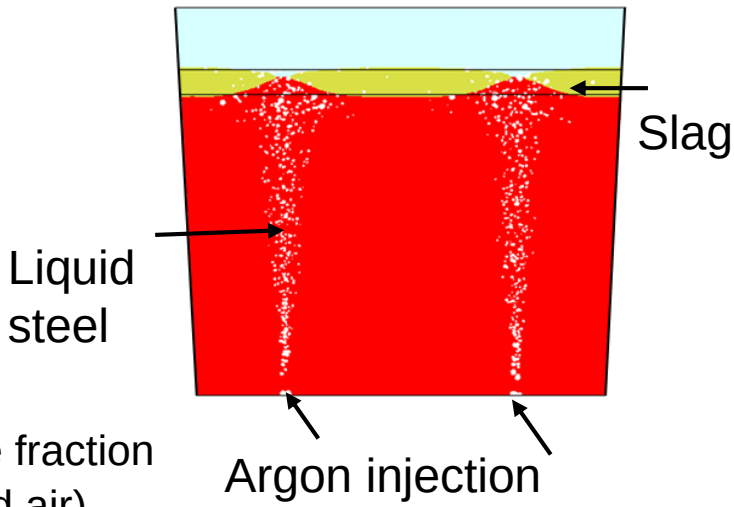
Project 3:
GAS-STIRRED LADLE MODEL

- Inclusion removal model

Methodology & CFD Models

Gas-stirring ladle model

- Fluid zones (slag, melt, inclusion and air)
  - Eulerian-Eulerian multiphase flow
  - Realizable k-epsilon turbulent model
- 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

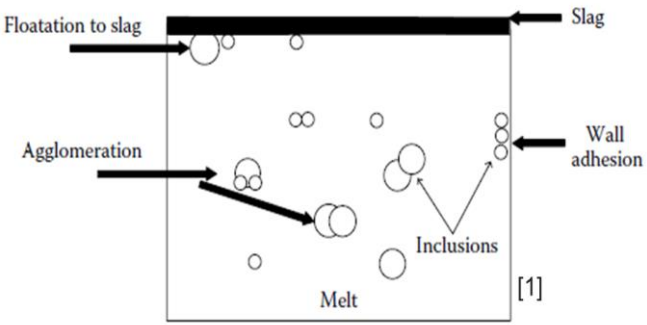
Inclusion removal and growth model

- **Inclusion removal and growth**
  - Population balance model (PBM) – continuum method
  - **Transport by bubble, removal by slag and wall**

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

  } Transport inclusion 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.".

Inclusion 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

- Overall inclusion removal rate

$$S_{\mathrm{i}} = S_{\mathrm{i}}^{\mathrm{wall}} + S_{\mathrm{i}}^{\mathrm{F}} + S_{\mathrm{i}}^{\mathrm{BF}} + S_{\mathrm{i}}^{\mathrm{TR}} + S_{\mathrm{i}}^{\mathrm{TS}} + S_{\mathrm{i}}^{\mathrm{wake}}$$

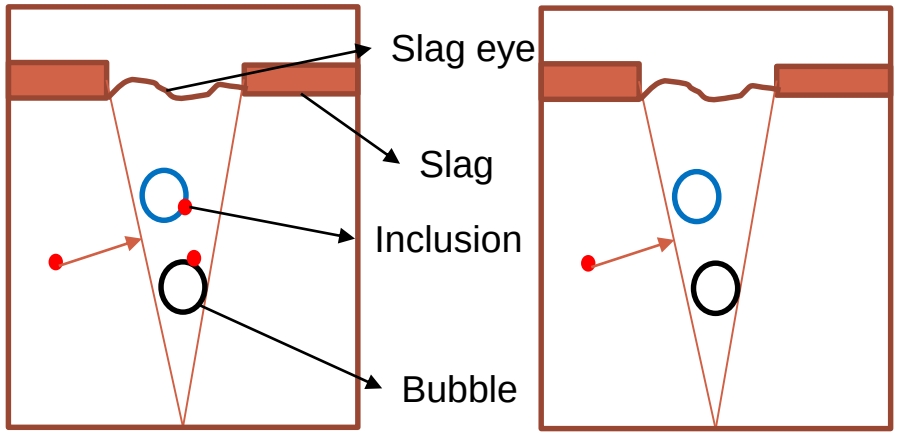
  - $S_{\mathrm{i}}^{\mathrm{wall}}$: Inclusion attach to wall
  - $S_{\mathrm{i}}^{\mathrm{F}}$: Inclusion floatation
  - $S_{\mathrm{i}}^{\mathrm{BF}}$: Turbulence buoyancy collision
  - $S_{\mathrm{i}}^{\mathrm{TR}}$: Turbulence random collision
  - $S_{\mathrm{i}}^{\mathrm{TS}}$:Turbulence shear collision
  - $S_{\mathrm{i}}^{\mathrm{wake}}$: Bubble wake capture collision

- Collision efficiency work for both inclusion growth and removal, assume colliding probability was 100% before.

- 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 Transport by Bubbles

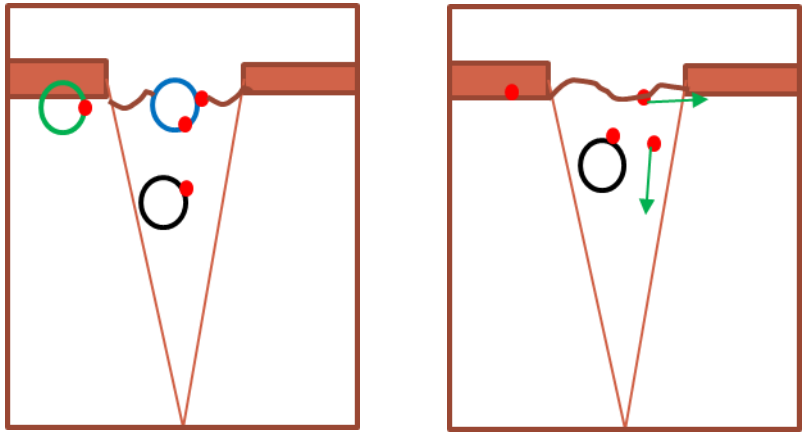
- Previous assumption



(1)

- Inclusions are removed as soon as in contact with bubbles.
- Over predicts inclusion removal.

- Model update (inclusion transport)



(2)

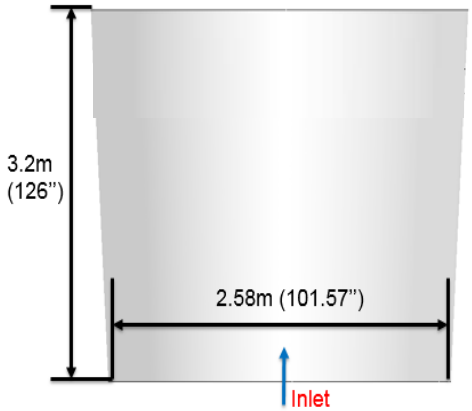
- Inclusions will be carried by bubbles.
  - At slag-metal interface → bubble breakup → inclusions capture by slag
  - At slag eye → bubble breakup → inclusions release to steel

INCLUSION REMOVAL VALIDATION

Model Validation

- Adopted work by Lou et al (2013)
  - 150-ton ladle
  - CFD-PBM coupled method
  - Multiphase (Steel & Inclusion)
  - Isothermal condition and top flat free surface
  - Flow rate: 200NL/min (7.45 SCFM) & 100NL/min (3.725 SCFM)
  - Bubble size: 4mm (constant)

Lou et al., 2013



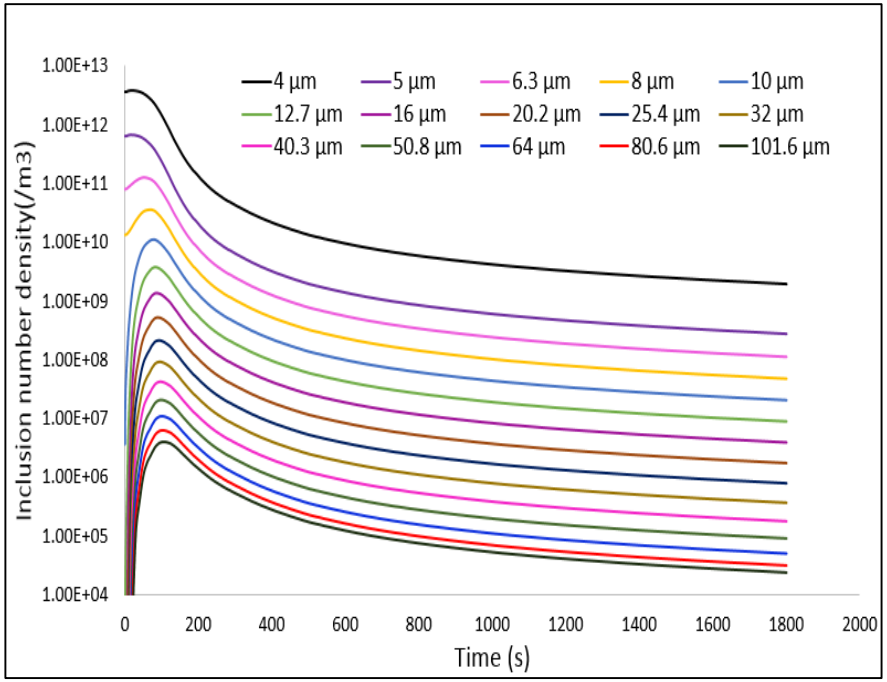
Parameters	Lou, et al. 2013
Diameter of ladle	2.58 m
Height of ladle	3.2 m
Number of plugs	1
Inclusion size	4~200 μm
Group of inclusion	18

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

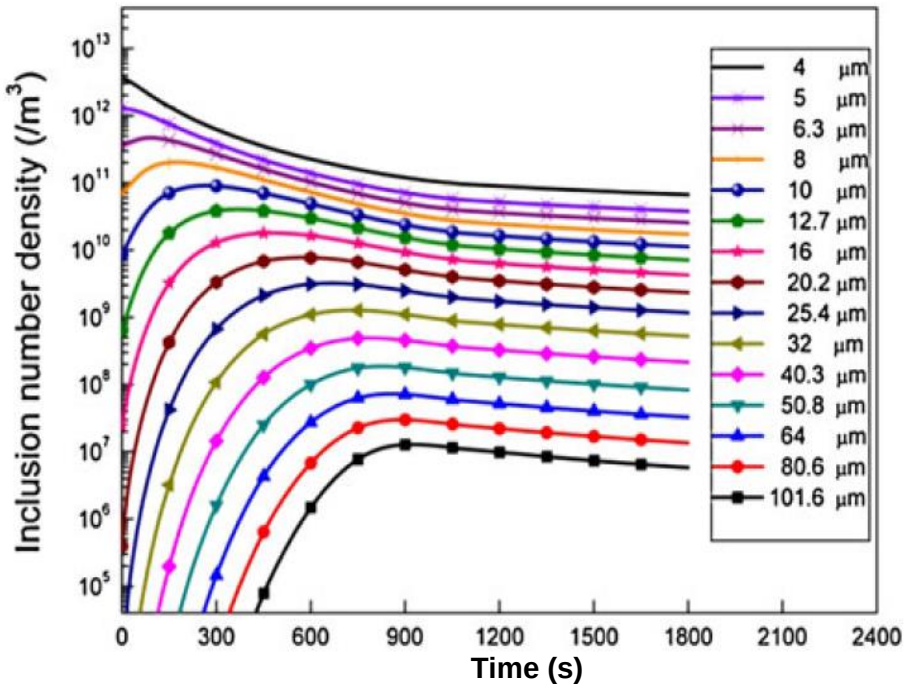
Inclusion Removal Validation

- Collision efficiency assume 100%, no transportation
- Inclusion growth and removal efficiency are assumed to 100% in validation.
- Removal rate based on mass for 200 NL/min is 93%, comparing to paper is 68.16%
- Overall trends of inclusion number density change are similar.

- SMSVC Validation (100 NL/min)

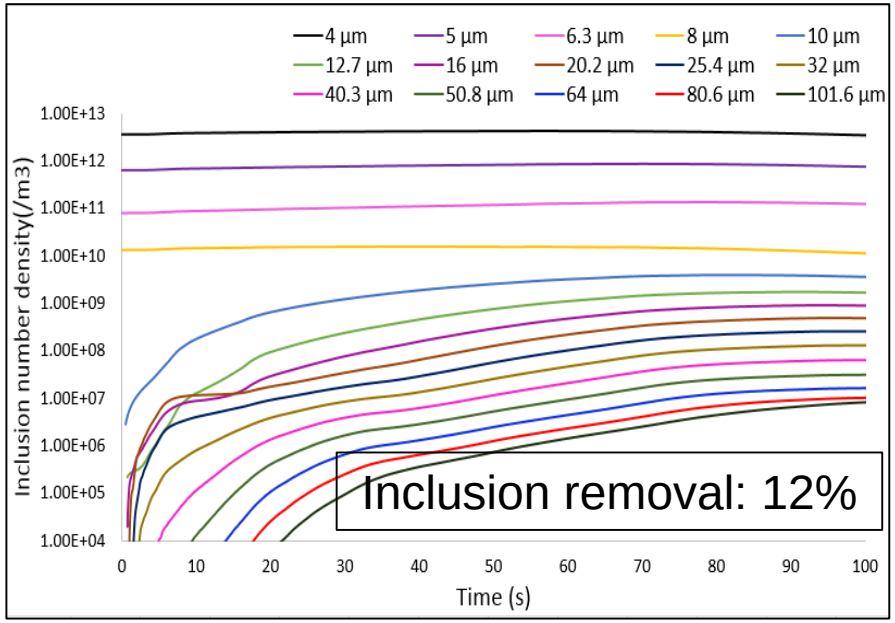


- Lou et al., 2013 (100 NL/min)

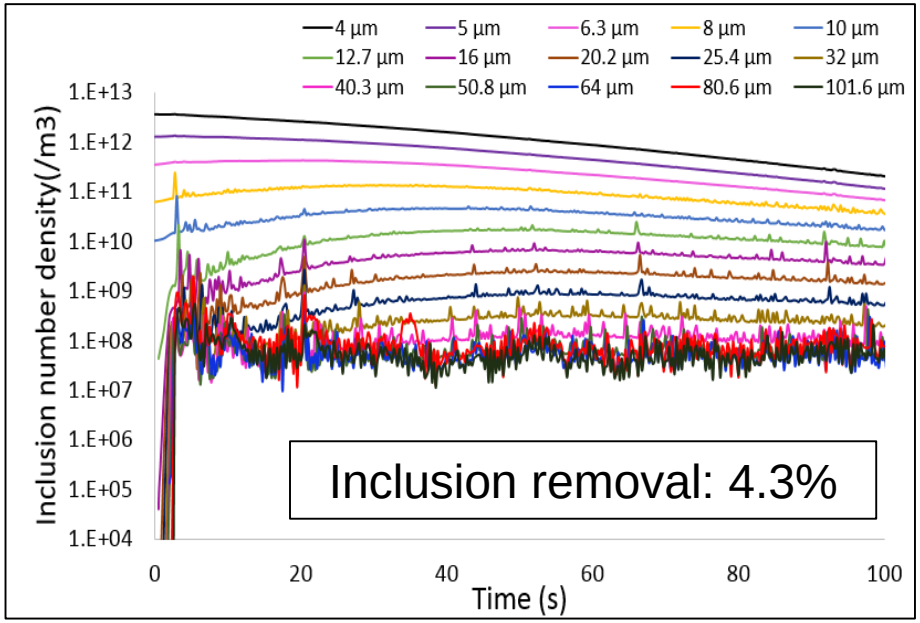


Inclusion Number Density Distribution

- Collision efficiency = f(θ,v), without transportation



- Collision efficiency = f(θ,v), with transportation



- Removal rate: 21% -> 12% -> 4.3% after add collision efficiency equation and transportation model at 100s
- Fluctuations of lines may caused by back source of inclusion from slag eye, transportation model need to be revised
- Simulation is ongoing. Will be compared to 1800s results by Lou et al.

Relative Inclusion Removal Rate

SMSVC (with inclusion transport)	Lou et al.
Wall	Slag
Slag	Turbulence random
Buoyancy	Buoyancy
Turbulence random	Wake capture
Wake capture	Turbulence shear
Turbulence shear (=0%)	Wall

High

Low

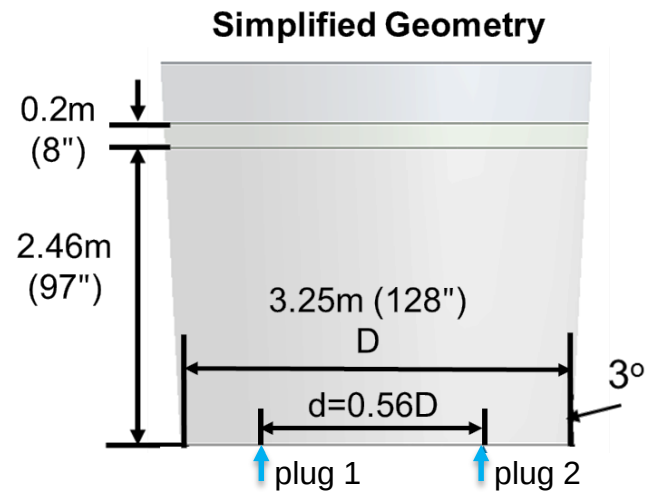
- The opposite trend of wall removal possibly due to turbulence model
- Removal by turbulence shear at 0% because of largest Kolmogorov's micro scale smaller than bubble size.
- Turbulence eddy size distribution and higher wall inclusion removal indicate that turbulence model need to be revised

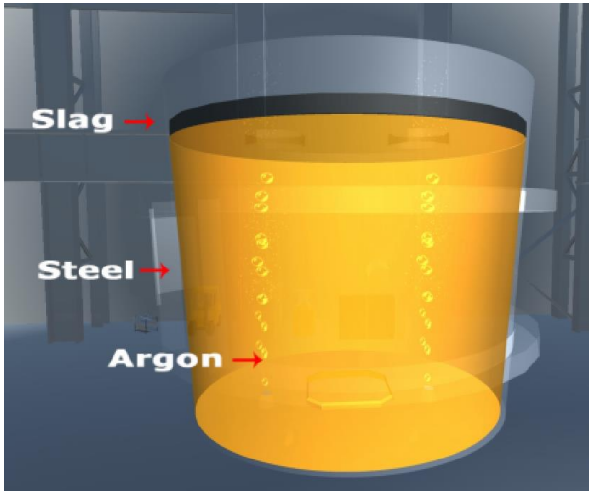
BASELINE CASE SIMULATION FOR INCLUSION REMOVAL

Generic Ladle Geometry

- Generic model based on Nucor Decatur ladle
- Model can be applied to other ladles

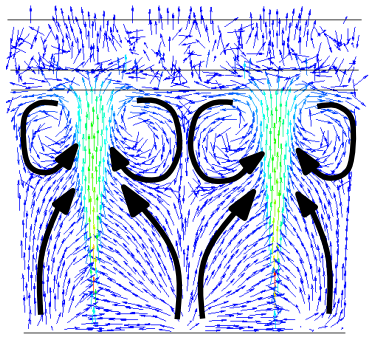
Parameters	Value
Melt depth (m)	2.46
Slag depth (m)	0.2
Wall taper angle	3°
Plug distance ratio $\left(\frac{\text{Distance between plugs}}{\text{Floor diameter}}\right)$	0.56
Aspect ratio $\left(\frac{\text{Melt height}}{\text{Diameter @ slag} - \text{metal interface}}\right)$	0.7
Separation angle	180°



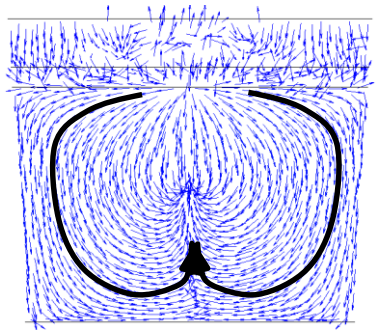


Flow Field Distribution

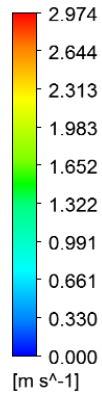
- Flow simulation is used previously validated model
- Gentle stirring (5SCFM/plug) – no slag eye
  - Argon flow rate: **5SCFM**/plug

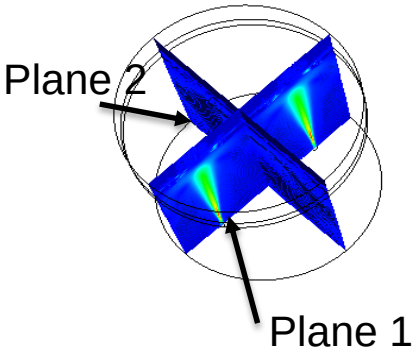


Plane 1

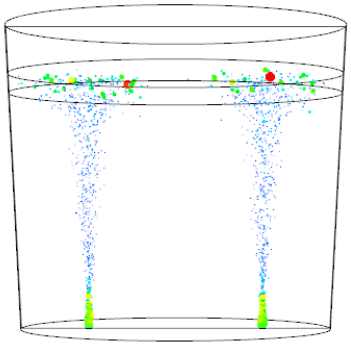


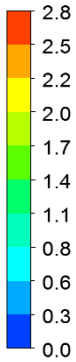
Plane 2





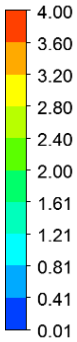
- Argon bubble distribution



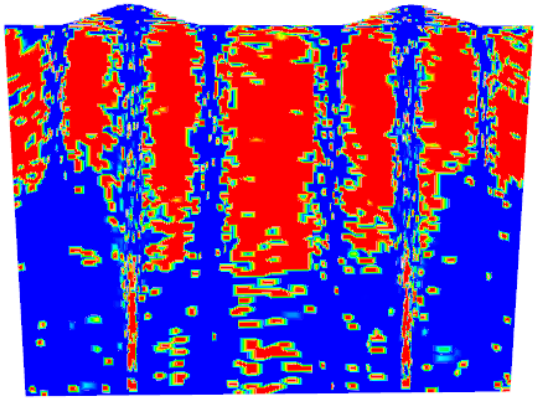


in

- Inclusion transport by bubble



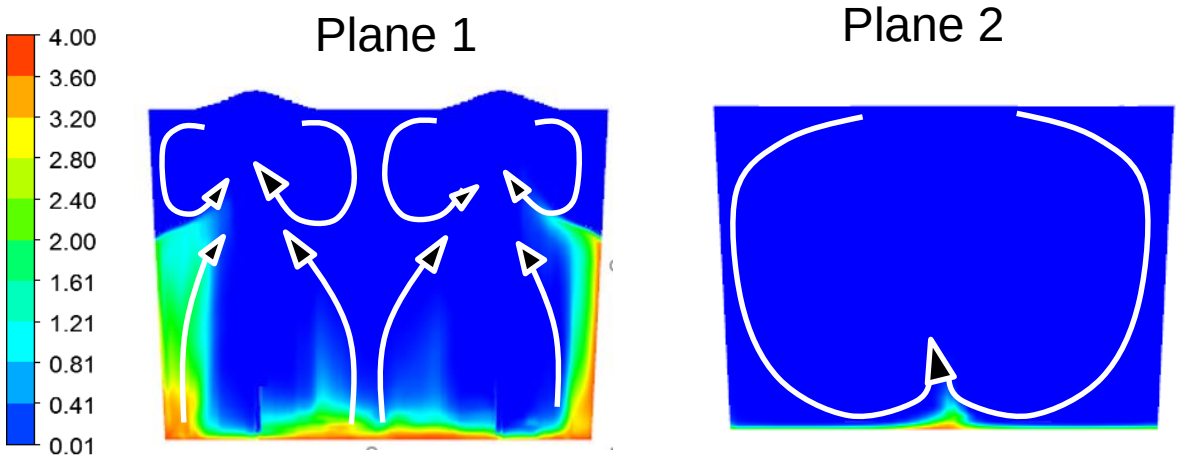
Inclusion number density (10^{12} n/m^3)



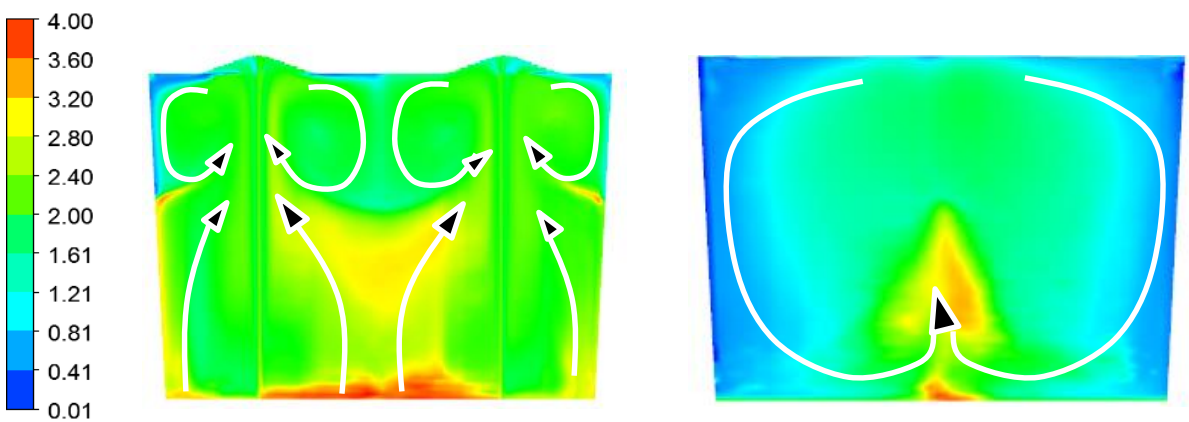
Plane 1

Model Comparison

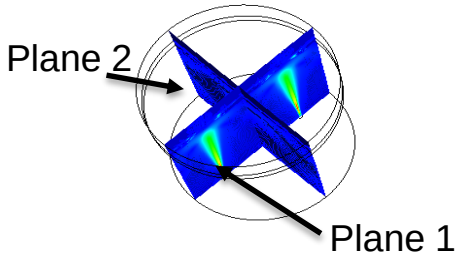
Inclusion number density (10^{12} n/m^3)



Collision efficiency = 100%, 300s



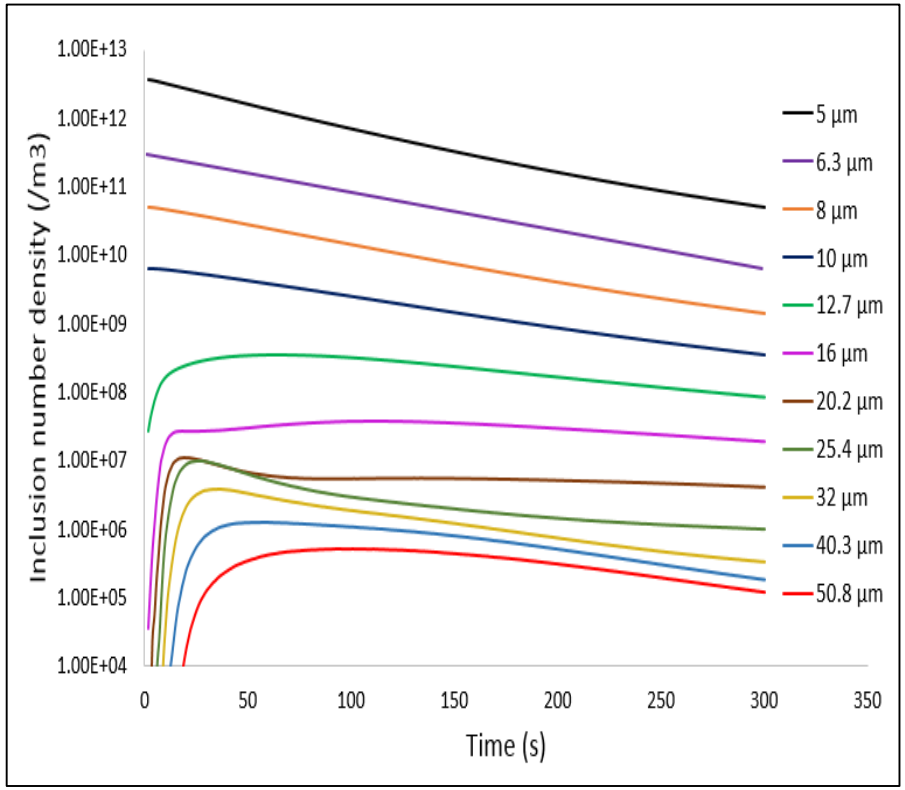
Collision efficiency = f(θ,v), 300s



- Note:
  - De-attachment = 0
- Clean steel gather to the upper part of ladle
- Higher inclusion removal by wall in top region
- Higher inclusion concentration in the center and bottom of ladle

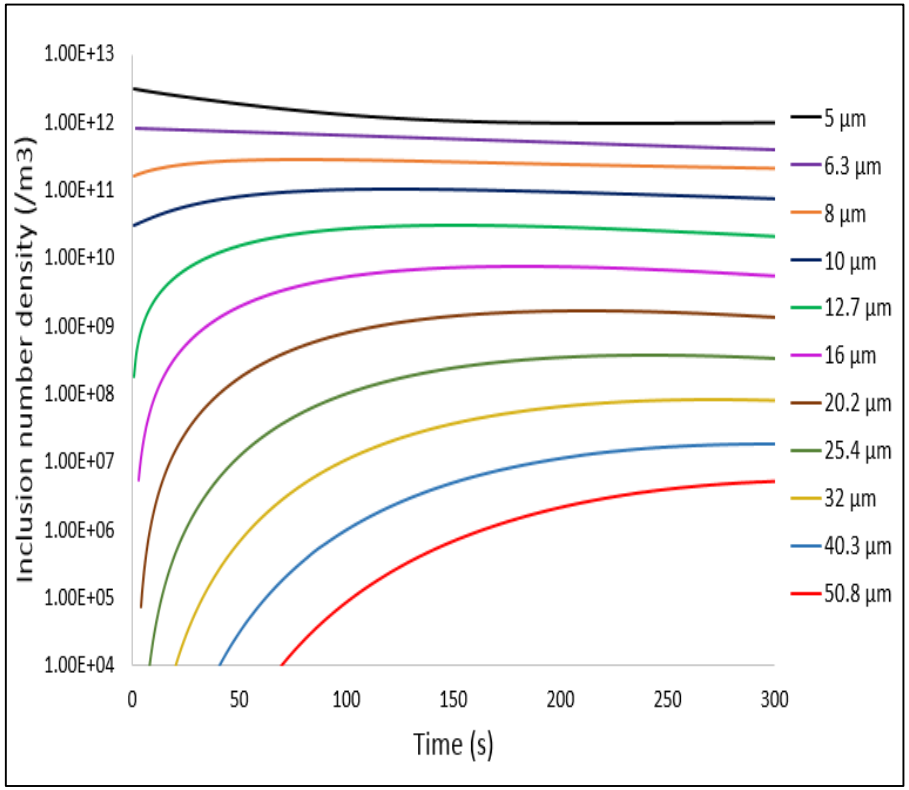
Inclusion Size Distribution (300s)

- Collision efficiency = 100%



- Removal rate = 97.1%

- Collision efficiency = f(θ,v)



- Removal rate = 30.5%

- Inclusion removal rate decreased
- Collision efficiency will affect both inclusion removal and growth

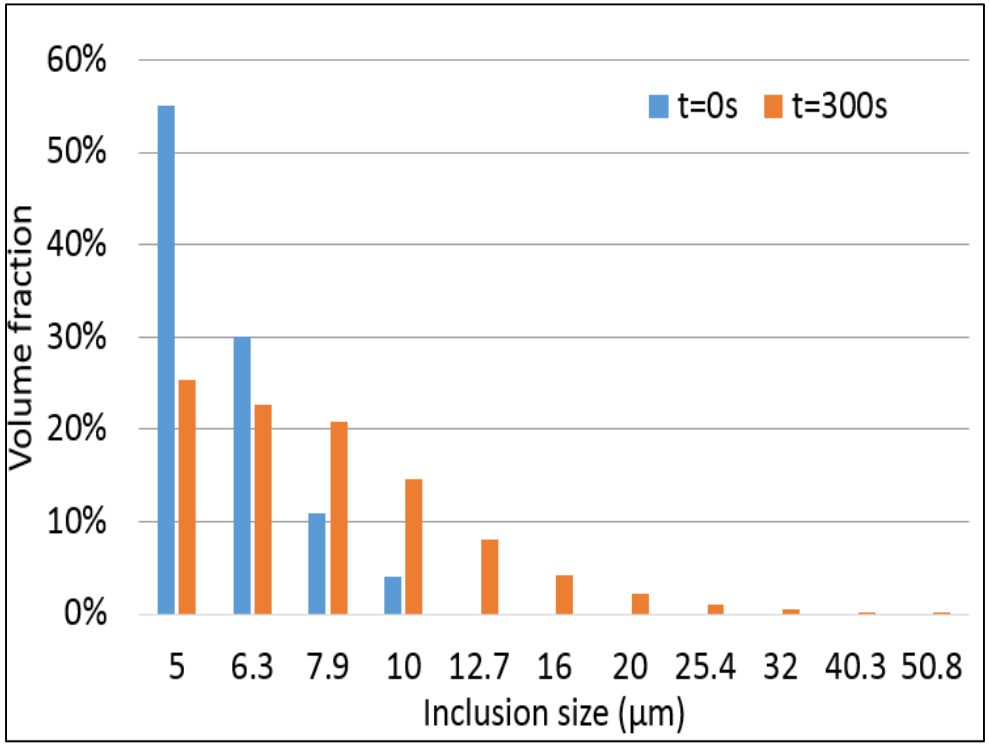
Inclusion Size Distribution

- Initial distribution can be calculate: (Lou et al. 2013)

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

- Larger inclusion size form due to inclusion aggregations.
- Inclusion Sauter diameter (d_{32}) at 300s = 15.3 µm

n	Size (µm)	Bin Volume fraction	
		t=0s	t=300s
Bin 10	5.0	55.0%	25.4%
Bin 9	6.3	30.0%	22.7%
Bin 8	7.9	11.0%	20.9%
Bin 7	10.0	4.0%	14.6%
Bin 6	12.7	0.0%	8.1%
Bin 5	16.0		4.3%
Bin 4	20.0		2.2%
Bin 3	25.4		1.1%
Bin 2	32.0		0.5%
Bin 1	40.3		0.2%
Bin 0	50.8		0.1%



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

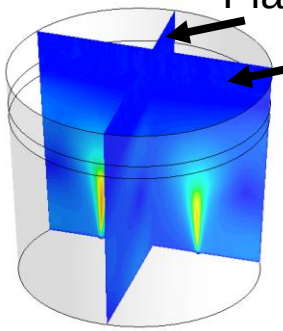
Project 3:
GAS-STIRRED LADLE MODEL

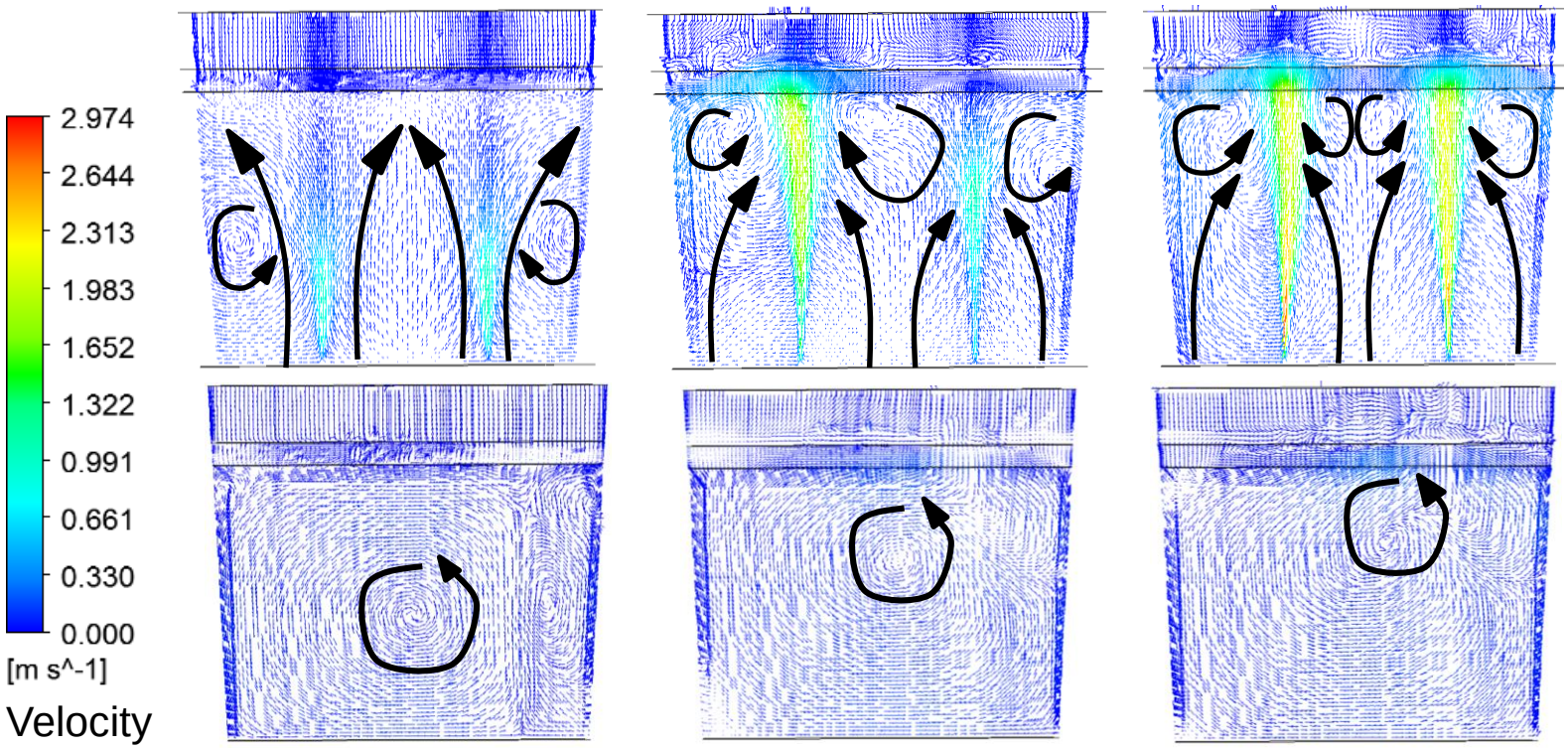
- Mixing efficiency parametric study

90 Degree Simplified Nucor Ladle

- Case matrix

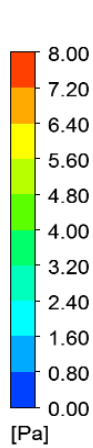
Plug separation angle	Argon flow rate (SCFM)	
	Plug 1	Plug 2
90º	5	5
90º	5	20
90º	20	20

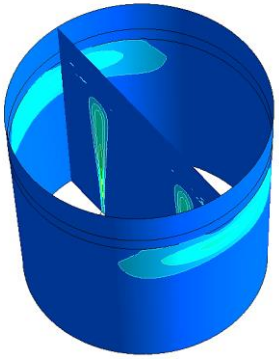




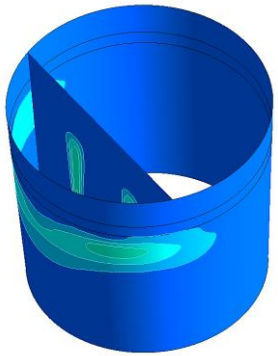
Wall Shear Stress

- Comparison between 180° and 90°





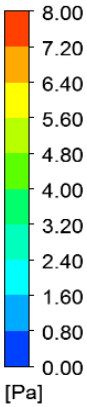
5/5 SCFM (180°)

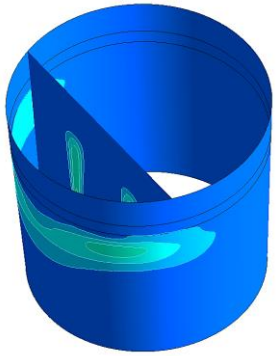


5/5 SCFM (90°)

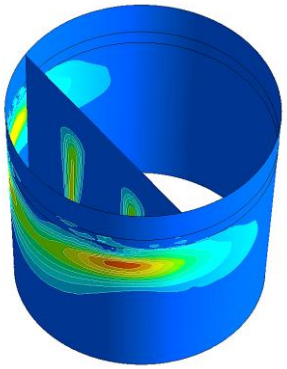
Case	Maximum Wall Shear Stress
5/5 (180°)	2.71 Pa
5/5 (90°)	2.82 Pa
5/20 (90°)	8.07 Pa
20/20 (90°)	8.07 Pa

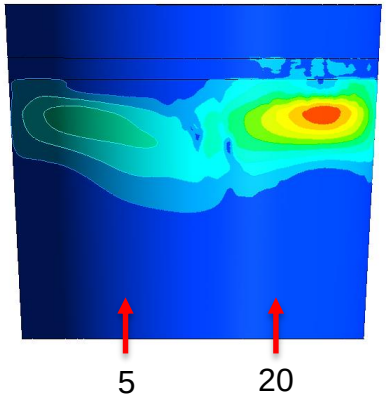
- Comparison at 90° separation angle



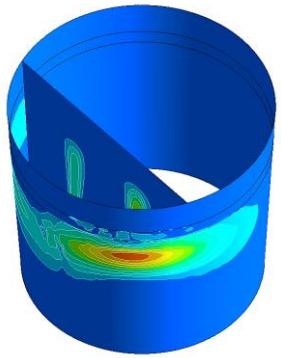


5/5 SCFM





5/20 SCFM

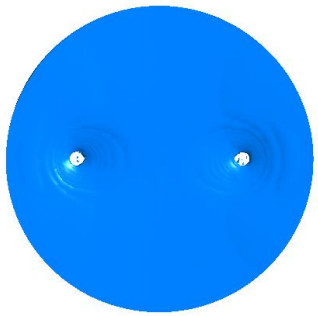


20/20 SCFM

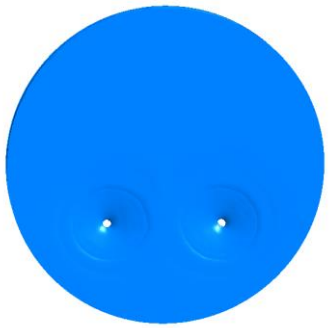
- Wall shear stress become greater and higher as flow rate increase

Slag Eye Diameter

- Comparison between 180° and 90°



5/5 SCFM(180°)

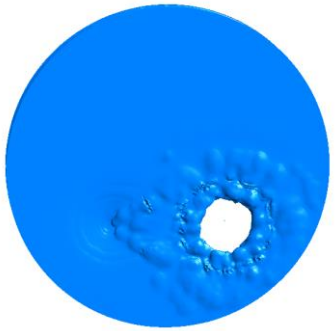


5/5 SCFM(90°)

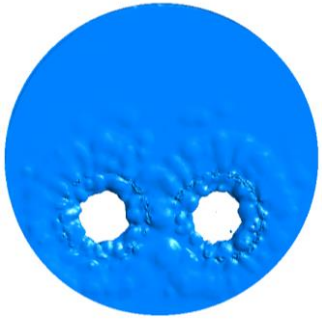
Case	Slag Eye Diameter
5/5(180°)	0.17 m
5/5 (90°)	0.20 m
5/20 (90°)	0.67 m
20/20 (90°)	0.62 m

- Comparison at 90° separation angle

5/5 SCFM



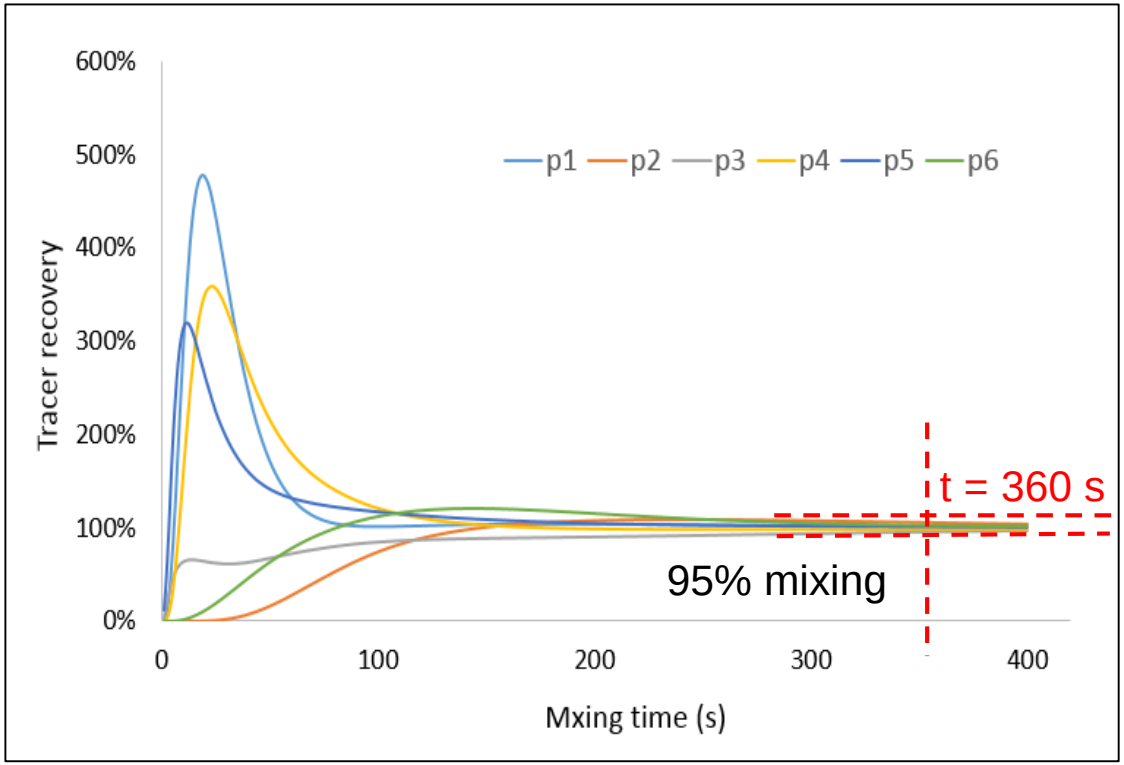
5/20 SCFM

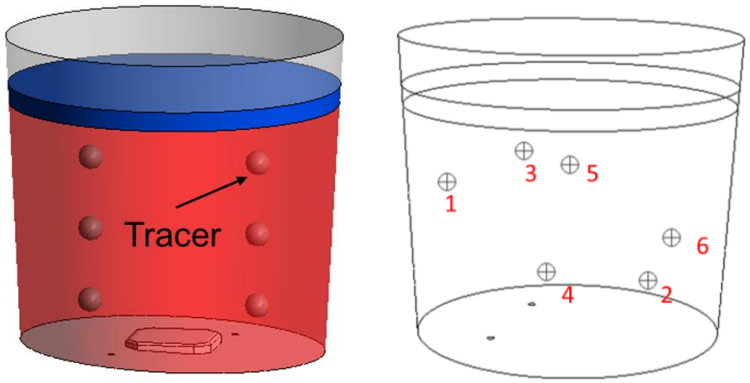


20/20 SCFM

Mixing Time Comparison

- Mixing time for case 2





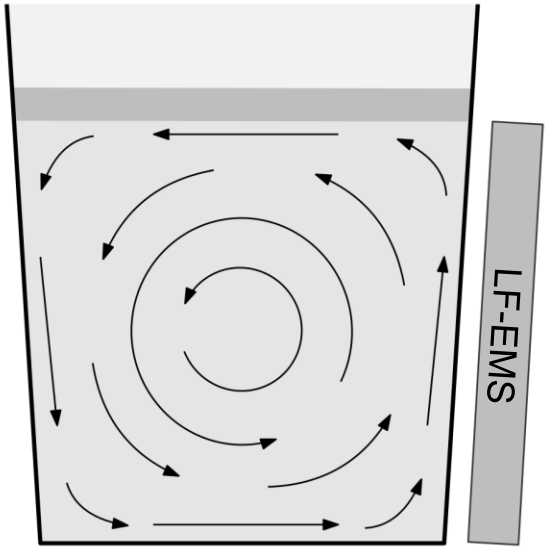
Case	Flow rate	Mixing Time
1	5/5(180°)	304 s
2	5/5	360 s
3	5/20	159 s
4	20/20	167 s

- Tracer recovery(%) = $\frac{\text{Current Tracer Concentration}}{\text{Equilibrium Tracor Concentration}}$
- Ladle separation angle of 180° has better mixing comparing to 90°
- Flow rate of 5/20 has best mixing efficiency among 90° ladles

Project 4:
EMS LADLE MODEL

Electromagnetic Stirring

- Uses applied magnetic field to stir conductive fluid (iron melt)
  - Induced Lorentz force stirs fluid volume
- Low-frequency (LF) EMS provides two potential benefits over gas-stirring:
  1. Homogeneity of melt
  2. Non-invasive stirring
- Can be combined with gas-stirring
- Simulated using Magnetohydrodynamics (MHD)
  - Combination of electromagnetics and fluid dynamics



Ladle & LF-EMS

EMS Simulation Process

- Simulation of EMS and inclusion removal requires four stages:

Modeling	EMF Simulation	CFD Simulation	Inclusion Removal
• Ladle Dimensions • Coil System Dimensions	• Electric Current Coils • Induced Magnetic Field	• 3D Transient • Multiphase • MHD Phenomena	• Population Balance Method • Inclusion Growth & Removal • Initial Distribution
Provides	**Provides**	**Provides**	**Provides**
• LF-EMS Unit • Numerical Meshes for EMF & CFD	• Magnetic Field Profile • (Lorentz force profile)	• Developed Flow Field • Slag Eye Formation	• Inclusion Removal Rates • Populations

EMS Simulation Work

- **<u>Modeling</u>** process done using ANSYS modeling tools
  - Two ladle geometries created
    1. Simplified ladle based on generalized Nucor design (using same parameters as gas-stirred simulations)
    2. Simplified ladle based on generalized ArcelorMittal ladle (needed for industry-provided EMF)

Modeling: Ladle Dimensions & Mesh

- All ladles are simplified
  - Nucor & ArcelorMittal have taper angles
  - Meshes use near-wall refinement due to MHD *skin depth*
- Comparison of results use paper by Sand, et al., 2009
  - Cylindrical ladle (no taper)

Simplified Nucor Ladle Mesh

Simplified ArcelorMittal Ladle Mesh

Ladle Parameters	Nucor	ArcelorMittal	Sand et al.
Top Radius [m]	1.79	2.19	-
Bottom Radius [m]	1.62	1.60	-
Inner Radius [m]	-	-	1.425
Steel Height [m]	2.46	3.15	2.80
Steel Volume [m^3]	22.49	35.82	17.86
Steel Tonnage [US Ton]	178.5	284.3	141.9
Mesh Element Count	8.5E5	1E6	-

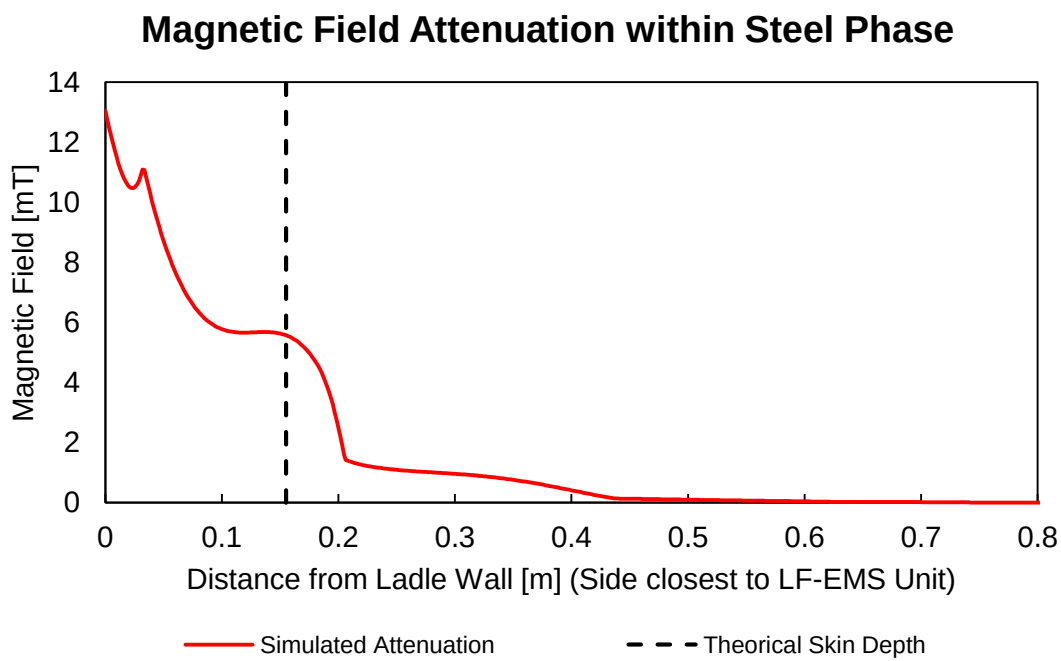
U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, "Numerical and Experimental Study on Fluid Dynamic Features of Combined Gas and Electromagnetic Stirring in Ladle Furnace." 2009

MHD: Stirring Force Region

- Magnetic field will provide the stirring force in the melt within the skin depth (F. T Ulaby)

$$\delta = \frac{1}{\sqrt{\pi f \, \mu\sigma}} = 0.155 \text{ [m]}$$

  - This region will contain the majority of the stirring force
    - Requires fine wall mesh to **capture** region of MHD interaction



F.T. Ulaby. Electromagnetics for Engineers

EMS Simulation Work

- Two **EMF Simulations** performed to obtain field generated by a LF-EMS unit
  1. Performed by SMSVC using in-house generalized LF-EMS unit and ANSYS Electronics Desktop
     - Allows for parametric studies
  2. Performed by industry partner using industry data and software
     - Purposed for **validation** of SMSVC magnetic field

EMF Simulation: General LF-EMS Unit

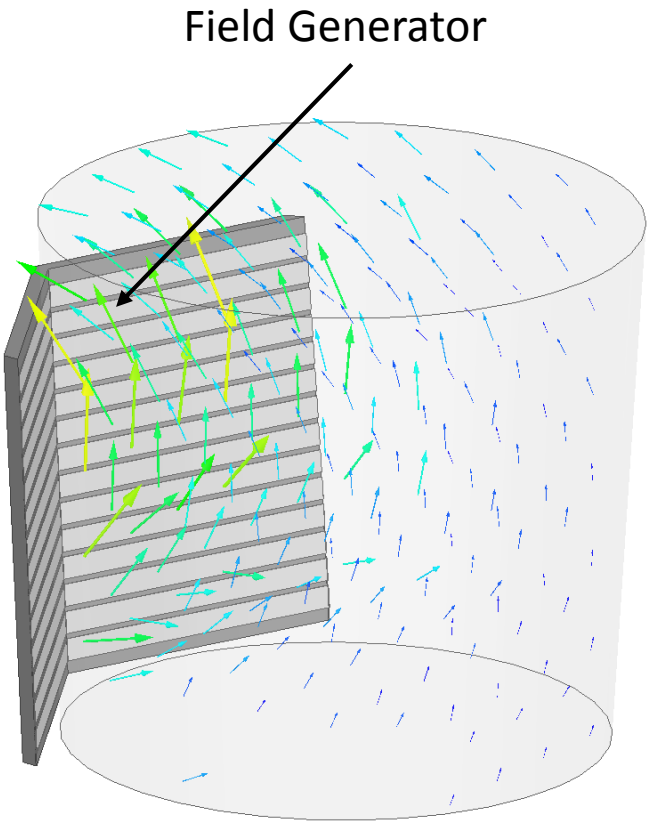
- Based off of literature and industry information
- Induced traveling magnetic field from AC

$$\text{Current } I = I_o \cos(\omega t + \phi_s)$$

where

$$\phi_s = \frac{180}{N}$$

Component	SMSVC Values	Industry Provided Values
Current Amplitude, I_o [A]	1500	1200
Frequency, f [Hz]	1.5	1.0
Number of Coils, N	14	-
Phase Shift, ϕ_s	12.857	-

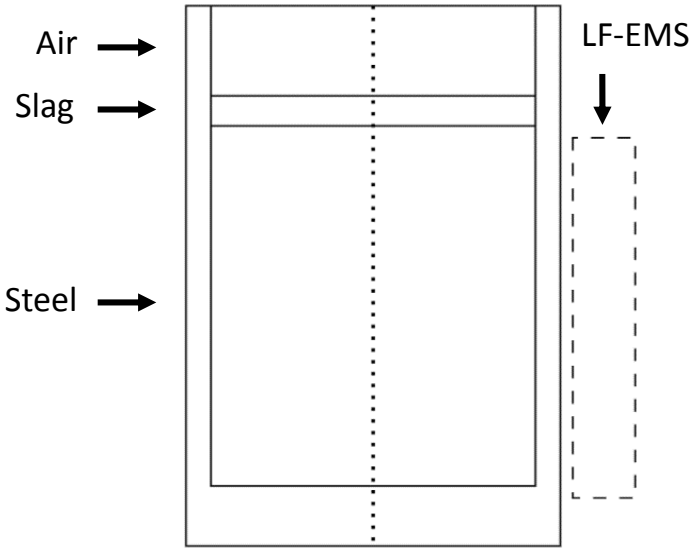


SMSVC LF-EMS Unit

V. Fireteanu Etienne Rousset. Simultaneous induction heating and electromagnetic stirring of a molten glass bath. 10 2015.

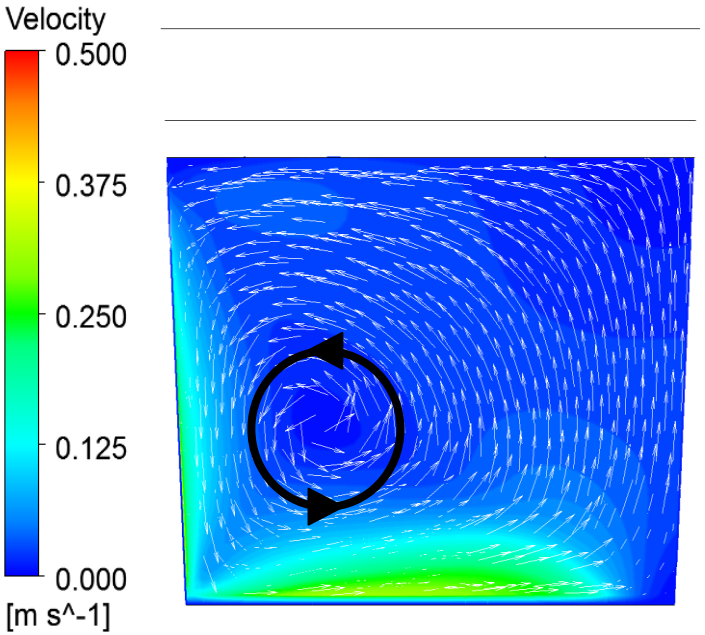
EMS Simulation Work

- **<u>CFD Simulation</u>** performed using ANSYS Fluent and the MHD Module
  - 3D Transient
    - Timestep: 0.01 [s] (limited by frequency of magnetic field)
  - Isothermal (Neglecting Joule Heating)
  - Multiphase
    - VOF Model
      - Steel – Primary Phase
      - Argon – Secondary Phase
      - Slag – Secondary Phase
    - Turbulent Model: k-ϵ, Realizable
  - FLUENT MHD Module
    - Imported simulated magnetic field

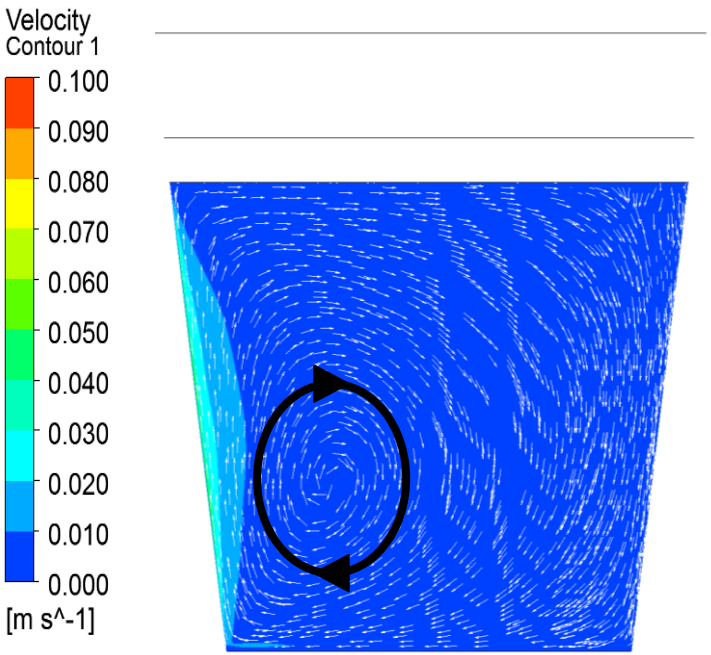


EMS Simulation Issues

- CFD Simulations result in average flow velocities well **below** expected values even using industry magnetic field data
  - Davidson, 2016 states metallurgy EMS velocity is limited by 1 [m/s]



Downward Stirring SMSVC



Upward Stirring Industry Provided Data

25 Seconds	CIVS Downward	[1] Downward	Industry Provided Upward	[1] Upward
Velocity [m/s]	0.05	0.7	0.003	0.5

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." 2009
P.A. Davidson. Introduction to Magnetohydrodynamics. 2 edition, 2016.

EMS Simulation Issues

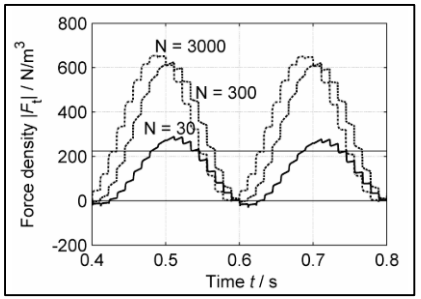
- Flow acceleration issues have been a recurring problem
- Many steps taken to identify problem source:
  - EMF import formatting? → Verified import format
  - Time step size → Frequency dependent
  - Mesh sensitivity? → Skin depth meshing
  - EMF simulation? → Industry collaboration
  - MHD settings? → **Field strength scaling**
- Literature (Javurek, et al.) mention Fluent MHD issues
- Field strength scaling produced appropriate velocity fields
- Alternatives to scaling being investigated:
  - Forced large number of iterations per timestep
  - Application of imported Lorentz force field as a source term
  - UDF of uncoupled MHD to replace MHD module

"During the solution process irregularities were detected: the resulting Lorentz-forces show a strong dependence from the number of iterations per time-step."

"At the beginning of each time-step, the force changes rapidly within the first few subiterations. Then the change rate decreases and one might have the impressions that the solution is converged, but if the iteration is continued, the force still changes but with a very small slope."

"The force according to [EMF force density equation] is about 40% less than the value reached for high numbers of *N*."

- Javurek, et al., 2008

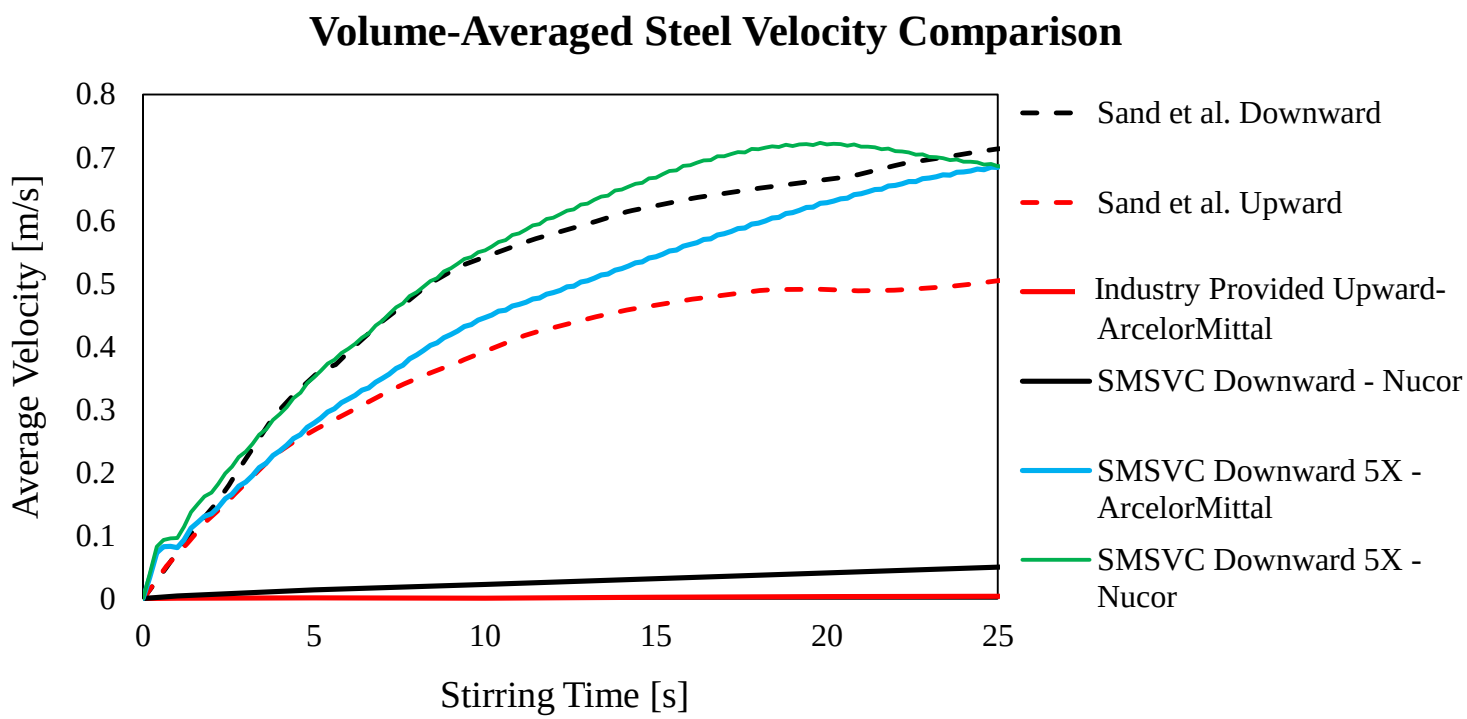


Force densities versus number of iterations *N*. Javurek, et al. 2008

Javurek, et al., "Flow Modelling in Continuous Casting of Round Bloom Strands with Electromagnetic Stirring", 2008

MHD Field Strength Scaling

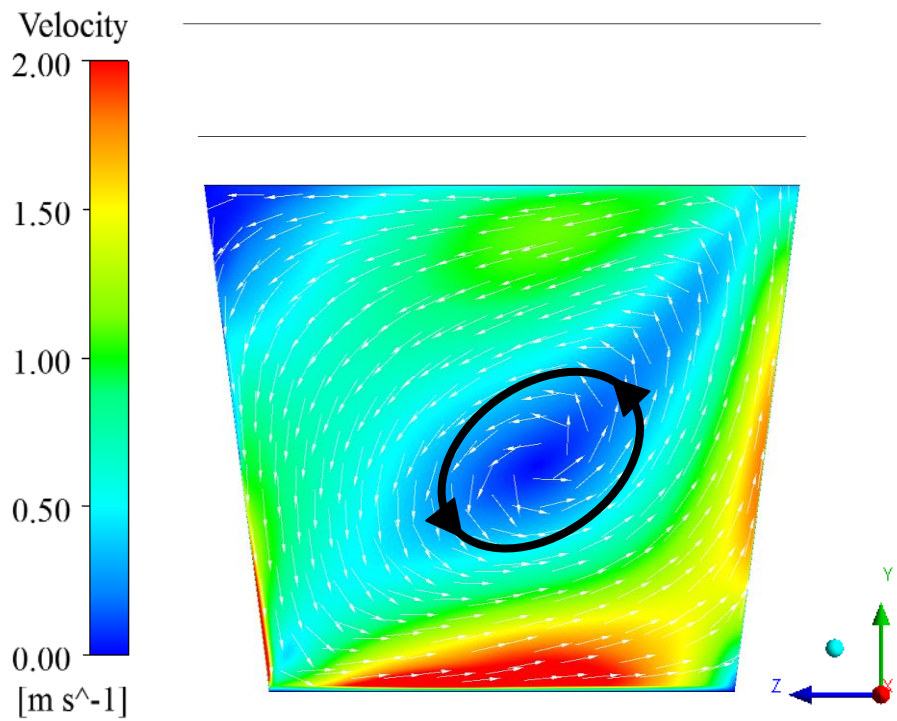
- MHD module contains a scaling feature for the magnetic field
  - Results are completely off when scaling is set to 1
  - Scaling by a factor of 5 results in expected velocity development trends
    - Velocity development **trend** agrees with literature



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."

Vortex – Developed Velocity Field

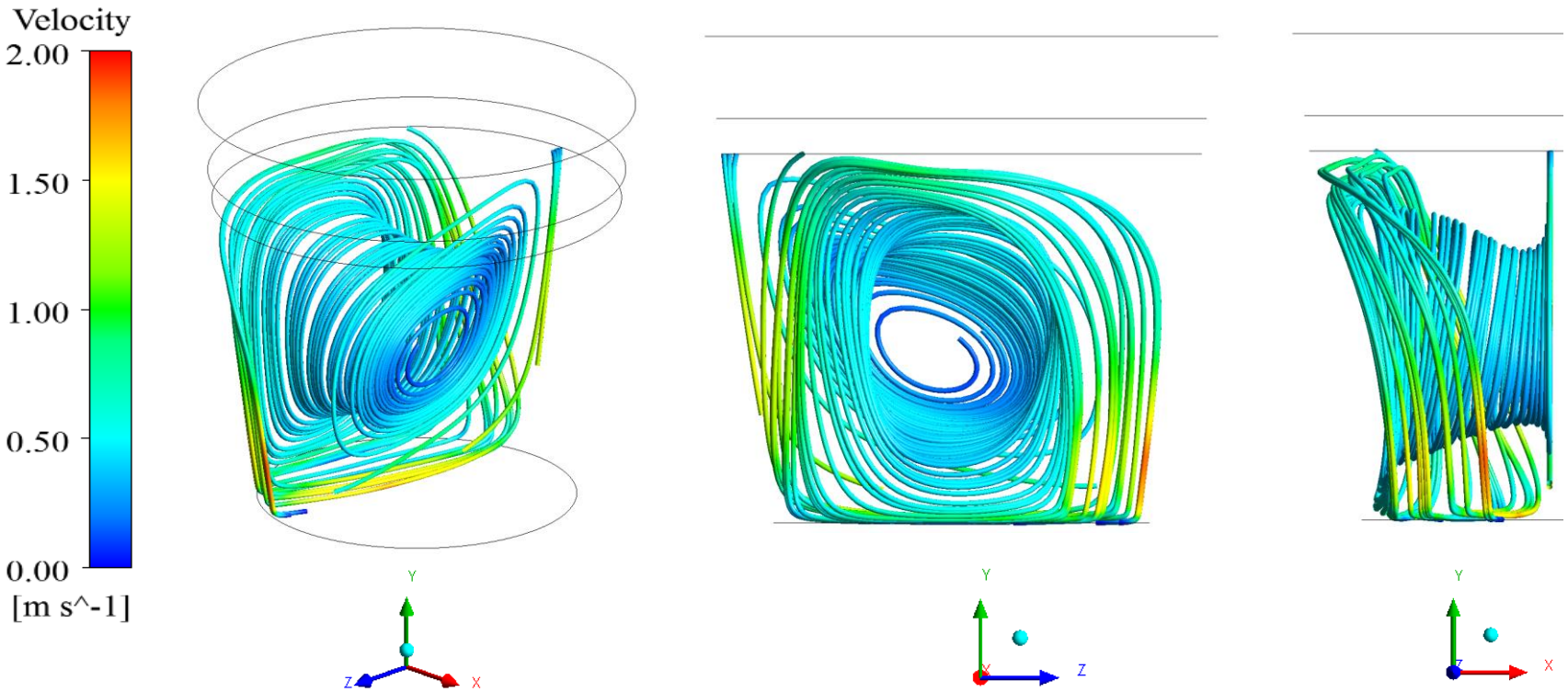
- Fully developed at 25 seconds
  - Volume-Averaged Velocity: 0.7 [m/s]
  - Single vortex in steel phase
  - Slight elongation with positive slope along the yz-plane



Velocity Vector/Contour Plot

Vortex – Velocity Distribution

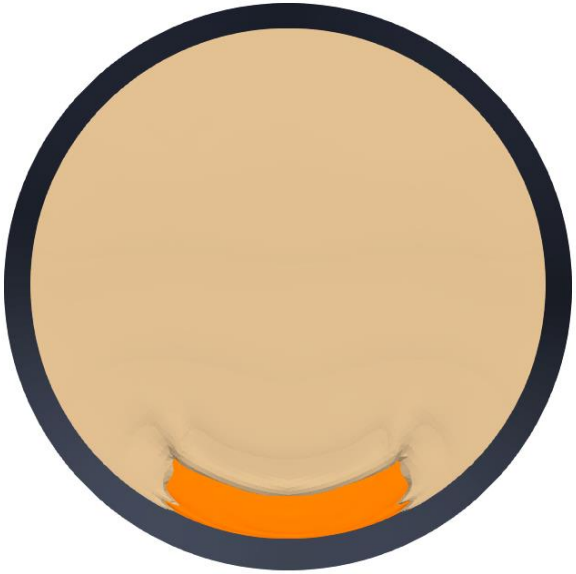
- Fully developed flow at 25 seconds
  - Vortex distributes the velocity field
  - The bulk flow is near the expected average velocity
  - Streamline representation:



Multiphase Flow – Slag Eye Formation

- Tangential surface flow creates opening in slag layer
- Slag eye to slag area ratio: 0.06

Isometric View



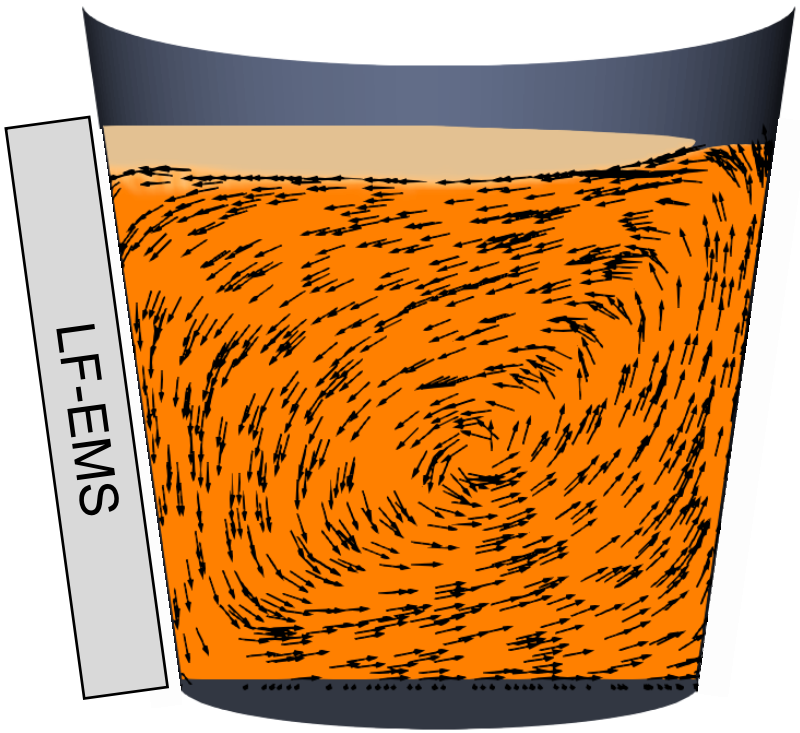
Top View

Cross Sectional View XZ-Plane

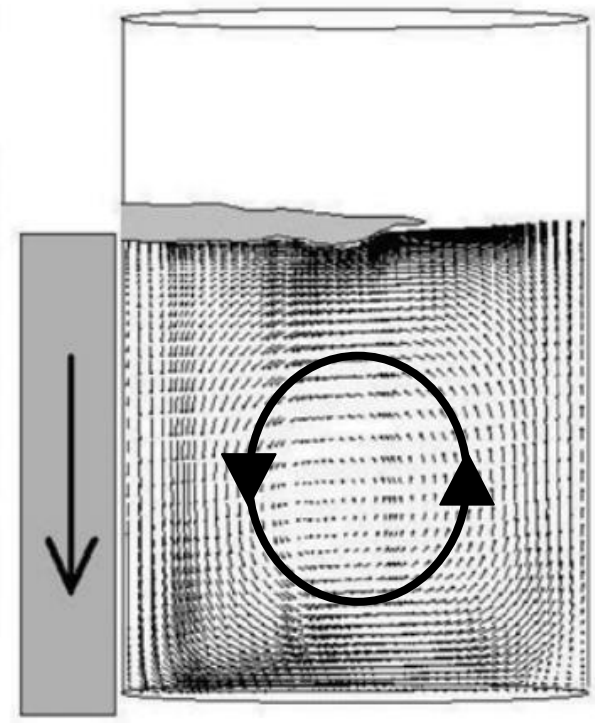
U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, "Numerical and Experimental Study on Fluid Dynamic Features of Combined Gas and Electromagnetic Stirring in Ladle Furnace.", 2009

Slag Eye Formation Comparison

- Velocity field impinges on the slag layer creating the slag eye
- Slag eye occurs in the same region as literature results depict



Cross Sectional View
YZ-Plane



Downward stirring slag eye
from Sand, et al. 2009

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.", 2009

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)**
    - Slag displacement from EMS effect
    - Effectiveness of inclusion removal (using same methods as gas-stirred investigation)
  - Combination of gas-stirring and EMS
    - Compare to gas-only and EMS-only inclusion removal trends

Future Work

- **Gas-stirred Ladle**
  - Revise current turbulence model
  - Revised current bubble model
  - Validate inclusion removal model with industrial measurement
  - Implement chemical reaction into the current model

- **EMS Ladle**
  - Validate EMS model against results obtained from Sand et al.
  - Inclusion removal simulation using developed flow field
    - Validate with literature and compare with gas-stirred ladle simulation
  - Explore other methods to obtain the developed flow
    - Iteration count, UDF, Lorentz force field, etc.
  - Combined EMS/Gas-stirring simulation

Comments from Industry Collaborator

Thank You
Questions and Comments

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